Planning & Development Services

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Public Comments on 2025 Critical Areas Ordinance and Development Regulations Update

Count	Name	Organization/ Address	Comment Method	Date Received
1	Jeff Poetsch	JCPoetsch Advisors (Skagit Environmental Bank)	Email	05/02/2025
2	Jan Edelstein	17173 West Big Lake Blvd Mount Vernon, WA 98274	Email	05/02/2025
3	Jake Koopmans		Email	05/05/2025
4	Kim Sanford		Email	05/05/2025
5	Jan Edelstein	17173 West Big Lake Blvd Mount Vernon, WA 98274	Email	05/06/2025
6	Jan Edelstein	17173 West Big Lake Blvd Mount Vernon, WA 98274	Email	05/06/2025
7	Stephen Aghjayan	7344 Skagit View Drive Concrete, WA 98237	Email	05/06/2025
8	Dean and Julie Seckel		Email	05/06/2025
9	Rosanna Wuebbels	11134 O Ave. Anacortes WA 98221	Email	05/06/2025
10	Tricia Sears	Washington Department of Natural Resources	Email	04/22/2025
11	Kimberley & Danny Sanford, Jacob Koopmans, Greg Wittendorf	PO BOX 839 Lyman WA 98263	Email	05/07/2025
12	Leslie Parks		Email	05/08/2025
13	Jenna Friebel	Skagit Drainage & Irrigation Districts Consortium	Email	05/08/2025
14	Irene Derosier	11260 Bayview Edison Rd. Mt Vernon 98273	Email	05/08/2025
15	Molly Doran	Skagit Land Trust	Email	05/08/2025

16	Heather Spore	Swinomish Indian Tribal Community	Email	05/08/2025
17	Jan Edelstein	17173 West Big Lake Blvd Mount Vernon, WA 98274	Email	05/08/2025
18	Mike Wolten	Sauk-Suiattle Indian Tribe	Email	05/08/2025
19	Kim Matthews	Western Washington Agricultural Association	Email	05/08/2025
20	Allen Bush	Guemes Island Planning Advisory Committee (GIPAC)	Email	05/08/2025
21	Ellen Bynum	Friends of Skagit County	Email	05/08/2025
22	Nora Kammer	Skagit River System Cooperative	Email	05/08/2025
23	Timothy Manns	Skagit Audubon Society	Mail	05/08/2025
24	Andrea Xaver	19814 State Route 9, Mount Vernon, WA 98274	Email	05/08/2025
25	Sophia Steele	Western States Petroleum Association	Email	05/08/2025
26	Lora Claus	Skagitonians to Preserve Farmland	Email	05/08/2025
27	Morgan Krueger	Washington Department of Fish and Wildlife	Email	05/08/2025
28	Tim Trohimovich	Futurewise	Email	05/08/2025
29	Kaia Hayes	RE Sources	Email	05/08/2025
30	Eddy Ury	RE Sources	Email	05/08/2025

Robby Eckroth

From: Jeff Poetsch <jeffcp@earthlink.net>
Sent: Friday, May 2, 2025 1:45 PM
To: PDS comments
Subject: 2025 Development Regulations and Critical Area Ordinance Update

My name if Jeff Poetsch and I live at 1028 Wilmington Way in Redwood City, California 94062. I am President of JCPoetsch Advisors, Inc. the managing member of Clear Valley Environmental Farm, LLC ("CVEF"). CVEF is the owner of the Skagit Environmental Bank ("SEB"). SEB is a 396-acre wetland mitigation environmental bank located in Skagit County just outside the city limits of Mt Vernon. certified by the regulatory agencies including the US Army Corps of Engineers, the Washington State Department of Ecology and Skagit County. SEB has received an initial release of 28.98 credits in December 2013 and a further release of 18.13 credits in May, 2020. Further credits will be released over the next 8-12 years as detailed performance criteria are met as specified in the mitigation banking instrument (MBI). Wetland mitigation credits from the SEB have been used as compensatory mitigation by Skagit County for both the Farm to Market / Josh Wilson road improvements and the Skagit Playfields. Other purchasers of wetland mitigation credits from SEB to addresss compensatory mitigation requirements for project development include the Port of Skagit, City of Sedro-Woolley, US Army Corps of Engineers, Skagit PUD, Washington Department of Fish and Wildlife, as well as multiple commercial development projects. In response to the current draft of the 2025 Critical Area Ordinance Update, we have the follow comments:

12.24.250 (1). Off Site Compensation - The current draft states "On-site compensation is generally preferred over offsite compensation". This statement is inconsistent with the best available science and recommedations of both the US Army Corps of Engineers and the Washington State Department of Ecology. The Final Rule issued by the US Army Corps of Engineers on April 10 2008 establishes a preference hierachy for compensatory mitigation options. The highest preference for compensatory mitigation is Mitigation Banks. Second preference is in-lieu fee programs and the third preference is Permitte Responsible mitigation under a watershed approach. Permittee Responsible Mitigation through "On-Site and In-Kind Mitigation" is the fourth preference with offsite mitigation by Mitigation Banks as the highest preference.

The Washington State Department of Ecology is equally definitive on the preference for the use of Mitigation Banks or In-Lui Fee Programs to address compensatory mitigation requirements. Specifically on Page 28 of Publication 22-06-014 - Wetlands Guidance for COA Updates, the document states - *"If a proposed project is located within the service area of a Corps-approve mitigation bank or ILF program, per the 2008 Federal Mitigation Rule, the application must first consider their use a compensatory mitigation before considering the permittee-responsible mitigation options ..."*

As such, the draft should be corrected to state *"Offsite compensation through the use of a Corp-approved Mitigation Bank or In-Lui Fee Program is generally preferred over Permittee responsible mitigation under the watershed approach or Permittee responsible mitigation through on-site and in-kind mitigation."*

14.24.250 (1) (a) - State sample wetland regulations (070.F.4.b - page A-21) specify that credits from a state-certified mitigation banks may be used as compensaltion in accordance with the bank service area rather than drainage basin. *"Off-site compensation must occur within the same drainage basin of the same watershed where the wetland loss occurs unless credits from a Corps certified wetland mitigation bank are used as compensation and the use of credits is consistent with the terms of the certified bank instrument."*

14.24.250 (1) (b) - Given that the order of preference for providing compensatory mitigation seeks to discourage on-site mitigation, this section should probably be deleted, or it should be clarified to state - *"Off-site compensation can be allowed only under 1 or more of the following circumstances unless credits from a Corps certified wetland mitigation bank are used as compensation."* While paragraph (v) alludes to state and federal requirements by permitting agencies, the preference for the use of mitigation banks to address

compensatory mitigation requirements should be expressed clearly and explicitly in the updated Critical Areas Ordinance.

Add Section Approaches to Compensatory Mitigation - In a similar manner as Section 14.24.250 (3) was added to match Ecology's guidance on Selecting Compensation Sites, it should be equally appropriate to include a Section to "match" guidance 070.D (Pages A-16 & A-17) in their Sample Wetland Regulations. Additionally, it is appropriate to add language reflecting the language of Page 28 of the Department of Ecology's Publication 22-06-014 - Wetlands Guidance for COA Updates I have pasted this section below and highlighted in "bold" the language from page 28 of Publication 22-06-014 :

> *Approaches to Compensatory Mitigation. Mitigation for lost or diminished wetland and buffer functions shall rely on the approaches listed below:* ***If a proposed project is located within the service area of a Corps-approve mitigation bank or ILF program, per the 2008 Federal Mitigation Rule, the application must first consider their use a compensatory mitigation before considering the permittee-responsible mitigation options."***
>
> *1. Wetland Mitigation Banks. Credits from a wetland mitigation bank certified under Chapter 173-700 WAC may be used to compensate for impacts located within the service area specified in the mitigation bank instrument if all the following are met: a. The [Administrator] determines that it would provide appropriate compensation for the proposed impacts; and b. The proposed use of credits is consistent with the terms and conditions of the mitigation bank instrument. c. Mitigation ratios are consistent with ratios specified in the mitigation bank instrument.*
>
> *2. In-Lieu Fee (ILF) Mitigation: Credits from an approved in-lieu fee program may be used when all the following apply: a. The [Administrator] determines that it would provide appropriate compensation for the proposed impacts. b. The proposed use of credits is consistent with the terms and conditions of the approved ILF program instrument. c. Projects using ILF credits shall have debits associated with the proposed impacts calculated by the applicant's qualified wetland professional using the credit assessment method specified in the approved instrument for the ILF program. d. The impacts are located within the service area specified in the approved ILF instrument.*
>
> *3. Permittee-responsible, advance mitigation. Advance mitigation is a form of permittee-responsible mitigation implemented before a permitted impact takes place. It is designed to compensate for impacts expected to occur in the future. The applicant proposing the advance mitigation is the only one who can use the credits generated. Credits cannot be sold or transferred to another applicant. Advance mitigation proposals should be developed in accordance with state and federal rules and guidance on advance mitigation (Interagency Regulatory Guide: Advance Permittee-Responsible Mitigation, Ecology Publication #12-06-015, and Chapter 4.2 of Wetland Mitigation in Washington State–Part 1: Policies and Guidance—Version 2, Ecology Publication #21-06- 003, or as revised).*
>
> *4. Permittee-responsible, concurrent mitigation. Concurrent mitigation is a form of permittee-responsible mitigation implemented at the same time permitted impacts are occurring. The permittee is responsible for implementation and success of the compensation. Concurrent mitigation may occur at the site of the permitted impacts or at an off-site location, usually within the same watershed. Permittee-responsible, concurrent mitigation shall be used only if the applicant's qualified wetland professional demonstrates to the [Administrator]'s satisfaction that the proposed approach is ecologically preferable to use of a bank or ILF program, consistent with the criteria in this Section.*

14.24.250 (4) - Innovative Wetland Mitigation Projects - With the inclusion of language similar to Section 070.D in the Sample Wetland Regulations from the Department of Ecology, it would seem that this Section could be deleted.

Thank you for the consideration of these comments and reccomdations regarding text corrections. Please do not hesitate to contact me with any questions, comments or concerns

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Comment #2

Robby Eckroth

From: Jan Edelstein <jmeten@comcast.net>
Sent: Monday, May 5, 2025 7:16 AM
To: PDS comments
Subject: Supplement to CAO comments filed May 2, 2025
Attachments: Supplement to Edelstein CAO Update Comments Dated May 2.2025 .pdf; 2018_Big-Lake-303d-Phosphorus.pdf; Dr.HornerOpinionBigLakeDegraded.pdf

Hello,

I submit the attached Supplement with 2 attachments to my comments filed on May 2, 2025, regarding the Critical Areas Ordinance Update hearing scheduled for May 6, 2025.

Attachments:

1. Print of Ecology's "Main Listing Information" for Big Lake for Total Phosphorus.
2. Dr. Richard Horner's

Please file and provide to the Planning Commissioners.

Regards,
Jan Edelstein
208-720-0709

Main Listing Information

Listing ID: 6163
Waterbody Name: BIG LAKE
Medium: Water
Parameter: Total Phosphorus
WQI Project: None
Designated Use: Aquatic Life - General

Year	Category
2018	2
2012	2
2010	2
2008	2
2004	2
1998	Y
1996	Y

Assessment Unit

Assessment Unit ID: 17110007000662_001_001
Size: 2.17 Square kilometers
Associated Components(s): Reach: 17110007000662, Type: Lakes
County: Skagit
WRIA: Lower Skagit-Samish

Basis Table

See Basis Statement field.

Basis Statement

HISTORICAL INFORMATION

O'Neal et al. (2001) concludes that designated uses are being supported.

In 1999, the mean measured total phosphorus concentration for Big Lake was 18.7. Pending a more thorough study, a tentative total phosphorus criterion of 20 µg/L was recommended.

Completed Lake Assessment Project in 1978 - Problems Encountered: Blue-green algae, low dissolved oxygen, tributary nutrient inputs. No control measures were implemented. URS Company, 1977.

Remarks

Assessment Cycle 2018 - A historic Category 2 determination was carried forward from a previous assessment or administrative decision. See Historic Basis Statement for previous assessment information.

Sumioka and Dion basis removed on 04/10/06. -kk According to O'Neal et al. (2001), shallow depths, dense residential development, and a location in a relatively large watershed may render Big Lake particularly susceptible to (and may have already caused) human-caused eutrophication. Future studies may likely recommend lowering the total phosphorus criterion.

Data Sources

No Source Records

Map Link

Map Link (https://apps.ecology.wa.gov/waterqualityatlas/wqa/map?lstid=6163)

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November 19, 2024

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To Whom It May Concern:

I reviewed the Stormwater Site Plan Overlook Crest Plat, Skagit County, Washington, July 2022 (the Stormwater Plan) submitted by the proponent of the Overlook Crest Plat development (Overlook Crest, the development, or the project) in the Skagit County (the County). I focused on the proposed system to manage the stormwater runoff from the development and its potential effects on the waters that would regularly receive the stormwater discharge (Big Lake and its outlet stream). In addition to the Stormwater Plan, I relied on sources from the literature of the stormwater management field and internet resources, all cited in footnotes. This letter presents the conclusions I reached.

In evaluating the Overlook Crest documents, I applied the experience of my 47 years of work in the stormwater management field and 11 additional years of engineering practice. During this period, I have performed research, taught, and offered consulting services on all aspects of the subject, including investigating the sources of pollutants and other causes of aquatic ecological damage, impacts on organisms in waters receiving urban stormwater drainage, and the full range of methods of avoiding or reducing these impacts. Attachment A to this letter presents a more complete description of my background and experience, and Attachment B contains my full *curriculum vitae*. The following Table of Contents is a directory of the topics in this letter.

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SUMMARY OF MY CONCLUSIONS AND OPINIONS

Based on my assessment, I have drawn conclusions and formulated opinions as follows:

- Big Lake provides habitat for salmonid and other fish and qualifies as a Critical Area under the County's Critical Areas Ordinance. Despite this status, it is listed as impaired by several water pollutants and is in a eutrophic (relatively highly phosphorus-enriched) condition, with excessive algal and aquatic plant growths degrading its beneficial uses.

- The construction phase of the Overlook Crest project poses substantial risk to Big Lake through soil erosion and the transport of sediments and the phosphorus they carry. This risk is amplified by the steep slopes on the site and the resulting elevated erosion tendency.

- The Stormwater Plan offers almost no detail on how this construction-phase risk will be countered. There must be a thorough analysis of all the factors contributing to it and, before development approval, a comprehensive plan presented to employ a range of source control practices and implement advanced construction runoff treatment to protect the lake.

- Based on extensive data collected in the stormwater management field, the finished and occupied development will generate higher runoff volumes and concentrations and mass loadings of a number of water pollutants, some not previously of concern, compared to the current open land. It is my opinion that the Overlook Crest development stormwater management plan as proposed will result in substantial increase in the discharge of phosphorus and other pollutants to, and degradation of, Big Lake.

- To counter this threat, the Stormwater Plan offers only sketchy pollutant source controls without commitments. It further proposes to manage runoff in adjacent, downslope golf course ponds modified to serve both as a detention basin for flow control and a wet pond for pollutant capture. Based on extensive data collected on wet ponds, it will not sufficiently reduce phosphorus in the discharge to prevent further eutrophication of Big Lake. It is my opinion that, given the deficiencies of the construction and post-construction stormwater management plans proposed for Overlook Crest, the development will aggravate the already eutrophic and degraded state of Big Lake.

- I recommend that, before development approval, the Stormwater Plan be extensively upgraded to specify and commit to a broad suite of pollutant source controls and supplement the golf course ponds with either: (1) comprehensive stormwater infiltration based on additional geotechnical work to identify any localized opportunities for runoff dispersion and assess deep infiltration via wells; or (2) bioretention units to collect and treat runoff from the road through the development and any runoff draining onto the road from residential properties. It is feasible in my opinion to construct these units without underdrains, except in locations where lateral drainage across the glacial till would cause some problem.

- It is my opinion that the success of any upgraded stormwater management plan for the Overlook Crest development will require significant inspection, maintenance and repair efforts which will need a secure funding source.

- The potential environmental harm associated with the development as proposed warrants a full environmental impact assessment.

The remainder of my letter elaborates on these points and justifies my conclusions and opinions.

THE PROPOSED DEVELOPMENT

The Site and Development Proposal

According to the Stormwater Plan, the proposed development would cover an area of approximately 180 acres east of Big Lake and north and east of the Overlook Golf Course located downslope from the project site. The project includes phased development of up to 105 residential lots with associated open space, utilities, and roadways. There will be approximately 59 acres of cluster development and 118 acres of open space with access via streets dedicated to the public. The residential lots will be along the slope east of the golf course and range in size from 1/3 acre to 1 acre.

Access will be via an existing private road to be improved to Skagit County standards and made public. The proposed roadway within the plat will also be public, encompassing approximately 13 acres and to be constructed to Skagit County Road standards within a 60-foot-wide right-of-way. A second emergency access to the development will be constructed along the northern property line.

The site is currently vegetated with grass, brush, and scattered tree cover. Topography of most of the site slopes down to the west towards the flat-lying golf course. Site topography at the east end of the site slopes downward in all directions from a hilltop feature. Site slopes range between 3 percent and 35 percent, with an average slope of approximately 13 percent.[1]

The Proposed Stormwater Management System

The Stormwater Plan states that the finished development will have two stormwater catchment areas, which it refers to as Threshold Discharge Areas (TDAs). TDA 1 is the much larger, encompassing the majority of the area producing stormwater runoff. It also receives run-on drainage entering from off the site. TDA 1 stormwater will drain to ponds on the golf course. The access road and associated sidewalk will comprise TDA 2, the runoff from which will disperse through existing vegetation.

Stormwater flow control and treatment for TDA 1 will be managed in the existing golf course Ponds 1-4. Pond 1 is the largest and farthest downstream. The ponds will function as both a detention basin for flow control and wet pond for water quality treatment. They will operate as a

[1] The Stormwater Plan is inconsistent regarding the average slope, with page 5 citing 13 percent and page 30, under the Stormwater Modeling Overview, stating 8 percent.

single system, since they are all have the same bottom elevation. Aqua-Swirl hydrodynamic separators will be installed at two inlets to the pond system for pre-treatment. The ponds will be expanded, interconnected, and have a flow control structure added to Pond 1. Berms will be constructed on the north and south ends of the ponds to create the necessary detention volume.

Water discharging from the golf course pond system travels through a smaller pond that turns into a channel as it leaves the site. From there it passes through a series of channel, culvert, and pipe conveyances to Big Lake. This downstream system will be upgraded as part of the project to handle additional flow. The Stormwater Plan implies that increased flow would result from failure of the pond control structure and that the upgrades will be designed for the 100-year peak storm discharge.

The Stormwater Plan fails to describe how the drainage at the east end of the site sloping downward from a hilltop feature will be managed. It is also vague on the dispersal of runoff from TDA 2. Although these flows may not affect Big Lake, the plan should cover their disposition.

THE BIG LAKE AQUATIC ECOSYSTEM

General Description

Big Lake, at 536 acres in size, is the largest lake in Skagit County. It provides important wildlife habitat, and offers recreational opportunities, including swimming, fishing, boating, and shoreline-related activities. The lake has a Washington Department of Fish and Wildlife boat ramp and is heavily used by both lake residents and the public for recreation. Beneficial uses of the lake have been severely impacted from dense, prolific growth of invasive aquatic plants.[2] Big Lake is listed as an impaired water body for the parameters in Table 1 in the Washington Department of Ecology (Ecology) Water Quality Assessment under Clean Water Act section 303(d).

Big Lake has existing or potential habitat for the salmonids coastal cutthroat trout, coho salmon,[3] bull trout, and Dolly Varden.[4] Angling opportunities include largemouth bass, yellow perch, pumpkinseed sunfish, and black crappie, in addition to the cutthroat trout.[3] Accordingly, Big Lake qualifies as a Critical Area under the Skagit County Code 14.24 Critical Areas Ordinance. Among other criteria for this designation, the ordinance lists areas with which endangered, threatened, and sensitive species and anadromous fish species have a primary association.

Big Lake is tributary to Nookachamps Creek, which hosts Chinook salmon (fall run) rearing and also has existing or potential habitat for coho salmon (spawning and rearing), bull trout, and Dolly Varden.[4] The creek has 303(d) impairment listings in common with Big Lake and some others,

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[2] https://www.skagitcounty.net/Departments/PublicWorksSurfaceWaterManagement/biglake.htm (accessed November 11, 2024).
[3] https://wdfw.wa.gov/fishing/locations/lowland-lakes/big-lake (accessed November 11, 2024).
[4] Montgomery Water Group, Inc. 2007. Big Lake Drainage Management Plan, Final Draft. Board of County Commissioners, Skagit County Public Works Department, Mount Vernon, WA. https://www.skagitcounty.net/PublicWorksNaturalResourcesManagement/Documents/Big%20Lake%20DMP/Text/Big%20Lake%20Drainage%20Management%20Plan%20Final%2011%2009%2007.pdf (accessed November 11, 2024).

including dissolved oxygen. That quantity could be affected by conditions in the lake, a subject I cover later.

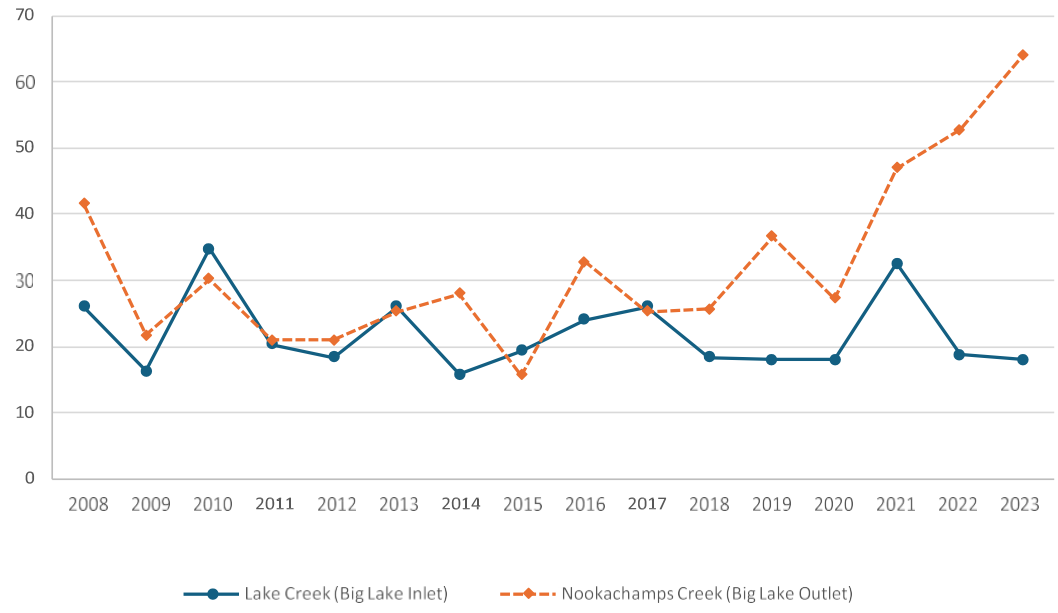
Table 1. Big Lake Impairments under Clean Water Act Section 303(d)[5]

Parameter	Medium	Category[a]
Hexachlorobenzene	Tissue	5
Dioxin	Tissue	5
Polychlorinated Biphenyls (PCBs)	Tissue	5
Invasive Exotic Species	Habitat	4C
Total Phosphorus	Water	2
2,3,7,8 TCDD TEQ	Tissue	2

[a] Water bodies are designated as Category 5 if they have: (1) data showing that water quality standards have been violated for one or more pollutants; (2) no Total Maximum Daily Load (TMDL) or pollution control program in place; and (3) impaired designated uses, such as for drinking, recreation, aquatic habitat, and industrial use. Category 4C waters are impaired by causes that cannot be addressed through a TMDL plan, including low water flow, stream channelization, and dams. In Category 2 are waters of concern based on evidence of problems.

Figure 1 presents annual mean total phosphorus (TP) concentrations measured by Skagit County Public Works Natural Resources Division at Big Lake's inlet and outlet since 2008. It may be seen that the inlet concentrations have been relatively stable around approximately 20 µg/L over those years. The outlet concentrations, representing those being released from the lake, were also fairly stable around approximately 30 µg/L through 2020 but then began to climb steeply. The mean concentration reached 64 µg/L, over twice the usual historic level, in the most recent year.

Figure 1. Mean Annual Total Phosphorus (µg/L) at Big Lake's Inlet and Outlet



[5] https://apps.ecology.wa.gov/waterqualityatlas/wqa/map?CustomMap=y&BBox=-14338616,5395963,-12562831,6503994&RT=0&Layers=27&Filters=y,n,n,n,n,n (accessed November 11, 2024).

In 1999, the Department of Ecology established the recommended TP maximum concentration for Big Lake as 20 ug/L.[6] This criterion is consistent with WAC 173-201A-230 establishing lake nutrient criteria.[7] While that level was exceeded more often than achieved in earlier years, the differential was not large until 2021 and more than tripled by 2023. Also, the data plotted in Figure 1 are annual means; some individual measurements are higher.

Eutrophication in Big Lake

What Eutrophication Is

Eutrophication is the process by which a body of water becomes enriched in nutrients that stimulate the growth of photosynthesizing primary producers (algae and plants), usually resulting in negative effects on the aquatic ecosystem. The growth of an algal cell or plant tends to be controlled by, more than any other agent, the nutrient in least supply relative to the physiological need, known as the limiting nutrient. That nutrient is generally either phosphorus (P) or nitrogen (N), but in fresh waters is more often P. N still can be limiting at times, for example when high algal biomass incorporates much of the P supply, leaving little available in the water.

Addition of the limiting nutrient not only increases algal abundance but also tends to change the community from single-celled organisms to filamentous forms, which are less desirable for several reasons. They are generally an inferior food source for wildlife; clog water intakes, conveyances, and boat motors; and foul beaches when they wash up on them. Some filamentous blue-green algae produce toxins that can kill an animal that drinks directly from the water and must be removed before distributing to humans.

When the increased masses of algae and plants die, bacteria decomposing them exert a large demand on the oxygen dissolved in the water and reduce the amount available for aquatic life. Other sources of organic material issuing from a construction site or urban community supplement this oxygen demand. It is not unusual for a eutrophic lake to have little or sometimes no oxygen in the colder waters at the bottom, and reduced oxygen even near the surface.

Oxygen depletion is not only an issue for the lake but also for the outlet stream, Nookachamps Creek, which is already impaired for dissolved oxygen (DO). DO tends to be lowest in the warmest months of the year, because as temperature rises the capacity for oxygen to dissolve in water decreases. In the June-August period of 2023, DO in Nookachamps Creek at the lake discharge averaged 2.85 mg/L lower than at the lake inlet. It was as low as 6.54 mg/L, well below the 10 mg/L state water quality criterion.[8] The salmonids in the stream are particularly sensitive to reduced oxygen levels. Decomposable algae and plants, as well as low-oxygen water, entering from the lake are aggravating factors.

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[6] https://apps.ecology.wa.gov/approvedwqa/approvedpages/viewapprovedlisting.aspx?ListingId=6163 (accessed November 13, 2024).
[7] https://app.leg.wa.gov/WAC/default.aspx?cite=173-201A-230&pdf=true (accessed November 13, 2024).
[8] Data from Emma Santana, Skagit County, emmas@co.skagit.wa.us.

An anaerobic condition at the water-sediment interface along the lake bed enables chemical reactions that release a variety of deleterious pollutants into the water column. One of these substances is phosphorus itself, which stimulates further algal growth. Thus, eutrophication sets up a feedback loop compounding the problem. Oxygen depletion at the sediments also releases ammonia, iron, manganese, other metals that are toxic to fish and invertebrates, hydrogen sulfide, methane, and other organic compounds.

Another negative effect of eutrophication is increased daytime pH, through heightened extraction of carbon dioxide during photosynthesis by the abundant algae and plants. Removal of carbon dioxide from the water raises pH through reduction of bicarbonate, a buffering agent, which chemically dissociates to replenish the lost carbon dioxide. The rise of water pH also drives ammonia toward the unionized form (NH_3), which is more toxic to aquatic life than ionized ammonia (NH_4^+).

Excessive aquatic plants have several additional negative impacts. They disrupt food chains by altering habitat availability for fish and block light, making it harder for fish to find food and avoid predators. Heavy plant growth interferes with navigation and recreational activities such as boating, swimming, fishing and water-skiing. They also create stagnant water, providing good breeding ground for mosquitoes.

Assessing Big Lake Eutrophication

Lake trophic state is a measure of the relative amount of primary production through photosynthesis by algae and plants, and thus the degree of eutrophication. Trophic states are based on lake fertility and are typically classified as one of the following:

- Oligotrophic—Relatively few nutrients (nitrogen and phosphorus), high levels of dissolved oxygen, low algal concentrations, clear water;

- Mesotrophic—Medium amount of nutrients, moderately clear water, some algal blooms mostly in late summer, oxygen depletion at the bottom of the lake as biomass decomposes;

- Eutrophic—Nutrient rich, high level of primary production, reduced clarity, seasonally deficient in oxygen; or

- Hypereutrophic: Extremely rich in nutrients, highest primary production, poor clarity, broadly oxygen deficient.

Various systems have been proposed to classify trophic state. Commonly used classifications use three variables: (1) total phosphorus (TP); (2) chlorophyll *a*, a pigment in algae and plants that is most essential for photosynthesis, proportional to and representative of the primary producer biomass present in a water sample; and (3) Secchi depth, a measure of water clarity, how deep light can penetrate, determined by lowering a weighted disk on a cord into the water until it's no longer visible, raising it until it just becomes visible again, and determining its depth below the surface with a scale marked on the cord.

The North American Lake Management Society assimilated systems developed by Carlson (1977),[9] Vollenweider and Kerekes (1980),[10] and Carlson and Simpson (1996)[11] as the bases for a recommended classification.[12] In addition to the three variables cited above, this system uses a Trophic State Index (TSI) from Carlson (1977). Carlson actually proposed three TSIs based on the three key variables. Table 2 shows the classification of Big Lake according to this system. In addition to the latest mean annual TP concentration presented earlier, there is a 2023 chlorophyll *a* value from a Western Washington University monitoring program.[13]

Table 2. Classification of Big Lake Trophic Status

Variable	Big Lake Value	Criterion Range Containing Big Lake Value	Classification
Total phosphorus (TP)	64 µg/L	24-96 µg/L	Eutrophic
Chlorophyll *a* (Chl)	11.8 µg/L[a]	7.3-56 µg/L	Eutrophic
TSI(TP)[b]	64	50-70	Eutrophic
TSI(Chl)[b]	54	50-70	Eutrophic

[a] Data from https://diatom.cenv.wwu.edu/?page=singlelake:BIG; the 2023 chlorophyll *a* concentration was the highest measured in the most recent 10 years.
[b] From Carlson (1977), TSI(TP) = 14.42 x ln(TP) + 4.15; TSI(Chl) = 9.81 x 1n(Chl) + 30.6; where ln is the natural logarithm.

This analysis places Big Lake roughly midway in the eutrophic category, clearly outside the less enriched mesotrophic zone. It is therefore already relatively advanced in eutrophication and experiencing the elevated algal and aquatic plant growths characteristic of that state. It is vulnerable to further deterioration with increase phosphorus input. It is my opinion that the Overlook Crest development as proposed will result in substantial increase in the phosphorus and other pollutants reaching Big Lake. I explain the reasons for my judgment and what should be done to avoid that outcome in the remainder of this letter.

PREFACE TO MY ASSESSMENT

The Overlook Crest development poses multiple threats to the Big Lake ecosystem both during construction and over the years when occupied by residents. Conventional practice in the stormwater management field is to counter these risks by measures to prevent the creation of problems (*i.e.*, excessive runoff and pollutants in that flow) as much as possible and then apply backup practices to control runoff quantities and recapture pollutants before they can damage

[9] Carlson, R.E. 1977. A Trophic State Index for Lakes. *Limnology and Oceanography* 22(2):361-369.
[10] Vollenweider R.A and J.J. Kerekes. 1980). Background and Summary Results of the DECO Cooperative Program on Eutrophication. In: Proceedings of the International Symposium on Inland Waters and Lake Restoration. U.S. Environmental Protection Agency, EPA 440-5-81-010, p. 25-36, https://nepis.epa.gov/Exe/ZyPDF.cgi/9100Z7H5.PDF?Dockey=9100Z7H5.PDF (accessed November 15, 2024).
[11] Carlson, R.E. and J. Simpson. 1996. A Coordinator's Guide to Volunteer Lake Monitoring Methods. North American Lake Management Society.
[12] https://www.nalms.org/secchidipin/monitoring-methods/trophic-state-equations/ (accessed on November 13, 2024).
[13] I have not found any Secchi depth readings for Big Lake.

receiving waters. Preventive techniques are called source controls. Flow modulation practices seek to maintain pre-development discharge volumes and peak flow rates, and treatment controls remove pollutants before discharge to the receiving water. There are many options in these categories, and they differ in performance.

In the next several sections of this letter, I evaluate source controls and backup practices put forth for both the construction and long-term phases of the Overlook Crest development, to the extent they have been presented. There are many details missing in the available information. In these circumstances, I critique the proposals that have been issued and offer my opinions regarding the practices that should be adopted.

ASSESSMENT OF THE CONSTRUCTION PHASE OF THE PROPOSED DEVELOPMENT

Introduction

The Stormwater Plan on page 12 states that a Stormwater Pollution Prevention Plan (SWPPP) narrative will be provided within the civil site plan drawings. It further declares that this SWPPP and corresponding Temporary Erosion & Sediment Control Plan (TESC) has been created using the 2019 Manual[14] to ensure that the BMPs selected will meet Construction General Stormwater NPDES permit from Ecology. It does not appear that these documents actually have been created. Because the proposed construction poses formidable problems for managing construction site pollutants, potentially damaging to the Big Lake ecosystem, they should be produced and presented to the County and citizens for evaluation before further project consideration. The documents should fully detail the best management practices (BMPs) that will be used to control pollutants from all construction-related sources. Next, I detail factors creating the challenges and how they should be met with effective practices.

Slope Considerations

As I noted above, site slopes range between 3 percent and 35 percent, with an average slope of approximately 13 percent. These relatively steep slopes pose definite challenges for successfully managing construction-phase stormwater to comply with the permit's requirements.

Slope is a leading factor in soil erosion and sediment loss from a construction site. Thus, it is especially crucial to comprehensively address means of avoiding sediment transport from this site or, at the very least, holding it to a *de minimis* level. Achieving this goal requires careful, detailed analysis and development of a SWPPP incorporating superior BMPs tailored to the site's circumstances.

Construction zones cleared of vegetation and not otherwise stabilized yield much more sediment compared to the original area well covered with plants and to the same area restablized with vegetative cover following construction. Measurements and estimates using a mathematical model

[14] Referring to edition of Ecology's Stormwater Management Manual for Western Washington issued in 2019. The manual was updated in 2024, and that edition should be the basis for all aspects of Overlook Crest stormwater management.

(Revised Universal Soil Loss Equation Version 2, RUSLE2) indicate 30 to more than 1000 times as much soil loss can occur after vegetation clearing compared to before clearing. Therefore, one year of construction with no or inadequate erosion controls can release into the environment as much sediment loading as occurred over decades or even centuries before the piece of land had been cleared. All soils contain phosphorus, and poorly controlled erosion and the resulting sediment transport would be very damaging to the Big Lake ecosystem.

Going further into the matter of slope as an important determinant of erosion, RUSLE2 estimates soil loss potential according to variables representing rainfall characteristics, soils, slope length, vegetation cover, BMPs, and contributing area, in addition to slope steepness. All other factors being equal, the equation predicts the approximate increases in soil loss at different slope gradients given in Table 3. It can be seen that the rate of soil loss escalates greatly with increasing gradient. Slopes in the upper ranges of Table 3, and even greater, do exist in the areas to be disturbed for the Overlook Crest development. Even with the average slope on the site, uncontrolled soil loss is projected to be more than four times as great as on relatively flat ground. Owing to these circumstances and the related high potential soil loss, before the project moves forward, there should be full analysis and construction SWPPP development, followed by assessment by the County and the public.

Soils and Hydrology

Beyond giving insufficient attention to the topographic challenges to limiting sediment export during construction, the project documents likewise have given little emphasis to the potential erosiveness of site's soils. RUSLE2 takes soils and their erosivity property into account with a variable termed the K Factor, an index that quantifies the relative susceptibility of the soil to sheet and rill erosion. Values range from about 0.02 for the least erodible soils to 0.64 for the most erodible.[15] Thus, the challenge of erosion on a construction site can vary by more than 30 times due to soils alone. Soil properties affecting the K Factor include texture, organic matter content, structure, and saturated hydraulic conductivity. These characteristics must be known for a proper analysis of erosion potential and effective strategizing to defeat it.

Table 3. Comparison of Estimated Soil Loss as Slope Increases from 3 Percent

Slope (%)	Estimated Soil Loss Compared to 3% Slope[a]
6	1.8 times
10	3.0 times
14	4.7 times
20	7.0 times
25	8.9 times
30	10.7 times

[a] From Table 4-3 of Renard, K.G., G.R. Foster, G.A. Weesies, D.K. McCool, and D.C. Yoder. 1997. Predicting Soil erosion by Water: A Guide to Conservation Planning with the Revised Universal Soil Loss Equation (RUSLE).

[15] Natural Resources Conservation Service. 2001. Revised Universal Soil Loss Equation (RUSLE2) Handbook. U.S. Department of Agriculture, Washington, DC, https://www.nrcs.usda.gov/sites/default/files/2022-10/RUSLE2%20Handbook_0.pdf, (accessed November 15, 2024).

Agricultural Handbook No. 703, U.S. Department of Agriculture, Washington, DC. The example is for a slope 50 ft in length.

Since this information is not available in comprehensive form, the K factors around the site cannot be firmly established. Tokul gravelly loam soil predominates on the site according to Figure 3 in the Stormwater Plan. Loams do not generally have the lowest K values but can be in the moderate or even higher ranges depending on the controlling characteristics. Without thorough attention to the exact characteristics of soils that will be disturbed, it is impossible to make a proper assessment of erosiveness and the BMPs that will be necessary to prevent or mitigate it.

Producing a truly site-specific SWPPP will require hydrologic modeling of flows to be generated during construction; passed through on-site conveyances; probably held the golf course ponds for a time; and then discharged. This modeling should be performed with the current version of the Western Washington Hydrologic Model (WWHM2012). Resource protection demands that flows are estimated as well as possible to avoid erosion of conveyance channels, to size equipment correctly, and to protect the receiving waters from high discharges during construction.

It is clear from the project documents that this essential hydrologic modeling has not occurred. Approval of the project should not move further with this project until these construction-phase soils and hydrology assessments occur. They must then be incorporated in a project-specific SWPPP, along with the topographic considerations, for proper judgment of the construction-phase stormwater management plan.

<u>The Importance of Effective Construction-Phase BMPs</u>

Contaminants from a poorly controlled construction site include sediments, the pollutants for which they are a transport medium, and a host of harmful substances associated with construction materials, wastes, and equipment. Fueling of vehicles, other equipment, or both almost always occurs on large construction sites. Maintenance and cleaning also sometimes take place. Careless operations release petroleum products, which are then picked up and transported in runoff. Paint, solvents, cleaners, and other chemicals used in construction are sources of toxic organics.

The Stormwater Plan's program to mitigate these pollutants is insufficient for me even to develop a critique. While there are some specific BMPs mentioned on page 9 of the Subsurface Exploration, Geologic Hazard, Infiltration Feasibility, and Preliminary Geotechnical Engineering Report (the Geotechnical Report) in the Appendix, there is no expressed commitment to use them. Also, there is no indication of how the construction runoff will ultimately be treated and discharged. I can speculate that the topography and flow patterns on the site will direct it into the golf course ponds, but that is not stated. If it is the case, will the ponds be in their present form or modified to the final configuration? In either case, there appears to be no assessment if they will be adequate for the purpose of minimizing sediment export to Big Lake. If in their final form, collection of construction sediments could reduce their volume, and hence their future effectiveness, unless those sediments are removed when construction is complete.

It is important that sediment addition to Big Lake be *de minimis* given that eroded soils transport phosphorus, which is generally present in soils and to which the lake is sensitive and already

degraded. As pointed out above, the prevalent slopes on the site complicate achieving this goal. In this situation the best available erosion and sediment controls must be employed. Because the Stormwater Plan is so sketchy regarding construction-phase stormwater management and it is so crucial, I have made the effort to outline a program to which the development applicant should commit and the County should demand, as follows.

Recommended Construction-Phase BMPs

Construction Management Practices

The program I recommend starts with source controls to prevent or reduce to the greatest extent possible soil erosion and sediment transport from the site. The first measures to consider and make maximum use of are construction management measures such as:

- Maintain existing vegetation cover, if it exists, to the greatest extent technically feasible.
- Perform ground-disturbing work in the dry season, with the smaller risk of erosion, and work off disturbed ground in the higher risk wet season.
- Limit ground disturbance to the amount that can be effectively controlled temporarily in the event of rain.
- Use natural depressions and plan excavations to drain runoff internally and isolate areas of potential sediment and other pollutant generation from draining off the site, so long as safe in large storms.
- Schedule and coordinate rough grading, finish grading and erosion control applications to be completed in the shortest possible time over-all and with the shortest possible lag between these work activities.

Soil Stabilization Practices

An effective construction-phase BMP plan continues with stabilizing exposed soil with a cover appropriate to the site conditions, season and future work plans; for example:

- Rapidly stabilize disturbed areas that could drain off the site and will not be worked again, with permanent vegetation supplemented with highly effective temporary erosion control measures until at least 90 percent vegetative soil cover is achieved.
- Rapidly stabilize disturbed areas that could drain off the site and will not be worked again for more than three days, with highly effective temporary erosion control measures.
- If 0.1 inch of rain or more is predicted with a probability of 40 percent or greater, before the rain falls, stabilize or isolate disturbed areas that could drain off the site, and that are being

actively worked or will be within three days, with measures that will prevent or minimize to the greatest extent technically feasible the transport of sediment off the property.

Additional Erosion and Sediment Transport Reduction Practices

Additional source control measures that should be employed as appropriate to the site and conditions are:

- Specify emergency stabilization and/or runoff collection procedures (e.g., using temporary depressions) for areas of active work when rain is forecast.

- If runoff can enter storm drains, use a perimeter control strategy as a backup where some soil exposure will still occur, even with the best possible erosion control (the above measures).

- Specify flow control BMPs to prevent or minimize to the greatest extent technically feasible the following:

    - Flow of relatively clean off-site water over bare soil or potentially contaminated areas;

    - Flow of relatively clean intercepted groundwater over bare soil or potentially contaminated areas;

    - High velocities of flow over relatively steep and/or long slopes, in excess of what erosion control coverings can withstand; and

    - Erosion of channels by concentrated flows either by using channel lining, velocity control, or both.

- Minimize the number of construction entrances. Specify stabilization of construction entrance and exit areas, provision of a nearby tire, undercarriage, and chassis wash for dirty vehicles leaving the site with a wash water sediment trap, and a sweeping plan.

- Stabilize construction roads with crushed rock.

Construction-Site Stormwater Runoff Treatment Practices

All of the above BMPs are source controls, designed to prevent or minimize erosion and sediment transport. They are essential and excellent measures to employ but are unlikely to be preventive enough for the protection of Big Lake during a large construction project on relatively steep slopes in its watershed. They must be backed by effective sediment capture. As I speculated earlier, the Overlook Crest construction-phase stormwater runoff will flow to the golf course ponds. For that purpose, I do not consider those ponds, in whatever configuration, to be adequate for capturing the transported sediments and keeping them out of Big Lake.

Ecology's Stormwater Management Manual for Western Washington states, under the topic BMP C250, that a sediment pond is effective at removing larger particulate matter by gravity settling, but ineffective at capturing smaller particulates and may not be adequate to ensure compliance with the water quality standards in the receiving water. It advises that BMPs C250 (chemical treatment) and C251 (filtration) can reliably provide exceptional reductions of turbidity and associated pollutants, which includes phosphorus. These practices have been employed at hundreds of construction projects in Washington over many years. It is my strong opinion that an appropriate selection of treatment elements among these technologies is essential to protect Big Lake from negative impacts caused by Overlook Crest construction.

The advanced treatments employed at Washington construction sites generally involve filtration assisted either by chemical polymer addition or electrostatic coagulation. For years, chitosan, a bio-polymer derived from crab and shrimp shells, has performed extremely well at construction sites in reducing sediment loadings through particle flocculation and subsequent filtration, as well as in reducing metallic and organic pollutants in contaminated groundwater exposed in dewatering construction sites. The polymer is generally employed in a chitosan-enhanced sand filtration (CESF) configuration. Testing and experience have shown CESF capable of greatly reducing concentrations of a range of pollutants, including TSS, zinc, other metals, petroleum derivatives, and nutrients (phosphorus and nitrogen) to levels far below the regulatory limits.[16]

Chemical polymer alternatives to chitosan yield even better results for some runoff streams. The optimum polymer is typically identified by conducting bench tests on several alternatives using the actual runoff from the site at issue to determine which one maximizes flocculation.

An alternative to chemical polymer coagulation is electrocoagulation. In an electrocoagulation cell, multiple reactions take place simultaneously. First, a metal ion is driven into the water from the anode (positive pole). Meanwhile, electrons flow from the cathode (negative pole) to destabilize surface charges on suspended solids and emulsified oils. As the reaction continues, flocculation occurs, forming large masses that entrain suspended solids, heavy metals, emulsified oils, and other contaminants. Finally, the masses are removed from the water in downstream solids separation and filtration process steps. Like CESF, electrocoagulation is now in industrial stormwater application. Testing and experience have also shown electrocoagulation to have performance capability equivalent to CESF, including decreasing the same range of pollutants, to levels far below the specified limits.[17] Another similarity with CESF is that the equipment is modular and flexible.

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[16] Crini, G., N. Morin-Crini, N. Fatin-Rouge, S. Deon, and P. Fievet. 2017. Metal removal from aqueous media by polymer-assisted ultrafiltration with chitosan. *Arabian Journal of Chemistry*, 10(2):S3826-S3839; see http://www.waterworld.com/articles/uwm/articles/print/volume-2/issue-1/features/biopolymer-offers-biodegradable-alternative-in-water-treatment.html (last accessed on April 25, 2023) and DMRs submitted by Industrial Stormwater General Permit holders using CESF in Washington state.

[17] Sahu, O., B. Mazumdar, and P.K. Chaudhari. 2014. Treatment of Wastewater by Electrocoagulation: a Review. *Environmental Science Pollution Research* 21:2397–2413.
Herrera Environmental Consultants. 2011. Literature Review of Existing Treatment Technologies for Industrial Stormwater. Washington Department of Ecology, Northwest Regional Office, Bellevue, Washington.

Several companies[18] market advanced treatment systems using such media. Treatment units can be installed flexibly where space exists, and vendors offer units in a modular form that can be moved onto a site quickly and even shifted around to different positions if circumstances change.

Control of Other Construction-Site Pollutants

The preceding discussion has emphasized the sediment that may issue from the construction site and compromise receiving water quality. Just as the Stormwater Plan is incomplete in covering this area, it is equally vague on management of construction site pollutants besides sediments. These sources include construction materials; wastes produced; and pollutants associated with vehicles and other mechanized equipment, such as fuels, lubricants, and cleaning materials. These substances can introduce toxic pollutants to storm runoff, such as heavy metals, petroleum products, and organic chemicals derived from fossil fuels. A SWPPP should be produced and evaluated before further project consideration, and it should fully detail the BMPs that will be used to control pollutants from all sources.

The construction site should be managed to avoid the release of these contaminants by preventing contact between rainfall or runoff and potentially polluting construction materials, processes, wastes, and vehicle and equipment fluids by such measures as enclosures, covers, and containments, as well as berming to direct runoff. Construction vehicles larger than pick-up trucks parked for more than two days should be located so that any fluid leaks cannot contaminate stormwater runoff. The best way of preventing contamination is to park in a location that cannot drain into any stormwater conveyance leaving the site. If a selected location could drain away, it should be modified by slightly recessing the parking spots to prevent draining out. An alternative if such a location cannot be found, is to place leakage collection trays under the vehicles. Any vehicle observed to be leaking any significant quantity of a fluid should be repaired immediately.

Inspection and Maintenance

All areas disturbed by construction activities, all BMPs, and all stormwater discharge points must be inspected at least once every calendar week and within 24 hours of any discharge from the site. All BMPs must be maintained and repaired as needed to ensure continued performance of their intended function.

POTENTIAL POST-CONSTRUCTION STORMWATER POLLUTANT DISCHARGES

<u>Water Pollutants of Concern and Their Sources</u>

Hundreds of water pollutants are associated with urban development and its human facilities and activities. These pollutants fall into the categories of: (1) solid particles, which create their own negative impacts and also transport pollutants in the other categories; (2) nutrients, particularly phosphorus and nitrogen, which as I have discussed over-enrich receiving waters and cause harmful algae and plant growths; (3) oxygen-demanding materials, which deplete dissolved oxygen needed

[18] For example, WaterTectonics, Inc., Everett, Washington; Clear Water Services, Everett, Washington; Clear Creek Systems, Pacific, Washington.

by aerobic life; (4) metals, some of which, like copper and zinc, are toxic to aquatic life; (5) petroleum products, which have toxic and nuisance effects in receiving waters; (6) organic chemicals, including pesticides and numerous other household and commercial chemicals, again many of them toxic to aquatic organisms as well as humans and wildlife; and (7) pathogenic (disease-causing) organisms. I further report on the negative impacts of these pollutants below under the topic heading Environmental Harm Associated with Stormwater Pollutants of Concern for the Big Lake Ecosystem.

After a development is occupied, human activities such as vehicular transportation, lawn care, and pet keeping introduce pollutants from several of the categories listed above. Pollutants in all seven categories listed above issue from a site such as Overlook Crest.

Quantification of Residential Land Use Pollutant Releases

Table 4 gives the concentrations of common stormwater pollutants associated with activities occurring during construction and occupation of a residential community in comparison to drainage from open (undeveloped) land, such as the present forested site. With the exceptions of total suspended solids, nitrate + nitrite-nitrogen, and total phosphorus, concentrations in flows from the developed land use range from 190 to 260 percent higher than in open land runoff. Total phosphorus concentration is 20 percent higher in runoff from the residential land use compared to open land.

In addition to concentration (mass/unit volume of water), pollutant mass loading (mass/unit time) is instrumental in water quality. Concentration represents exposure to the contaminant at a point in time and thus is the major factor in acute effects on receptor organisms. Mass loading represents a cumulative exposure over time, creating a chronic stress on life forms and aggregate contaminant collection in a repository such as the aquatic sediments. Loading is the multiplication product of concentration times flow volume over the time period and can be expressed on the basis of unit area (kg/ha-year) or total catchment (kg/year). With the construction of impervious surfaces and lawns in place of native landscapes, urbanization increases runoff volume. Table 4 shows that it generally also increases concentrations. Therefore, we would anticipate seeing substantially elevated pollutant mass loadings in developed versus undeveloped runoff.

Table 5 shows that expectation to be borne out. Loadings from the developed compared to undeveloped land uses are generally about 50-400 percent greater, although ranging much higher for TSS, total phosphorus, and total lead. Mass loading of phosphorus, the particularly critical pollutant in the Big Lake case, is projected to be 10 times (1000 percent) as high. The ultimate, long-term burden of unmitigated urban stormwater runoff on water quality is thus a function of both hydrologic modification and release of chemical, physical, and biological agents by urban inhabitants and their possessions and activities.

Table 4. Median Pollutant Concentrations in Stormwater Runoff from Two Land Use Types from the National Stormwater Quality Database[19]

Pollutant	Unit	Open Space	Residential
Total suspended solids (TSS)	mg/L	51	48
Total phosphorus	µg/L	25	30
Total Kjeldahl nitrogen[a]	µg/L	60	140
Nitrate + nitrite-nitrogen	µg/L	60	60
Biochemical oxygen demand (BOD	mg/L	4.2	9.0
Chemical oxygen demand (COD)	mg/L	21	55
Total copper	µg/L	5	12
Total lead	µg/L	5	12
Total zinc	µg/L	39	73
Fecal coliform bacteria	No./100 mL	3100	7750

[a] Nitrogen in the organic plus inorganic ammonia and ammonium forms.

Table 5. Pollutant Loadings in Storm Runoff from Three Land Use Types as Reported in the Stormwater Literature[a]

Pollutant	Unit	Undeveloped[b]	Residential[c]
Total suspended solids (TSS)	kg/ha-year	3	250
Total phosphorus	kg/ha-year	0.03	0.3
Total Kjeldahl nitrogen	kg/ha-year	2.5 as total nitrogen*	2.5
Nitrate + nitrite-nitrogen	kg/ha-year		1.4
Biochemical oxygen demand (BOD)	kg/ha-year	NA[d]	27
Chemical oxygen demand (COD)	kg/ha-year	NA[d]	50
Total copper	kg/ha-year	0.01**	0.03
Total lead	kg/ha-year	0.005	0.05
Total zinc	kg/ha-year	0.03**	0.10
Fecal coliform bacteria***	No./ ha-year	1.0×10^{10}	3.8×10^{10}

[a] Source: Burton, G.A., Jr. and R.E. Pitt. 2002. *Stormwater Effects Handbook: A Toolbox for Watershed Managers, Scientists, and Engineers*. Lewis Publishers, Boca Raton, FL (Table 2.5), except:

* Beaulac, M.N. and K.H. Reckhow. 1982. An Examination of Land Use - Nutrient Export Relationships. *Journal of the American Water Resources Association* 18:1013-1024.

** Wanielista, M.P. and Y.A. Yousef. 1993. *Stormwater Management*. John Wiley and Sons, Inc., New York, New York, USA (Table 5.19).

*** Shaver, E., R. Horner, J. Skupien, C. May, and G. Ridley. 2007. *Fundamentals of Urban Runoff Management: Technical and Institutional Issues*, 2nd Ed. North American Lake Management Society, Madison, Wisconsin, USA (Table 3-13).

[b] "Woodland" for total copper and total zinc; "parks" for total suspended solids, total phosphorus, and total lead; "forest" for remaining pollutants (Note: Multiple sources were consulted for the undeveloped category since data for the various pollutants were not reported in consistent land use terms.).

[c] Medium-density residential (approximately 20 percent impervious).

[d] Not available.

[19] Shaver, E., R. Horner, J. Skupien, C. May, and G. Ridley. 2007. *Fundamentals of Urban Runoff Management: Technical and Institutional Issues*, 2nd Ed. North American Lake Management Society, Madison, Wisconsin, USA.

ASSESSMENT OF THE PROPOSED POST-CONSTRUCTION STORMWATER MANAGEMENT PRACTICES

Pollution Source Controls

Introduction

Effective stormwater management begins with controls implemented to prevent or reduce the release of pollutants in the first place. Source controls can be 100 percent effective if they fully isolate potential contaminant sources from contact with rainfall or runoff. In contrast, conventional stormwater treatment systems are not nearly 100 percent efficient. Even the best available do not achieve that performance level. There are two categories of source controls: (1) operational, which are procedures that reduce the potential for exposure of pollutants; and (2) structural, which physically separate contaminants from rainfall and runoff.

In this section of my letter I list the source controls proposed in the Stormwater Plan and assess each with respect its potential to accomplish the goal of pollutant isolation. In following sections I present my opinions of the Stormwater Plan's proposals to treat runoff over the long term in the finished development.

My Assessment of Proposed Source Controls

The Stormwater Plan makes the following claims, which I present in summary form with page number references and then critique each.

Page10: The proposed plat development is not expected to create new pollutant sources.

> Tables 4 and 5 above demonstrate that this claim is fatuous.

Page10: No sources of bacteria are known to exist onsite or are proposed.

> There is no plan to prohibit pets or impervious surfaces, which collect and concentrate bird and other wildlife droppings. Again Tables 4 and 5 refute this claim.

Page10: Chemicals for grounds and landscape maintenance, including detergents, cleaning products, and fertilizers will be stored indoors to prevent contact with stormwater.

> They may be stored in indoors, but they will be spread outdoors through lawn and garden work and vehicle, pavement, and structure washing.

Pages 12-13: Pollutant sources for residential plat and road projects include vehicular traffic, fertilizers, and other detergents or chemicals typical to residential building and road maintenance activities. Pollution will be controlled at the source to the maximum extent possible.

> The passage names ten source control BMPs from the 2019 Manual that have been reviewed for this project but goes no farther to reveal which, if any, will go beyond review to implementation.

Specific source controls should be formulated in all of these categories and detailed in the Stormwater Plan.

Assessment of Proposed Post-Construction Stormwater Treatment and Recommendations for Improvement

Critique of the Pond Proposal

As described earlier, the proposal is to use revised golf course ponds to serve for both stormwater flow control and treatment. The size to which the ponds are to be revised was determined with Ecology's Western Washington Hydrologic Model (2012 version). Like all mathematical models intended to represent natural conditions, it has simplifications. One is having only three categories of slopes: 0-5 percent, flat; 5-15 percent, moderate; and 15+ percent, steep. In contrast to the earlier characterization of the average site slope at 13 percent, the Stormwater Plan states in the modeling section that the average is 8 percent and that the site was modeled as moderate in slope. That choice tends to underestimate runoff production and hence the pond volume necessary to control flow and reduce pollutants to the regulatory requirements. A superior approach would be to divide the site into the three slope categories by the respective areas, model them separately, and rout the combined flow to the ponds.

While my recommended modeling alteration would tend to improve pond performance, I do not consider any wet pond configuration as the lone stormwater treatment to be sufficiently protective of Big Lake. The International Stormwater BMP Database summarizes the results of 75 studies performed on wet ponds and reports the median total phosphorus concentration discharged as 120 µg/L, with a maximum of 129 and minimum of 104 µg/L.[20] It is clear from this extensive database and relatively consistent performance that a wet pond cannot be expected to discharge phosphorus at less than about double the current Big Lake concentration. The Aqua-Swirl pre-treatment devices at the two pond inlets, while approved for some purposes under Ecology's TAPE BMP assessment program, are not recognized for phosphorus as a target pollutant and will offer essentially no benefit in that regard. The wet pond must either be replaced or supplemented by another stormwater management practice to protect the lake. I see two options for doing so, which I discuss in the following paragraphs. The Stormwater Plan must be updated with an improved treatment system and submitted for County and citizen assessment before further consideration of the development proposal.

Consideration of Infiltration

On page 15, the Stormwater Plan says that native soils do not infiltrate and infiltration systems are infeasible for use at this site. There are inconsistencies in the evidence regarding this point. Pages 5-6 state, "Tokul gravelly loam, the predominate soil on the site, consists of volcanic ash

[20] https://www.waterrf.org/system/files/resource/2020-11/DRPT-4968_0.pdf, Table 4.3 (accessed November 15, 2024).

mixed with loess over glacial till and is classified as hydrologic group 'B'. Hydrologic group 'B' soils have moderate infiltration rates when thoroughly wetted." Figure 3, in fact, shows the Tokul soil to cover 85 percent of the site. The infiltration characteristics of the site should be investigated more broadly and thoroughly. There may be localized areas that could infiltrate sufficiently to disperse roof, driveway, and/or lawn runoff.

It is true that the Tokul soil is generally underlain by Vashon lodgement till, which is restrictive to percolation. In these circumstances, there is still the possible option of deep infiltration, which uses wells to discharge water below the restrictive layer. The Geotechnical Report states that investigation of deeper stormwater infiltration strategies was outside of the scope of the investigation and proposes additional work. That work should be conducted to determine its feasibility. The Manual offers BMP T7.50, Drywells, to accomplish deep infiltration.

The advantage of infiltration is that it would prevent or minimize the discharge of any runoff and the accompanying pollutant loading from the areas draining to the wells or dispersion areas. If analysis determines that stormwater from even the largest storms would infiltrate in the deep wells and by dispersion, the lake would be spared increased pollutant discharges. In that case, the golf course ponds need not be modified in any way. If there could still be discharge from the development in relatively large storms, the golf course ponds would be altered only as necessary to control the rate of flows released downstream.

The Bioretention Alternative

The second option is installing bioretention systems within the development. Bioretention is a stormwater management practice that uses the chemical, biological, and physical properties of plants, soil microbes, and the mineral aggregate and organic matter in soils to transform, remove, or retain pollutants from stormwater runoff. Bioretention BMPs are:

- Shallow landscaped depressions with a designed soil mix and plants adapted to the local climate and soil moisture conditions;

- Designed to mimic natural forested conditions, where healthy soil structure and vegetation promote the infiltration, storage, filtration, and slow release of stormwater flows; and

- Typically, small- to medium-scale, dispersed, and integrated into the site as a landscape amenity.

In my concept there would likely be a set of several units placed to receive all of the runoff from the new road extended through the development, the greatest pollutant source, and any stormwater that flows onto the road from the residential properties. Designing the development to keep as much runoff as possible from entering the road would reduce the size and therefore the cost of bioretention.

Bioretention should be designed, constructed, and maintained as specified by BMP T7.30 in the 2024 Stormwater Management Manual for Western Washington. This updated specification

incorporates new high performance bioretention soil mixes based on recent research. The mix that best captures phosphorus, as well as the other pollutants of concern, and improves vegetation success for enhanced pollutant removal, labeled Type 3, includes a 2-inch compost surface layer over a primary layer and, below it, a polishing layer. The 18-inch primary layer contains 70 percent sand, 20 percent coir, and 10 percent high carbon wood ash (biochar) by volume. The 12-inch polishing layer has 90 percent sand, 7.5 percent activated alumina, and 2.5 percent iron aggregate by volume. It is very important that this specific medium be specified, because it has been expressly formulated and verified to be the best choice for reducing phosphorus.

According to Manual page 902, bioretention can be used, with or without an underdrain, near phosphorus-sensitive waterbodies. Constructing without an underdrain is the better configuration, because it offers the opportunity to reduce the quantity of surface discharge that would still contain some contaminants, if some infiltration occurs even if it is not complete. It should be carefully determined what portions of the site can host bioretention without underdrains and what areas must have them. With the relatively steep slopes, there are probably areas where flow across the till layer could surface at locations causing problems such as slope instability and basement wetting.

With this alternative, I envision that the golf course ponds would still be converted to a combined detention/wet pond system, generally as laid out in the Stormwater Plan. They probably would not have to be enlarged as much, or perhaps not at all, because bioretention would reduce runoff quantity. How much depends on the water loss that accrues from infiltration and evapotranspiration. There would still have to be an outlet structure for discharge flow control.

The Importance of BMP Maintenance

Wet ponds and bioretention units require regular inspection and maintenance to retain effectiveness. Bioretention and wet pond maintenance specifications are on Manual pages 934-935 and 1016, respectively. The U.S. Environmental Protection Agency has also produced maintenance guidance for bioretention[21] and wet ponds.[22] The Overlook Crest developer must develop detailed maintenance instructions consistent with these specifications and set up mechanisms to ensure that they are funded and regularly and thoroughly implemented.

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[21] Stormwater Best Management Practice Bioretention (Rain Gardens), EPA-832-F-21-031L, https://www.epa.gov/system/files/documents/2021-11/bmp-bioretention-rain-gardens.pdf; and Operation and Maintenance of Green Infrastructure Receiving Runoff from Roads and Parking Lots, Technical Memorandum, https://www.epa.gov/sites/default/files/2016-11/documents/final_gi_maintenance_508.pdf (both accessed November 15, 2024).

[22] Stormwater Wet Pond and Wetland Management Guidebook, EPA 833-B-09-001 https://www3.epa.gov/npdes/pubs/pondmgmtguide.pdf (accessed November 15, 2024).

ENVIRONMENTAL HARM ASSOCIATED WITH STORMWATER POLLUTANTS OF CONCERN FOR THE BIG LAKE ECOSYSTEM

Phosphorus

As I covered extensively above, phosphorus is a pollutant of particular concern for Big Lake, a discussion I do not repeat here. The deficiencies of the construction and post-construction stormwater management plans that I have described will aggravate the already eutrophic state in my opinion. The improvements I recommend are crucial for any chance to avoid exacerbating that condition in the face of such a major land use change in the lake's watershed.

Particulates

Solid particles discharged to water (measured as TSS and turbidity) have a number of potential negative ecological effects, regardless of their specific physical or chemical nature, including:

- Changing the structure and chemical characteristics of the lake's bed, thus altering the optimum habitat for benthic invertebrates and bottom-dwelling fish;
- Reducing visibility, making it harder for fish to find food and avoid predators;
- Reducing light penetration to underwater plants and algae;
- Abrading the soft tissues of fish and juvenile amphibians, especially gills; and
- Transporting other pollutants, such as phosphorus and the metals sourced from lubricants and wear of vehicle components.

As I have demonstrated, construction and occupancy of the development as planned will increase particulate input to the lake. Only excellent mitigation measures such as I have proposed offer the opportunity avoid that outcome.

Decomposable Organics

Organic residues decompose over time from their original complex formulations to their constituent compounds and, ultimately, chemical elements. The breakdown begins in surface deposits as a physical deconstruction, with reduction of larger pieces to smaller particles and, less visibly, to very small dust particles. Simultaneously, a biochemical process begins in which heterotrophic bacteria and fungi exploit the wood material as a carbon source to support their growth. This process advances the particle size reduction. When the particles flow with stormwater runoff into a water body, the decomposition process continues. The microorganisms consume oxygen taken from the water, thus exerting what is termed an "oxygen demand." BOD and COD are commonly used measures of oxygen depletion potential associated with biological decomposition. Organics already broken down into relatively small particulates degrade more rapidly and, consequently, exert more

oxygen demand than a larger piece of equivalent mass.[23] Oxygen dissolves from the atmosphere into water bodies, but the oxygen demand exerted by decomposing microorganisms can exceed the rate of oxygen dissolution with a large supply of degradable organics.

Aerobic aquatic life, including fish and their invertebrate food sources, require sufficient oxygen to support their physiological processes. Highly depleted dissolved oxygen is fatal, at somewhat different levels depending on species. Salmonids, including threatened and endangered salmon, are the most sensitive fish in this respect. Even if not drawn down to a lethal level, somewhat depleted oxygen interferes with such processes as feeding, avoiding predators, and growth.

As I pointed out above, Nookachamps Creek downstream of Big Lake is impaired by low dissolved oxygen. If organic matter input rises, both from the development upslope and excessive algal and plant growth in the lake, the increase will worsen this situation.

Reducing organic sources and transport is necessary to avoid these impacts. The Stormwater Plan does not provide sufficient source controls and treatment to do so effectively and must be upgraded as I have proposed.

Metals

Both copper and zinc are toxic to fish and other aquatic life, much more so than to mammals. There is a large body of literature on the specific lethal and negative sublethal effects of these metals on fish and other aquatic life. Particularly in the dissolved forms, they are toxic to aquatic organisms in relatively low concentrations. Equivalent concentrations and higher are often measured in urban stormwater. The effects of both metals on aquatic organisms can be directly lethal or sublethal but detrimental to such life cycle functions as migration, reproduction, rearing, feeding, growth, disease resistance, and predator avoidance.

Copper, especially, has received a great deal of attention for its inhibition of various salmonid physiological processes, to the detriment of migration, feeding, reproduction, and rearing. The mechanisms bringing about these adverse effects include fraying of gills, diminishing their physiological processes, and reduction of olfactory ability (sense of smell).[24] The onset of negative consequences depends on species and water pH, dissolved organic carbon, and hardness but begins as low as approximately 5 µg/L or even less.

Baldwin et al. (2003)[25] used coho salmon olfactory capacity, a reliable indicator of sublethal toxicity, in a series of studies. Exposure to 10 µg/L of copper for 30 minutes reduced responses to three odorants by 35-67 percent, and the reduced olfactory function persisted for hours. Impairment was evident within 10 minutes for exposures ranging from 2 to 20 µg/L. The researchers defined

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[23] *E.g.*, Rex J., S. Dubé, P. Krauskopf, and S. Berch. 2016. Investigating Potential Toxicity of Leachate from Wood Chip Piles Generated by Roadside Biomass Operations. *Forests*, 7, 40.

[24] Solomon, F. 2009. Impacts of Copper on Aquatic Ecosystems and Human Health. MINING.com, January 2009, pp. 25-28.

[25] Baldwin, D.H., J.F. Sandahl, J.S. Labenia, and N.L. Scholz. 2003. Sublethal effects of copper on coho salmon: Impacts on nonoverlapping receptor pathways in the peripheral olfactory nervous system. *Environmental Toxicology and Chemistry* 22(10):2266-2274.

the threshold for sublethal, copper-induced coho neurotoxicity to be 25 percent reduction in olfactory responses. They found the threshold to be 2.3-3.0 µg/L (depending on odorant) above the 3.0 µg/L background in source water; i.e., the presence of approximately 5-6 µg/L of copper reduced olfactory function by 25 percent.

Zinc concentrations as low as 93 µg/L have been found to be lethal to 50 percent of juvenile rainbow trout in 96 hours of exposure.[26] Sublethal effects at even lower concentrations include avoidance of rearing habitat and inhibited immune response.[27] Such negative effects interfere with growth, ability to avoid predators, and resistance to disease.

The negative effects of metal toxins are not necessarily limited to short-term, acute lethal or medium-term sublethal impacts. Over time an organism can accumulate metals in tissue, a process known as bioaccumulation. When predators consume organisms with bioaccumulated metals, they concentrate them in their tissues. The top predator in an aquatic ecosystem tends to have the highest concentrations, through biomagnification up the food chain. Fish and their food sources in the benthic macroinvertebrate community are subject to these impacts.

Aquatic sediments become repositories for particulate metals through gravity settling and for dissolved metals through various adsorption and ion exchange processes. In addition to their toxicity to bottom-dwelling organisms, these captured metals can become remobilized into the water column by disturbance and dissolution, and thus harm pelagic aquatic life long after their initial release.

As with the other sources of environmental harm, stormwater management as currently conceived for the development will not control metals sufficiently to avoid adding to the toxic burden on life in the Big Lake ecosystem. It must be improved in the ways I have recommended.

Bacteria

As Tables 4 and 5 demonstrate, development increases bacteria in stormwater. Sources include pets, leaking recreational vehicles, and concentration of wildlife droppings on impervious surfaces. According to WAC 173-201A-600, as a water of the state not named in Table 602, Big Lake is to be protected for primary contact recreation. Controls counteracting the sources and runoff treatment supplementary to the golf course ponds are needed to comply.

Petroleum Derivatives

Crude oil and its derivatives contain numerous chemicals, certain ones (*e.g.*, many in the polyaromatic hydrocarbon group) of which are toxic to aquatic life. They produce harmful sublethal, if not immediately lethal, reactions negatively affecting reproduction, development, and behavior. These materials decompose relatively slowly and tend to accumulate in the aquatic

[26] Chapman, G.A. 1978. Toxicities of Cadmium, Copper, and Zinc to Four Juvenile Stages of Chinook Salmon and Steelhead. *Transactions of the American Fisheries Society* 107: 841-847.
[27] Price, M.H.H. 2013. Sub-lethal Metal Toxicity Effects on Salmonids: A Review. Report prepared for SkeenaWild Conservation Trust. Smithers, BC.

environment. The gradual decomposition reduces the oxygen supply needed by aerobic water life, from fish to the microorganisms responsible for the breakdown themselves. This oxygen demand aggravates that created by biodegradable particles.

Tire Rubber Additive

Recently, an obscure additive to tire rubber was identified as instrumental in coho salmon pre-spawn mortality, previously unexplained acute mortality when adult salmon migrate to creeks to reproduce and are exposed to stormwater flows. The compound is the quinone transformation product of *N*-(1,3-dimethylbutyl)-*N*′-phenyl-p-phenylenediamine (6PPD), a globally ubiquitous tire rubber antiozonant (preventive of deterioration by ozone) and antioxidant. 6PPD is mobile within the rubber and slowly "blooms" to the tire surface where it forms a scavenger-protective film, reacting with the ozone more quickly that the ozone can react with the rubber.[28] This process forms 6PPD-quinone, among other products.[29]

Analysis of representative roadway runoff and stormwater-affected creeks of the U.S. West Coast indicated widespread occurrence of 6PPD-quinone (< 0.3 to 19 µg/L) at toxic concentrations (median lethal concentration, LC_{50}, of 0.8 ± 0.16 µg/L).[30] More recent work has set the LC_{50} for juvenile coho salmon even lower, at 95 ng/L (0.095 µg/L).[31]

Developing Overlook Crest will substantially increase automotive traffic in the Big Lake watershed, and the Stormwater Plan gives no attention to mitigating its negative consequences. Based on research by Spromberg et al. (2016),[32] Ecology has rated bioretention such as I have recommended to have a "high" level of effectiveness in removing 6PPD-Q from stormwater runoff.[33] This BMP also performs relatively well among the available alternatives in capturing petroleum derivatives; metals; and particulates; and, with the appropriate soil, nutrients as well. The Stormwater Plan should make maximum use of it.

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[28] Lattimer, R.P., E.R. Hooser, R.W. Layer, and C.K. Rhee. 1983. Mechanisms of Ozonation of N-(1,3-Dimethylbutyl)-N′-Phenyl-p-Phenylenediamine. *Rubber Chemistry and Technology 56(2):431–439.*

[29] Seiwert, B., M. Nihemaiti, M. Troussier, S. Weyrauch, and T. Reemtsma. 2022. Abiotic Oxidative Transformation of 6-PPD and 6-PPD Quinone from Tires and Occurrence of their Products in Snow from Urban Roads and in Municipal Wastewater. *Water Research* 212:118122.

[30] Tian, Z. et al. 2020. A Ubiquitous Tire Rubber-Derived Chemical Induces Acute Mortality in Coho Salmon. *Science* 371(6525):185–189.

[31] Tian, Z., M. Gonzalez, C.A. Rideout, H.N. Zhao, X. Hu, J. Wetzel, E. Mudrock, C.A. James, J.K. McIntyre, and E.P. Kolodziej. 2022. 6PPD-Quinone: Revised Toxicity Assessment and Quantification with a Commercial Standard. *Environmental Science & Technology Letters* 9(2):140–146.

[32] Spromberg, J. A., Baldwin, D. H., Damm, S. E., Mcintyre, J. K., Huff, M., Sloan, C. A., Anulacion, B. F., Davis, J. W., & Scholz, N. L. (2016). EDITOR'S CHOICE: Coho salmon spawner mortality in western US urban watersheds: Bioinfiltration prevents lethal storm water impacts. Journal of Applied Ecology, 53(2), 398–407. https://doi.org/10.1111/1365-2664.12534 (accessed November 14, 2024).

[33] Environmental Assessment and Water Quality Programs. 2022. 6PPD in Road Runoff, Assessment and Mitigation Strategies, Publication 22-03-020. Washington State Department of Ecology Olympia, Washington, https://apps.ecology.wa.gov/publications/documents/2203020.pdf (accessed November 15, 2024).

A FINAL WORD

In this letter I have described a number of potential negative impacts consequential to the Big Lake ecosystem. I further pointed out major shortcomings in the development proponent's plans for construction and post-construction stormwater management, making it highly probable that those problems will occur. For these reasons, the proposed development should be subjected to a full environmental impact assessment.

I would be pleased to answer any questions you may have and invite you to contact me if you wish.

Sincerely,



Richard R. Horner

Attachments: Attachment A; Background and Experience; Richard R. Horner, Ph.D.
Attachment B; *Curriculum Vitae*

ATTACHMENT A

BACKGROUND AND EXPERIENCE

RICHARD R. HORNER, PH.D.

I have 57 years of professional experience, 44 teaching and performing research at the college and university level. For the last 46 years I have specialized in research, teaching, and consulting in the area of stormwater runoff and surface water management.

I received a Ph.D. in Civil and Environmental Engineering from the University of Washington in 1978, following two Mechanical Engineering degrees from the University of Pennsylvania in 1965 and 1966. Although my degrees are all in engineering, I have had substantial course work and practical experience in aquatic biology and chemistry.

For 12 years beginning in 1981, I was a full-time research professor in the University of Washington's Department of Civil and Environmental Engineering. From 1993 until 2011, I served half time in that position and had adjunct appointments in two additional departments (Landscape Architecture and the College of the Environment's Center for Urban Horticulture). I spent the remainder of my time in private consulting through a sole proprietorship. My appointment became emeritus in late 2011, but I have participated in some research and teaching since then while maintaining my consulting practice.

My research, teaching, and consulting embrace all aspects of stormwater management, including determination of pollutant sources; their transport and fate in the environment; physical, chemical, and ecological impacts; and solutions to these problems through better structural and non-structural management practices.

I have conducted numerous research investigations and consulting projects on these subjects. Serving as a principal or co-principal investigator on more than 40 research studies, my work has produced three books, approximately 30 papers in the peer-reviewed literature, and over 20 reviewed papers in conference proceedings. I have also authored or co-authored more than 80 scientific or technical reports.

In addition to graduate and undergraduate teaching, I have taught many continuing education short courses to professionals in practice. My consulting clients include federal, state, and local government agencies; citizens' environmental groups; and private firms that work for these entities, primarily on the West Coast of the United States and Canada but in some instances elsewhere in the nation.

Over a 17-year period beginning in 1986 I spent a major share of my time as the principal investigator on two extended research projects concerning the ecological responses of freshwater resources to urban conditions and the urbanization process. I led an interdisciplinary team for 11 years in studying the effects of human activities on freshwater wetlands of the Puget Sound lowlands. This work led to a comprehensive set of management guidelines to reduce negative

effects and a published book detailing the study and its results. The second effort involved an analogous investigation over 10 years of human effects on Puget Sound's salmon spawning and rearing streams. These two research programs had broad sponsorship, including the U.S. Environmental Protection Agency, the Washington Department of Ecology, and a number of local governments.

Nationally, I conducted research sponsored by the National Science Foundation, U.S. Environmental Protection Agency, Water Environment Research Foundation, Transportation Research Board, and Electric Power Research Institute. In Washington, I have performed research for the Washington State Department of Transportation, Washington Department of Ecology, City of Seattle Public Utilities, King County Water and Land Resources Division and its predecessor Municipality of Metropolitan Seattle, King County Roads Division, and Washington Sea Grant.

I now serve or have served on technical advisory panels concerning stormwater issues for Seattle-Tacoma International Airport and King County Water and Land Resources Division. I was one of 14 signatories from the scientific community of a 2006 letter to the Puget Sound Partnership giving recommendations for improving water quality and aquatic and human ecosystems through improved stormwater runoff management (https://special.seattletimes.com/s/ABPub/2008/05/10/2004406008.pdf).

I have helped to develop stormwater management programs in Washington State, California, and British Columbia and studied such programs around the nation. I was one of four principal participants in a U.S. Environmental Protection Agency-sponsored assessment of 32 state, regional, and local programs spread among 14 states in arid, semi-arid, and humid areas of the West and Southwest, as well as the Midwest, Northeast, and Southeast. This evaluation led to the 1997 publication of "Institutional Aspects of Urban Runoff Management: A Guide for Program Development and Implementation" (subtitled "A Comprehensive Review of the Institutional Framework of Successful Urban Runoff Management Programs").

In California I have been a federal court-appointed overseer of stormwater program development and implementation at the city and county level and for two California Department of Transportation districts. I was directly involved in the process of developing the 13 volumes of Los Angeles County's Stormwater Program Implementation Manual, working under the terms of a settlement agreement in federal court as the plaintiffs' technical representative. My role was to provide quality-control review of multiple drafts of each volume and contribute to bringing the program and all of its elements to an adequate level. I have also evaluated and contributed in various ways to the stormwater programs in Los Angeles, San Diego, Orange, Riverside, San Bernardino, Ventura, Santa Barbara, San Luis Obispo, and Monterey Counties, as well as a regional program for the San Francisco Bay Area. At the recommendation of San Diego Baykeeper, I have been a consultant on stormwater issues to the City of San Diego, the San Diego Unified Port District, and the San Diego County Regional Airport Authority.

Over the past 30 years I have been a consultant to and expert witness for the U.S. Department of Justice and a number of national and regional environmental organizations in Clean Water Act cases. They include Natural Resources Defense Council, Earthjustice, Center for Biological

Diversity, and members of the Waterkeeper Alliance in the states of Washington, Oregon, and California.

I have been a member of the science team for Salmon-Safe, Inc. for 20 years. Salmon-Safe recognizes landowners who meet prescribed standards for aiding salmon protection and recovery. My role is to assess candidates' programs and performance, mainly concentrating on stormwater, and participate with other members of the team in certification decisions.

I was a member of the National Academy of Sciences-National Research Council ("NAS-NRC") committee on Reducing Stormwater Discharge Contributions to Water Pollution. NAS-NRC committees bring together experts to address broad national issues and give unbiased advice to the federal government. The present panel was the first ever to be appointed on the subject of stormwater. Its broad goals were to understand better the links between stormwater discharges and impacts on water resources, to assess the state of the science of stormwater management, and to apply the findings to make policy recommendations to the U.S. Environmental Protection Agency relative to municipal, industrial, and construction stormwater permitting. My principal contribution to the committee's final report, issued in October 2008, was the chapter presenting the committee's recommendations for broadly revamping the nation's stormwater program.

ATTACHMENT B

CURRICULUM VITAE

HORNER, Richard Ray

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University of Washington:
Emeritus Research Associate Professor,
Departments of Landscape Architecture and Civil and Environmental Engineering and
Sole Proprietor Consultant

EDUCATION

1976 - 1978 University of Washington, Seattle, Washington; Ph.D. (Civil Engineering)

1965 - 1966 University of Pennsylvania, Philadelphia, Pennsylvania; M.S. (Mechanical Engineering)

1961 - 1965 University of Pennsylvania, Philadelphia, Pennsylvania; B.S. *Cum Laude* (Mechanical Engineering)

HONORS AND AWARDS

Augustus Trask Ashton Scholarship, University of Pennsylvania, 1961 - 65
Annual Academic Honors, University of Pennsylvania, 1961 - 65
Tau Beta Pi National Engineering Honor Society
National Science Foundation Traineeship, University of Pennsylvania, 1965 - 66

EMPLOYMENT

1986 - Present Richard R. Horner, Sole Proprietor (offering services in environmental engineering and science)

2011 - Present University of Washington, Seattle, Washington
Emeritus Research Associate Professor

1981 - 2011 University of Washington, Seattle, Washington
Research Associate Professor

1986 - 1990 King County, Seattle, Washington
Coordinator of Puget Sound Wetland and Stormwater Management Research Program (part-time; continued under contract to University of Washington)

1969 - 1981 Northampton Community College, Bethlehem, Pennsylvania
Engineering Department (Coordinator, 1971 - 73 and 1978 - 79)

	Environmental Studies Department (Co-coordinator, 1973 - 76 and 1978 - 1981) Professor, 1978 - 1981; Associate Professor, 1973 - 78; Assistant Professor, 1969 - 73, Leave of Absence, 1977 - 78; Sabbatical Leave, 1976 - 77
1977 - 1978	University of Washington, Seattle, Washington Department of Civil Engineering Research Engineer, Highway Runoff Water Quality Project
1976 - 1977	University of Washington, Seattle, Washington Department of Civil Engineering and Institute for Environmental Studies Research Assistant and Teaching Assistant
1966 - 1969	Exxon Research and Engineering Company, Florham Park, New Jersey; Project Engineer
1965 - 1966	University of Pennsylvania, Philadelphia Pennsylvania Department of Mechanical Engineering; Research Assistant

NATIONAL COMMITTEES

National Academy of Sciences Panel on Reducing Stormwater Discharge Contributions to Water Pollution, 2007-2008.

Technical Advisory Panel for Water Environment Federation projects on Decentralized Stormwater Controls for Urban Retrofit and Combined Sewer Overflow Reduction, 2005-2007.

Co-chair, Engineering Foundation Conference on Effects of Watershed Development and Management on Aquatic Ecosystems, 1996.

National Academy of Sciences Panel on Costs of Damage by Highway Ice Control, 1990-91.

U.S. Environmental Protection Agency National Wetland Research Planning Panel, 1988, 1991.

RESEARCH PROJECTS

* Principal Investigator.
** Co-Principal Investigator. (Where undesignated, I was a member of the faculty investigation team without principal investigator status).

Effects of Waterfront Stormwater Solutions Prototypes on Water Quality Runoff in Puget Sound near Pomeroy Park - Manchester Beach; Washington Sea Grant; $148,838; 2015-17.

Development of a Stormwater Retrofit Plan for Water Resources Inventory Area (WRIA) 9 and Estimation of Costs for Retrofitting all Developed Lands of Puget Sound; U.S. Environmental Protection Agency and King County (WA); $243,619; 2010-13.

Ultra-Urban Stormwater Management; Seattle Public Utilities; $1,130,000; 1999-2008.*

Roadside Vegetation Management Study; Washington State Department of Transportation; $50,000; 2004-05.

The Ecological Response of Small Streams to Stormwater and Stormwater Controls; U. S. Environmental Protection Agency, cooperating with Watershed Management Institute (Crawfordsville, FL); $579,117; 1995-2003.*

Vegetated Stormwater Facility Maintenance; Washington State Department of Transportation; $86,000; 1998-2000.*

Roadside Drainage System Management for Water Quality Improvement; King and Snohomish (WA) Counties; $70,000; 1997-2000.*

Standardization of Wet Weather Protocols for Stream Impact and Treatment Technology Performance Assessments; Water Environment Research Foundation, cooperating with Water Research Center (Huntington Valley, Pennsylvania) and University of Illinois; $125,000; 1996-97.

Road Shoulder Treatments for Water Quality Protection; Washington State Department of Transportation and King County Roads Division; $90,000; 1995-96.**

Control of Nuisance Filamentous Algae in Streams by Invertebrate Grazing; National Science Foundation; $193,691; 1994-96.

Criteria for Protection of Urban Stream Ecosystems; Washington Department of Ecology; $230,000; 1994-96.

Region-Specific Time-Scale Toxicity in Aquatic Ecosystems; Water Environment Research Foundation, cooperating with Water Research Center (Huntington Valley, Pennsylvania) and University of Illinois; $670,000; 1994-96.

Establishing Reference Conditions for Freshwater Wetlands Restoration; U. S. Environmental Protection Agency; $75,000; 1993-97.

Stormwater Management Technical Assistance to Local Governments; Washington Department of Ecology; $115,000; 1992-93.*

Center for Urban Water Resources Management; Washington Department of Ecology; $336,490; plus $157,400 matching support from seven local governments; 1990-93.*

University of Washington Cooperative Unit for Wetlands and Water Quality Research; King County, Washington; amount varied by year; 1987-95.*

Assessment of Portage Bay Combined Sewer Overflows; City of Seattle; $132,676; 1990-91.*

Velocity-Related Critical Phosphorus Concentrations in Flowing Water, Phase 3; National Science Foundation; $108,332; 1988-90.**

Design of Monitoring Programs for Determining Shellfish Bed Bacterial Contamination Problems; Washington Department of Ecology; $12,000; 1988-89.*

Puget Sound Protocols Development; Tetra Tech, Inc. and Puget Sound Estuary Program; $10,144; 1988.*

Improving the Cost Effectiveness of Highway Construction Site Erosion/ Pollution Control, Phase 2; Washington State Department of Transportation; $97,000; 1987-89.*

Wetland Mitigation Project Analysis; Washington State Department of Transportation; $74,985; 1987-89.*

Lake Chelan Water Quality Assessment; Harper-Owes, consultant to Washington State Department of Ecology; $42,977; 1986-88.

Quality of Management of Silver Lake; City of Everett; $67,463; 1986-88.

Effectiveness of WSDOT Wetlands Creation Projects; Washington State Department of Transportation; $42,308; 1986-87.*

Improving the Cost Effectiveness of Highway Construction Site Erosion/Pollution Control; Washington State Department of Transportation; $41,608; 1986-87.*

Management Significance of Bioavailable Phosphorus in Urban Runoff; State of Washington Water Research Center and Municipality of Metropolitan Seattle; $32,738; 1986-87.**

Environmental Monitoring and Evaluation of Calcium Magnesium Acetate (CMA); Transportation Research Board of National Academy of Sciences; $199,943; 1985-87.*

Conceptual Design of Monitoring Programs for Determination of Water Quality and Ecological Change Resulting from Nonpoint Source Discharges; Washington State Department of Ecology; $49,994; 1985-86.**

Development of an Integrated Land Treatment Approach for Improving the Quality of Metalliferous Mining Wastewaters; Washington Mining and Mineral Resources Research Institute; $4,000; 1985-86.*

Preliminary Investigation of Sewage Sludge Utilization on Roadsides; Washington State Department of Transportation; $6,664; 1984-85.*

Source Control of Transit Base Runoff Pollutants; Municipality of Metropolitan Seattle; $26,867; 1984-85.**

Lake Sammamish Future Water Quality; Municipality of Metropolitan Seattle; $28,500; 1984-85.

Implementation of Highway Runoff Water Quality Research Results; Washington State Department of Transportation; $13,998; 1984-85.*

Performance Evaluation of a Detention Basin and Coalescing Plate Oil Separator for Treating Urban stormwater Runoff; Washington State Water Research Center; 1984-85; $11,724.**

Velocity-Related Critical Phosphorus Concentrations in Flowing Water, Phase 2; National Science Foundation; $99,088; 1983-85.**

Development of a Biological Overland Flow System for Treating Mining Wastewaters; Washington Mining and Mineral Resources Research Institute; $6,030; 1983-84.*

Nutrient Contributions of Agricultural Sites to the Moses Lake System; Moses Lake Conservation District; $15,039; 1982-84.*

Planning Implementation of Runoff Water Quality Research Findings; Washington State Department of Transportation; $12,735; 1982-83.**

Transport of Agricultural Nutrients to Moses Lake; Brown and Caldwell Engineers; $22,725; 1982-83.**

Investigation of Toxicant Concentration and Loading Effects on Aquatic Macroinvertebrates; University of Washington Graduate School Research Fund; $3,788; 1982.*

Sampling Design for Aquatic Ecological Monitoring; Electric Power Research Institute; $542,008; 1981-86.

Velocity-Related Critical Phosphorus Concentrations in Flowing Water; National Science Foundation; $70,310; 1980-82.

Highway Runoff Water Quality; Washington State Department of Transportation; $461,176; 1977-82.

BOOKS

Shaver, E., R. Horner, J. Skupien, C. May, and G. Ridley. *Fundamentals of Urban Runoff Management: Technical and Institutional Issues*, 2nd Edition. U.S. Environmental Protection Agency, Washington, D.C., 2007.

Azous, A. L. and R. R. Horner. *Wetlands and Urbanization: Implications for the Future*. Lewis Publishers, Boca Raton, FL, 2000.

Horner, R. R., J. J. Skupien, E. H. Livingston, and H. E. Shaver. *Fundamentals of Urban Runoff Management: Technical and Institutional Issues*. Terrene Institute, Washington, D. C., 1994.

REFEREED JOURNAL PUBLICATIONS AND BOOK CHAPTERS

Wright, O.M., E. Istanbulluoglu, R.R. Horner, C.L. DeGasperi, and J. Simmonds. 2018. Is There a Limit to Bioretention Effectiveness? Evaluation of Stormwater Bioretention Treatment Using a Lumped Ecohydrologic Watershed Model and Ecologically-Based Design Criteria. *Hydrological Processes* 2018:1-17.

Chapman, C. and R.R. Horner. Performance Assessment of a Street-Drainage Bioretention System. *Water Environment Research* 82(2): 109-119, 2010.

Horner, R. R. et al. Structural and Non-Structural Best Management Practices (BMPs) for Protecting Streams. In *Linking Stormwater BMP Designs and Performance to Receiving Water Impact Mitigation*, B. K. Urbonas (ed.), American Society of Civil Engineers, New York, pp. 60-77, 2002.

Comings, K. J., D. B. Booth, and R. R. Horner. Storm Water Pollutant Removal by Two Wet Ponds in Bellevue, Washington. *Journal of Environmental Engineering* 126(4):321-330, 2000.

Anderson, E. L., E. B. Welch, J. M. Jacoby, G. M. Schimek, and R. R. Horner. Periphyton Removal Related to Phosphorus and Grazer Biomass Level. *Freshwater Biology* 41:633-651, 1999.

Horner, R. R., D. B. Booth, A. Azous, and C. W. May. Watershed Determinants of Ecosystem Functioning. In *Effects of Watershed Development and Management on Aquatic Ecosystems*, L. A. Roesner (ed.), American Society of Civil Engineers, New York, pp. 251-274, 1997.

Horner, R.R. Toward Ecologically Based Urban Runoff Management. In *Urban Runoff and Receiving Systems*, E.E. Herricks (ed.), Lewis Publishers, Boca Raton, Florida, pp. 365-378, 1995.

Walton, S. P., E. B. Welch, and R. R. Horner. Stream Periphyton Response to Grazing and Changes in Phosphorus Concentration. *Hydrobiologia* 302:31-46, 1994.

Reinelt, L. E. and R. R. Horner. Pollutant Removal from Stormwater Runoff by Palustrine Wetlands Based on a Comprehensive Budget. *Ecological Engineering* 4:77-97, 1995.

Horner, R.R. and M.V. Brenner. Environmental Evaluation of Calcium Magnesium Acetate for Highway Deicing Applications. *Resources, Conservation and Recycling* 7:213-237, 1992.

Brenner, M.V. and R.R. Horner. Effects of Calcium Magnesium Acetate on Dissolved Oxygen in Water. *Resources, Conservation and Recycling* 7:239-265, 1992.

Reinelt, L.E., R.R. Horner, and R. Castensson. Nonpoint Source Water Quality Management: Improving Decision-Making Information through Water Quality Monitoring. *Journal of Environmental Management* 34:15-30, 1992.

Horner, R.R., M.V. Brenner, R.B. Walker, and R.H. Wagner. Environmental Evaluation of Calcium Magnesium Acetate. In *Calcium Magnesium Acetate (CMA): An Emerging Bulk Chemical for Multi-purpose Environmental Applications*, D.L. Wise, Y.A. Lavendis, and M. Metghalchi (eds.), Elsevier Science Publishers B.V., The Netherlands, pp. 57-102, 1991.

Horner, R.R., E.B. Welch, M.R. Seeley, and J.M. Jacoby. Responses of Periphyton to Changes in Current Velocity, Suspended Sediments and Phosphorus Concentration. *Freshwater Biology* 24:215-232, 1990.

Horner, R.R. Long-Term Effects of Urban Stormwater on Wetlands. In *Design of Urban Runoff Quality Controls*, L.A. Roesner, B. Urbonas, and M.B. Sonnen (eds.), American Society of Civil Engineers, New York, pp. 451-466, 1989.

Welch, E.B., R.R. Horner, and C.R. Patmont. Phosphorus Levels That Cause Nuisance Periphyton: A Management Approach. *Water Research* 23(4):401-405, 1989.

Butkus, S.R., E.B. Welch, R.R. Horner, and D.E. Spyridakis. Lake Response Modeling Using Biologically Available Phosphorus. *Journal of the Water Pollution Control Federation* 60(9):1663-1669, 1988.

Reinelt, L.E., R.R. Horner, and B.W. Mar. Nonpoint Source Pollution Monitoring Program Design. *Journal of Water Resources Planning and Management* 114(3):335-352, 1988.

Welch, E.B., J.M. Jacoby, R.R. Horner, and M.R. Seeley. Nuisance Biomass Levels of Periphytic Algae in Streams. *Hydrobiologia*, 157:161-168, 1988.

Reinelt, L.E., R. Castensson, and R.R. Horner. Modification of an Existing Monitoring Program to Address Nonpoint Source Pollution, A Case Study of the Svarta River Basin, Sweden. *Vatten* 43:199-208, 1987.

Mar, B.W., R.R. Horner, J.S. Richey, D.P. Lettenmaier, and R.N. Palmer. Data Acquisition, Cost-Effective Methods for Obtaining Data on Water Quality. *Environmental Science and Technology* 20(6):545-551, 1986.

Horner, R.R., J.S. Richey, and G.L. Thomas. A Conceptual Framework to Guide Aquatic Monitoring Program Design for Thermal Electric Power Plants. *Rationale for Sampling and Interpretation of Ecological Data in the Assessment of Freshwater Ecosystems*, Special Technical Publication 894 of the American Society for Testing and Materials, Philadelphia, Pennsylvania, pp. 86-100, 1986.

Welch, E.B., D.E. Spyridakis, J.I. Shuster, and R.R. Horner. Declining Lake Sediment Phosphorus Release and Oxygen Deficit Following Wastewater Diversion. *Journal of the Water Pollution Control Federation* 58(1):92-96, 1986.

Richey, J.S., B.W. Mar, and R.R. Horner. The Delphi Technique in Environmental Assessment, Part 1: Implementation and Effectiveness. *Journal of Environmental Management* 21:135-146, 1985.

Richey, J.S., R.R. Horner, and B.W. Mar. The Delphi Technique in Environmental Assessment, Part 2: Consensus on Critical Issues in Environmental Monitoring Program Design. *Journal of Environmental Management* 21:147-159, 1985.

Horner, R.R. and B.W. Mar. Assessing Impacts of Operating Highways on Aquatic Ecosystems. *Transportation Research Record* 1017:47-55, 1985.

Horner, R.R., E.B. Welch, and R.B. Veenstra. Development of Nuisance Periphytic Algae in Laboratory Streams in Relation to Enrichment and Velocity. In *Periphyton of Freshwater Ecosystems*, R.G. Wetzel (ed.), Dr. W. Junk BV, the Hague, The Netherlands, pp. 121-134, 1983.

Horner, R.R. and B.W. Mar. A Guide for Assessing Water Quality Impacts of Highway Operations and Maintenance. *Transportation Research Record* 948:31-40, 1983.

Chui, T.W., B.W. Mar, and R.R. Horner. A Pollutant Loading Model for Highway Runoff. *Journal of Environmental Engineering Division*, ASCE 108:1193-1120, 1982.

Horner, R.R. and E.B. Welch. Stream Periphyton Development in Relation to Current Velocity and Nutrients. *Canadian Journal of Fisheries and Aquatic Sciences* 38:449-457, 1981.

REVIEWED PROCEEDINGS PUBLICATIONS

Horner, R. R. Stormwater Runoff Flow Control Benefits of Urban Drainage System Reconstruction According to Natural Principles. Presentation at Puget Sound—Strait of Georgia Research Conference, Vancouver, B. C., 2003.

May, C.W. and R.R. Horner. 2002. The Limitations of Mitigation-Based Stormwater Management in the Pacific Northwest and the Potential of a Conservation Strategy Based on Low-Impact Development Principles. Proc. 2002 ASCE Stormwater Conference, Portland, OR.

Horner, R. R. and C. R. Horner. Performance of a Perimeter ("Delaware") Sand Filter in Treating Stormwater Runoff from a Barge Loading Terminal. Proc. Comprehensive Stormwater and Aquatic Ecosystem Management Conf.; Auckland, New Zealand; February 1999, pp. 183-192, 1999.

Horner, R. R. and C. W. May. Regional Study Supports Natural Land Cover Protection as Leading Best Management Practice for Maintaining Stream Ecological Integrity. Proc. Comprehensive Stormwater and Aquatic Ecosystem Management Conf.; Auckland, New Zealand; February 1999, pp. 233-248, 1999.

Horner, R. R. Constructed Wetlands for Urban Runoff Water Quality Control. Proc. National Conf. on Urban Runoff Management; Chicago, Illinois; March 1993, pp. 327-340, 1995.

Horner, R. R. Training for Construction Site Erosion Control and Stormwater Facility Inspection. Proc. National Conf. on Urban Runoff Management; Chicago, Illinois; March 1993, pp. 426-450, 1995.

Horner, R. R. Overview of the Puget Sound Wetlands and Stormwater Management Research Program. Proc. Puget Sound Water Quality Authority Research Meeting; Seattle, Washington; January 1995, pp. 141-145, 1995.

Horner, R. R. and L. E. Reinelt. Guidelines for Managing Urban Wetlands. Proc. Puget Sound Water Quality Authority Research Meeting; Seattle, Washington; January 1995, pp. 171-178, 1995.

Taylor, B. K. Ludwa, and R. R. Horner. Urbanization Effects on Wetland Hydrology and Water Quality. Proc. Puget Sound Water Quality Authority Research Meeting; Seattle, Washington; January 1995, pp. 146-154, 1995.

Reinelt, L.E. and R.R. Horner. Urban Stormwater Impacts on the Hydrology and Water Quality of Palustrine Wetlands in the Puget Sound Region. Proc. Puget Sound Water Quality Authority Research Meeting; Seattle, Washington; January 1991; pp. 33-42.

Horner, R.R. Environmental Effects of Calcium Magnesium Acetate, Emphasizing Aquatic Ecosystem Effects. Proc. Conf. on Environmental Impacts of Highway Deicing, Institute of Ecology Publication No. 33, University of California, Davis; 1990; pp. 97-119.

Stockdale, E.C. and R.R. Horner. Using Freshwater Wetlands for Stormwater Management: A Progress Report. Proc. Wetlands 1988: Urban Wetlands and Riparian Habitat Symposium; Oakland, California, June 1988.

Horner, R.R. Highway Construction Site Erosion and Pollution Control: Recent Research Results. Proc. 39th Annual Road Builders' Clinic; Moscow, Idaho; March 1988; pp. 37-54.

Horner, R.R., F.B. Gutermuth, L.L. Conquest, and A.W. Johnson. Urban Stormwater and Puget Trough Wetlands. Proc. 1st Annual Meeting on Puget Sound Research; Seattle, Washington; March 1988; pp. 723-746.

Weiner, R.F., R.R. Horner, and J. Kettman. Preliminary Comparative Risk Assessment for Hanford Waste Sites. Proc. Waste Management 88; Tucson, Arizona; February 1988.

Stockdale, E.C. and R.R. Horner. Prospects for Wetlands Use in Stormwater Management. Proc. Coastal Zone 87 Conf.; Seattle, Washington; May 1987; pp. 3701-3714.

Horner, R.R. A Review of Wetland Water Quality Functions, Proc. Conf. on Wetland Functions, Rehabilitation, and Creation in the Pacific Northwest: The State of Our Understanding; Port Townsend, Washington; May 1986; pp. 33-50.

Bain, R.C., Jr., R.R. Horner, and L. Nelson. Nonpoint Pollution Control Strategies for Moses Lake, Washington. Proc. Fifth Annual Conf. North American Lake Management Society; Lake Geneva, Wisconsin; November 1985; pp. 170-176.

Shuster, J.I., E.B. Welch, R.R. Horner, and D.E. Spyridakis. Response of Lake Sammamish to Urban Runoff Control. Proc. Fifth Annual Conf. North American Lake Management Society; Lake Geneva, Wisconsin; November 1985; pp. 229-234.

Horner, R.R., J.S. Richey, and B.W. Mar. A General Approach to Designing Environmental Monitoring Programs. Proc. Pacific Section AAAS Sym. on Biomonitors, Bioindicators and Bioassays of Environmental Quality; Missoula, Montana; June 1985.

Horner, R.R. Improvement of Environmental Impact Assessment of Nonpoint Sources of Water Pollution. Proc. Non-point Pollution Abatement Sym.; Milwaukee, Wisconsin; April 1985.

Horner, R.R., E.B. Welch, M.M. Wineman, M.J. Adolfson, and R.C. Bain, Jr. Nutrient Transport Processes in an Agricultural Watershed. Proc. Fourth Annual Conf. North American Lake Management Society; McAfee, New Jersey; October 1984; pp. 221-228.

Horner, R.R. and B.W. Mar. A Predictive Model for Highway Runoff Pollutant Concentrations and Loadings. Proc. Stormwater and Water Quality Management Model Users' Group Meeting. EPA 600/9-82-015; Alexandria, Virginia; March 1982; pp. 210-224.

TECHNICAL REPORTS

Horner, R.R. Development of a Stormwater Retrofit Plan for Water Resources Inventory Area 9: Flow and Water Quality Indicators and Targets. King County Water and Land Resources Division, Seattle, Washington, 2013.

Horner, R.R. and J. Gretz. Investigation of the Feasibility and Benefits of Low-Impact Site Design Practices Applied to Meet Various Potential Stormwater Runoff Regulatory Standards. Report to U.S. Environmental Protection Agency by Natural Resources Defense Council, 2011.

Horner, R.R. Section 4-2, Protection and Restoration Strategies for Watersheds and Tributaries; Chapter 4: A Science-Based Review of Ecosystem Protection and Restoration Strategies for Puget Sound and Its Watersheds; Puget Sound Science Update. Puget Sound Partnership, Tacoma, WA, 2010.

Garrison, N., R.C. Wilkinson, and R. Horner. How Greening California Cities Can Address Water Resources and Climate Challenges in the 21st Century. Natural Resources Defense Council, 2009.

Horner, R. R. Supplementary Investigation of the Feasibility and Benefits of Low-Impact Site Design Practices ("LID") for the San Francisco Bay Area. Natural Resources Defense Council, 2009.

Horner, R. R. Initial Investigation of the Feasibility and Benefits of Low-Impact Site Design Practices ("LID") for the San Francisco Bay Area. Natural Resources Defense Council, 2009.

Horner, R. R. Investigation of the Feasibility and Benefits of Low-Impact Site Design Practices ("LID") for Ventura County. Natural Resources Defense Council, 2008.

Horner, R. R. and C. Chapman. NW 110th Street Natural Drainage System Performance Monitoring, With Summary of Viewlands and 2nd Avenue NW SEA Streets Monitoring. Report to City of Seattle Public Utilities, 2007.

Horner, R. R. Investigation of the Feasibility and Benefits of Low-Impact Site Design Practices ("LID") for the San Diego Region. Natural Resources Defense Council, 2006.

Horner, R. R. SPU Drainage Rate Analysis Options: Recommendations on Certain Technical Issues. Report to City of Seattle Public Utilities, 2005.

Hill, K. and R. Horner. Assessment Of Alternatives In Roadside Vegetation Management. Report to Washington State Department of Transportation, 2005.

Horner, R. R. and Entranco, Inc. Regional Detention Facilities Retrofit Project: Evaluation of Regional Stormwater Ponds for Water Quality Improvements. Report to City of Bellevue Utilities Department, 2005.

Horner, R. R. and T. Osborn. Removal of Fecal Coliforms from Stormwater Runoff: A Literature Review. Report to City of Blaine, 2005.

Horner, R.R., H. Lim, and S.J. Burges. Hydrologic Monitoring of the Seattle Ultra-Urban Stormwater Management Projects: Summary of the 2000-2003 Water Years, Water Resources Series Technical Report Number 181. Department of Civil and Environmental Engineering, University of Washington, Seattle, WA. Report to City of Seattle Public Utilities, 2004.

Horner, R.R., C.W. May, and E.H. Livingston. Linkages Between Watershed and Stream Ecosystem Conditions in Three Regions of the United States. Report to U.S. Environmental Protection Agency by Watershed Management Institute, Inc., Crawfordville, FL, 2003.

Karr, J. R., R. R. Horner, and C R. Horner. EPA's Review of Washington's Water Quality Criteria: An Evaluation of Whether Washington's Criteria Proposal Protects Stream Health and Designated Uses. Report to National Wildlife Federation, 2003.

Horner, R.R., H. Lim, and S.J. Burges. Hydrologic Monitoring of the Seattle Ultra-Urban Stormwater Management Projects, Water Resources Series Technical Report Number 170. Department of Civil and Environmental Engineering, University of Washington, Seattle, WA. Report to City of Seattle Public Utilities, 2002.

Miller, A.V., S.B. Burges, and R.R. Horner. Hydrologic Monitoring of the Seattle Ultra-Urban Stormwater Management Projects, Water Resources Series Technical Report Number 166. Department of Civil and Environmental Engineering, University of Washington, Seattle, WA. Report to City of Seattle Public Utilities, 2001.

Mills, M. and R. R. Horner. Comprehensive Ditch and Culvert Program. Report to City of Seattle Public Utilities, 2001.

Colwell, S., R. R. Horner, D. B. Booth, and D. Gilvydis. A Survey of Ditches Along County Roads for Their Potential to Affect Storm Runoff Water Quality. Report to Snohomish County Surface Water Management Division, Snohomish County Road Maintenance, King County Land and Water Resources Division, King County Department of Transportation Road Maintenance, 2000.

Cammermayer, J. W. and R. R. Horner. Vegetated Stormwater Facility Maintenance. Report to Washington State Department of Transportation, WA-RD-495.1, 2000.

Azous, A. L. and R. R. Horner (eds.). Wetlands and Urbanization: Implications for the Future. Report to Washington Department of Ecology, 1997.

May, C. W., E. B. Welch, R. R. Horner, J. R. Karr, and B. W. Mar. Quality Indices for Urbanization Effects in Puget Sound Lowland Streams. Report to Washington Department of Ecology, 1997.

Livingston, E. H., H. E. Shaver, J. J. Skupien, and R. R. Horner. Operation, Maintenance, and Management of Stormwater Management Systems. Report to U. S. Environmental Protection Agency, 1997.

Livingston, E. H., H. E. Shaver, R. R. Horner, and J. J. Skupien,. Watershed Management Institute. Institutional Aspects of Urban Runoff Management: A Guide for Program Development and Implementation. Report to U. S. Environmental Protection Agency, 1997.

St. John, M. S. and R. R. Horner. Effect of Road Shoulder Treatments on Highway Runoff Quality and Quantity. Report to Washington State Department of Transportation, WA-RD-429.1, 1997.

Horner, R.R. Storm Drainage Water Quality Rate Basis Recommendations. Report to City of Bellevue Utilities Department, 1996.

Horner, R. R. and C. R. Horner. Impacts on Aquatic Ecosystems and Organisms of Airplane and Airport Runway Deicing Chemicals. Report to Port of Seattle, Seattle, Washington, 1996.

Horner, R. R. Constituents and Sources of Water Pollutants in Urban Stormwater Runoff. Report to Natural Resources Defense Council, Los Angeles, California, 1995.

Horner, R. R. Program Recommendations and Review of Submittals for Los Angeles County Stormwater NPDES Compliance. Report to Natural Resources Defense Council, Los Angeles, California, 1995.

Horner, R. R. and C. R. Horner. Design, Construction, and Evaluation of a Sand Filter Stormwater Treatment System, Part II, Performance Monitoring. Report to Alaska Marine Lines, Seattle, Washington, 1995.

Horner, R. R. Review of Draft Design Memorandum, Lakemont Boulevard Extension. Report to City of Bellevue, Washington, 1995.

Economic and Engineering Services, Inc. and R. R. Horner. Wetpond Restoration for Water Quality Enhancement. Report to City of Bellevue, Washington and Washington Department of Ecology, 1995.

City of Bellevue Utilities Department (R. R. Horner contributing author). Characterization and Source Control of Urban Stormwater Quality. Report to Washington Department of Ecology, 1995.

Horner, R. R. Constituents and Sources of Water Pollutants in Highway Stormwater Runoff. Report to Natural Resources Defense Council, Los Angeles, California, 1994.

Horner, R. R. Program Recommendations and Review of California Department of Transportation Submittals for Santa Monica Bay Watershed Stormwater NPDES Compliance, Support Materials. Report to Natural Resources Defense Council, Los Angeles, California, 1994.

Horner, R. R. Peer Review of Assessment of Potential Impacts from Sediment and Phosphorus Loading to Lewis Creek and Lake Sammamish - Lakemont Boulevard Extension Project. Report to City of Bellevue, Washington, 1994.

Horner, R. R. Review of the Literature on Constructed Wetlands for Municipal Wastewater Treatment. Report to Kramer, Chin and Mayo, Inc., Seattle, Washington, 1994.

Engineering Technologies Associates, Inc. and R. R. Horner. Conceptual Framework for Hydrograph Classification. Report to Water Research Center, Huntington Valley, Pennsylvania, 1994.

Horner, R. R. Phantom Lake Stormwater Controls Evaluation, Review of Water Quality Data and Literature. Report to CH2M-Hill, City of Bellevue Storm and Surface Water Utility, and Boeing Computer Services Corporation, Bellevue, Washington, 1993.

Horner, R. R. Boeing Customer Service Training Center Stormwater Quality Monitoring and Assessment Program. Report to Boeing Commercial Airplane Company, Sverdrup Corporation, and City of Renton, Washington, 1992.

Welch, E.B., R.J. Totorica and R.R. Horner. Approach to Developing Nutrient Loading Criteria for Franklin D. Roosevelt Lake. Report to Washington Department of Ecology, Olympia, 1992.

Municipality of Metropolitan Seattle (R. R. Horner contributing author). Biofiltration Swale Performance, Recommendations, and Design Considerations. Report to Washington Department of Ecology, Olympia, 1992.

Horner, R.R. and P. Kalina. Water Quality Assessment of Portage Bay. Report to City of Seattle, 1991.

Horner, R.R. and C.R. Horner. Transport and Fate of Metal and Organic Toxicants in Arid-Region Wetlands. Report to U.S. Environmental Protection Agency, Corvallis Laboratory, 1991.

King County Resource Planning Section (R. R. Horner contributing author). Development of Guidance for Managing Urban Wetlands and Stormwater. Report to Washington Department of Ecology, Olympia, 1991.

Horner, R.R. and C.R. Horner. Use of Underdrain Filter Systems for the Reduction of Stormwater Runoff Pollutants: A Literature Review. Report to Kramer, Chin and Mayo, Inc., 1990.

Reinelt, L.E. and R.R. Horner. Characterization of the Hydrology and Water Quality of Palustrine Wetlands Affected by Urban Stormwater. Report prepared for the Puget Sound Wetlands and Stormwater Management Research Program, Seattle, WA, 1990.

Horner, R. R. Analysis of Proposed Surface Water Source Control Requirements for the Commencement Bay Nearshore/Tideflats Superfund Area. Report to Port of Tacoma, Washington, 1989.

Horner, R.R. and K.J. Raedeke. Guide for Wetland Mitigation Project Monitoring. Report to Washington State Department of Transportation, 1989.

Horner, R.R., J. Guedry, and M.H. Kortenhof. Improving the Cost-Effectiveness of Highway Construction Site Erosion and Pollution Control. Report to Washington State Department of Transportation, 1989.

Horner, R.R., J. Guedry, and M.H. Kortenhof. Highway Construction Site Erosion and Pollution Control Manual. Report to Washington State Department of Transportation, 1989.

Horner, R.R., M.V. Brenner, and C.A. Jones. Design of Monitoring Programs for Determining Sources of Shellfish Bed Bacterial Contamination Problems. Report to Washington Department of Ecology, 1989.

Horner, R. R. and C. R. Horner. A Technical Review of the Sediment/Toxicant Retention and Nutrient Removal Transformation Functions of WET 2.0. Report to AScI Corporation and U. S. Environmental Protection Agency, Duluth, Minnesota, 1989.

Horner, R. R. and M. Benjamin. Washington State Pulp and Paper Plant Water Treatment Effluent Limitations. Report to Technical Resources, Inc., Rockville, Maryland, 1988.

Tetra Tech, Inc., University of Washington (R.R. Horner), and Battelle Pacific Northwest Laboratories. Recommended Protocols for Measuring Conventional Water Quality Variables and Metals in Fresh Waters of the Puget Sound Region. Report to Puget Sound Estuary Program, U.S. Environmental Protection Agency, Region 10, Seattle, 1988.

Horner, R.R. Biofiltration Systems for Storm Runoff Water Quality Control. Report to Municipality of Metropolitan Seattle, Seattle, 1988.

URS Consultants, R.R. Horner, Matrix Management Group, Weston/Northwest Cartography, and Water Resources Associates. City of Puyallup Stormwater Management Program. Report to City of Puyallup, 1988.

Welch, E.B., J. Oppenheimer, R.R. Horner, and D.E. Spyridakis. Silver Lake Water Quality Nutrient Loading and Management. Report to City of Everett, 1988.

Horner, R.R. Environmental Monitoring and Evaluation of Calcium Magnesium Acetate (CMA)--Final Report. Report to National Research Council, National Academy of Sciences, 1988.

Horner, R.R., E.B. Welch, S.R. Butkus, and D.E. Spyridakis. Management Significance of Bioavailable Phosphorus. Report to Municipality of Metropolitan Seattle and State of Washington Water Research Center, 1987.

Horner, R.R. and S.E. Cassatt. Effectiveness of Wetlands Creation in Mitigating Highway Impacts. Report to Washington State Department of Transportation, 1987.

Horner, R.R. and M.H. Kortenhof. Improving the Cost-Effectiveness of Highway Construction Site Erosion/Pollution Control, Phase 1. Report to Washington State Department of Transportation, 1987.

Horner, R.R., B.W. Mar, L.E. Reinelt, and J.S. Richey. Design of Monitoring Programs for Determination of Ecological Change Resulting from Nonpoint Source Water Pollution in Washington State. Report to Washington State Department of Ecology, 1986.

Horner, R.R., E.B. Welch, M.R. Seeley, and J.M. Jacoby. Velocity-Related Critical Phosphorus Concentrations in Flowing Water, Phase II. Report to National Science Foundation, 1986.

Horner, R.R., J.S. Richey, and D.P. Lettenmaier. Source Control of Transit Base Runoff Pollutants--Final Report. Report to Municipality of Metropolitan Seattle, 1985.

Welch, E.B., R.R. Horner, D.E. Spyridakis, and J.I. Shuster. Response of Lake Sammamish to Past and Future Phosphorus Loading. Report to Municipality of Metropolitan Seattle, 1985.

Horner, R.R. and S.R. Wonacott. Performance Evaluation of a Detention Basin and Coalescing Plate Oil Separator for Treating Urban Stormwater Runoff. Report to State of Washington Water Research Center and U.S. Geological Survey, 1985.

Cahn, D.C. and R.R. Horner. Preliminary Investigation of Sewage Sludge Utilization in Roadside Development. Report to Washington State Department of Transportation, 1985.

Horner, R.R. Highway Runoff Water Quality Research Implementation Manual, Vol. 1-2, FHWA WA-RD 72.1,2. Report to Washington State Department of Transportation, 1985.

Horner, R.R. Suggested Revisions to WSDOT Manuals for Implementing Washington State Highway Runoff Water Quality Research Results, FHWA WA-RD 72.3. Report to Washington State Department of Transportation, 1985.

Mar, B.W., D.P Lettenmaier, R.R. Horner, J.S. Richey, R.N. Palmer, S.P. Millard, and M.C. MacKenzie. Sampling Design for Aquatic Ecological Monitoring, Vol. 1-5. Final Report on Electric Power Research Institute, Project RP1729-1, 1985.

Horner, R.R., J.S. Richey, D.P. Lettenmaier, and J.F. Ferguson. Source Control of Transit Base Runoff Pollutants, Task 1--Interim Report. Report to Municipality of Metropolitan Seattle, 1984.

Brown and Caldwell Engineers and R.R. Horner. Moses Lake Clean Lake Project, Phase I. Report to Moses Lake Irrigation and Rehabilitation District, 1984.

Mar, B.W., D.P. Lettenmaier, J.S. Richey, R.R. Horner, R.N. Palmer, S.P. Millard, and G.L. Thomas. Sampling Design for Aquatic Ecological Monitoring, Phase II--Methods Development, Vol. 1-2. Report to Electric Power Research Institute, 1984.

Horner, R.R. Highway Runoff Water Quality Technology Transfer Workshop Handbook. Prepared for Washington State Department of Transportation, 1983.

Pedersen, E.R., R.R. Horner, and G.L. Portele. SR 528 - 4th Street Extension, Marysville, Snohomish County, Washington: Draft Environmental Impact Statement. Prepared for City of Marysville, 1983.

Horner, R.R., B.W. Mar, B. Chaplin, and F. Conroy. Implementation Plan for Highway Runoff Water Quality Research Results. Report to Washington State Department of Transportation, 1983.

Little, L.M., R.R. Horner, and B.W. Mar. Assessment of Pollutant Loadings and Concentrations in Highway Stormwater Runoff, FHWA WA-RD-39.17. Report to Washington State Department of Transportation, 1983.

Horner, R.R., and E.B. Welch. Velocity-Related Critical Phosphorus Concentrations in Flowing Water. Final Report to National Science Foundation for award number (CME) 79-18514, 1982.

Horner, R.R., and E.B. Welch. Impacts of Channel Reconstruction on the Pilchuck River, FHWA WA-RD-39.15. Report to Washington State Department of Transportation, 1982.

Mar, B.W., R.R. Horner, J.F. Ferguson, D.E. Spyridakis, and E.B. Welch. Summary - Highway Runoff Water Quality, 1977-1982, FHWA WA-RD-39.16. Report to Washington State Department of Transportation, 1982.

Horner, R.R. and B.W. Mar. Guide for Water Quality Assessment of Highway Operations and Maintenance, FHWA WA-RD-39.14. Report to Washington State Department of Transportation, 1982.

Mar, B.W., D.P. Lettenmaier, R.R. Horner, D.M. Eggers, R.N. Palmer, G.J. Portele, J.S. Richey, E.B. Welch, G. Wiens, and J. Yearsley. Sampling Design for Aquatic Ecological Monitoring, Phase 1. Report to Electric Power Research Institute, 1982.

Portele, G.J., B.W. Mar, R.R. Horner, and E.B. Welch. Effects of Seattle, Area Highway Stormwater Runoff on Aquatic Biota, FHWA WA-RD-39.11. Report to Washington State Department of Transportation, 1982.

Wang, T.S., D.E. Spyridakis, B.W. Mar, and R.R. Horner. Transport, Deposition, and Control of Heavy Metals in Highway Runoff, FHWA WA-RD-39.10. Report to Washington State Department of Transportation, 1982.

Chui, T.W., B.W. Mar, and R.R. Horner. Highway Runoff in Washington State: Model Validation and Statistical Analysis, FHWA WA-RD-39.12. Report to Washington State Department of Transportation, 1981.

Mar, B.W., J.F. Ferguson, D.E. Spyridakis, E.B. Welch, and R.R. Horner. Year 4, Runoff Water Quality, August 1980-August 1981, FHWA WA-RD-39.13. Report to Washington State Department of Transportation, 1981.

Horner, R.R. and S.M. Grason. An Ecological Study of the Monocacy Creek and its Groundwater Sources in the Vicinity of Camels Hump. Report to the Monocacy Creek Watershed Association, Bethlehem, Pennsylvania, 1981.

Horner, R.R. and E.B. Welch. Background Conditions in the Lower Pilchuck River Prior to SR-2 Construction. Report to Washington State Department of Transportation, 1979.

Horner, R.R. and B.W. Mar. Highway Runoff Monitoring: The Initial Year, FHWA WA-RD-39.3. Report to Washington State Department of Transportation, 1979.

Horner, R.R. and E.B. Welch. Effects of Velocity and Nutrient Alterations on Stream Primary Producers and Associated Organisms, FHWA WA-RD-39.2. Report to Washington State Department of Transportation, 1978.

Horner, R.R., T.J. Waddle, and S.J. Burges. Review of the Literature on Water Quality Impacts of Highway Operations and Maintenance. Report to Washington State Department of Transportation, 1977.

Horner, R.R. A Method of Defining Urban Ecosystem Relationships Through Consideration of Water Resources. U.S. Man and the Biosphere Project 11 Report, 1977.

Horner, R.R. and R. Gilliom. Bear Lake: Current Status and the Consequences of Residential Development. Report to Bear Lake Residents' Association, Kitsap County, Washington, 1977.

PRESENTATIONS AND DISCUSSIONS

*Presented by a co-author. In all other cases, I presented the paper.

Stormwater Runoff Flow Control Benefits of Urban Drainage System Reconstruction According to Natural Principles. Puget Sound/Georgia Strait Research Meeting; Vancouver, British Columbia; April 2003.

Structural and Non-Structural Best Management Practices (BMPs) for Protecting Streams. Invited presentation at the Engineering Foundation Conference on Linking Stormwater BMP Designs and Performance to Receiving Water Impact Mitigation; Snowmass, Colorado; August 2001.

Performance of a Perimeter ("Delaware") Sand Filter in Treating Stormwater Runoff from a Barge Loading Terminal. Invited presentation at the Comprehensive Stormwater and Aquatic Ecosystem Management Conf.; Auckland, New Zealand; February 1999.

Regional Study Supports Natural Land Cover Protection as Leading Best Management Practice for Maintaining Stream Ecological Integrity. Invited presentation at the Comprehensive Stormwater and Aquatic Ecosystem Management Conf.; Auckland, New Zealand; February 1999.

Watershed Determinants of Ecosystem Functioning. Invited presentation at the Engineering Foundation Conference on Effects of Watershed Development on Aquatic EcosystemsUrban Runoff and Receiving Systems; Snowbird, Utah; August 1996.

Overview of the Puget Sound Wetlands and Stormwater Management Research Program. Puget Sound Water Quality Authority Research Meeting; Seattle, Washington; January 1995.

Guidelines for Managing Urban Wetlands. Puget Sound Water Quality Authority Research Meeting; Seattle, Washington; January 1995.

Urbanization Effects on Wetland Hydrology and Water Quality. Puget Sound Water Quality Authority Research Meeting; Seattle, Washington; January 1995 (prepared with B. Taylor and K. Ludwa).*

Constructed Wetlands for Urban Runoff Water Quality Control. Invited presentation at National Conf. on Urban Runoff Management; Chicago, Illinois; March 1993.

Training for Construction Site Erosion Control and Stormwater Facility Inspection. Invited presentation at National Conf. on Urban Runoff Management; Chicago, Illinois; March 1993.

Toward Ecologically Based Urban Runoff Management. Invited presentation at The Engineering Foundation Conference on Urban Runoff and Receiving Systems; Crested Butte, Colorado; August 1991.

How Stormwater Harms Shellfish. Invited presentation at the Pacific Rim Shellfish Sanitation Conference; Seattle, Washington; May 1991.

Environmental Evaluation of Calcium Magnesium Acetate for Highway Deicing Applications. Invited presentation at Conference on Calcium Magnesium Acetate, An Emerging Chemical for Environmental Applications; Boston, Massachusetts; May 1991.

Issues in Stormwater Management. Statement to State Senate Environment and Natural Resources Committee; Olympia, Washington; January 1991.

Urban Stormwater Impacts on the Hydrology and Water Quality of Palustrine Wetlands in the Puget Sound Region. Invited presentation at Puget Sound Water Quality Authority Research Meeting; Seattle, Washington; January 1991 (prepared with L.E. Reinelt).

The Impact of Nonpoint Source Pollution on River Ecosystems. Invited presentation at the Northwest Rivers Conference; Seattle, Washington; November 1990.

Research Program Overview and Discussion of Hydrologic and Water Quality Studies. Presented at the Puget Sound Wetlands and Stormwater Management Research Program Workshop; Seattle, Washington; October 1990.

Control of Urban Runoff Water Quality. Invited presentations at American Society of Civil Engineers Urban Stormwater Short Courses; Bellevue, Washington; April, 1990; Portland, Oregon; July 1990.

Various Aspects of Erosion Prevention and Control. Invited presentations at University of Wisconsin Erosion Control Short Course; Seattle, Washington; July 1990.

Examination of the Hydrology and Water Quality of Wetlands Affected by Urban Stormwater. Presented at the Society of Wetland Scientists Annual Meeting; Breckenridge, Colorado, June 1990 (prepared with L.E. Reinelt).*

Analysis of Plant Communities of Wetlands Affected by Urban Stormwater. Presented at the Society of Wetland Scientists Annual Meeting; Breckenridge, Colorado; June 1990 (prepared with S.S. Cooke).*

Environmental Evaluation of Calcium Magnesium Acetate. Invited presentation at the Symposium on the Environmental Impact of Highway Deicing; Davis, California; October 1989.

Application of Wetland Science Principles in the Classroom and Community. Invited presentation at the Annual Meeting of the Association of Collegiate Schools of Planning; Portland, Oregon; October 1989.

Structural Controls for Urban Storm Runoff Water Quality. Invited presentation at the Northwest Regional Meeting of the North American Lake Management Society; Seattle, Washington; September 1989.

The Puget Sound Wetlands and Stormwater Management Research Program. Invited presentation at the U.S. Environmental Protection Agency Workshop on Wetlands and Stormwater; Seattle, Washington; September 1989.

An Overview of Storm Runoff Water Quality Control. Invited presentation at the American Water Resources Association Workshop on Forest Conversion; LaGrande, Washington; November 1988.

Progress in Wetlands Research. Invited presentation at the Pacific Northwest Pollution Control Association Annual Meeting; Coeur d'Alene, Idaho; October 1988.

Long-Term Effects of Urban Stormwater on Wetlands. Invited presentation at the Engineering Foundation Conference on Urban Stormwater; Potosi, Missouri; July 1988.

Highway Construction Site Erosion and Pollution Control: Recent Research Results. Invited presentation at the 39th Annual Road Builders' Clinic; Moscow, Idaho; March 1988.

Urban Stormwater and Puget Trough Wetlands. Presented at the 1st Annual Puget Sound Water Quality Authority Research Meeting; Seattle, Washington; March 1988 (prepared with F.B. Gutermuth, L.L. Conquest, and A.W. Johnson).

Preliminary Comparative Risk Assessment for Hanford Waste Sites. Presented at Waste Management 88; Tucson, Arizona; February 1988 (prepared with R.F. Weiner and J. Kettman).*

What Goes on at the Hanford Nuclear Reservation? Invited presentation at the Northwest Association for Environmental Studies Annual Meeting; Western Washington University, Bellingham, WA; November 1987.

The Puget Sound Wetlands and Stormwater Management Research Program. Invited presentation at the Pacific Northwest Pollution Control Association Annual Meeting; Spokane, Washington; October 1987.

Design of Cost-Effective Monitoring Programs for Nonpoint Source Water Pollution Problems. Invited presentation at the American Water Resources Association, Puget Sound Chapter, Annual Meeting; Bellevue, Washington; November 1986.

A Review of Wetland Water Quality Functions. Invited plenary presentation at the Conference on Wetland Functions, Rehabilitation, and Creation in the Pacific Northwest: The State of Our Understanding; Port Townsend, Washington; May 1986.

Nonpoint Discharge and Runoff session leader. American Society of Civil Engineers Spring Convention; Seattle, Washington; April 1986.

Prevention of Lake Sammamish Degradation from Future Development. Invited presentation at the American Society of Civil Engineers Spring Convention; Seattle, Washington; April 1986.

Design of Monitoring Programs for Nonpoint Source Water Pollution Problems. Invited presentation at the American Society of Civil Engineers Spring Convention; Seattle, Washington, April 1986 (prepared with L.E. Reinelt, B.W. Mar, and J.S. Richey).*

Nonpoint Pollution Control Strategies for Moses Lake, Washington. Presented at the Fifth Annual Meeting of the North American Lake Management Society; Lake Geneva, Wisconsin; November 1985 (prepared with R.C. Bain, Jr., and L. Nelson).

Response of Lake Sammamish to Urban Runoff Control. Presented at the Fifth Annual Meeting of the North American Lake Management Society; Lake Geneva, Wisconsin; November 1985 (prepared with J.I. Shuster, E.B. Welch, and D.E. Spyridakis).*

A General Approach to Designing Environmental Monitoring Programs. Invited presentation at the Pacific Section AAAS Symposium on Biomonitors, Bioindicators, and Bioassays of Environmental Quality; Missoula, Montana; June 1985 (prepared with J.S. Richey and B.W. Mar).

Panel Discussion on the Planning Process for Non-point Pollution Abatement Programs. Non-point Pollution Abatement Symposium; Milwaukee, Wisconsin; April 1985.

Nutrient Transport Processes in an Agricultural Watershed. Presented at the Fourth Annual Meeting of the North American Lake Management Society; McAfee, New Jersey; October 1984 (prepared with E.B. Welch, M.M. Wineman, M.J. Adolfson, and R.C. Bain Jr.).*

Nutrient Transport Processes in an Agricultural Watershed. Presented at the American Society of Limnology and Oceanography Annual Meeting; Vancouver, British Columbia; June 1984 (prepared with M.M. Wineman, M.J. Adolfson, and R.C. Bain, Jr.).

Factors Affecting Periphytic Algal Biomass in Six Swedish Streams. Presented at the American Society of Limnology and Oceanography Annual Meeting; Vancouver, British Columbia; June 1984 (prepared with J.M. Jacoby and E.B. Welch).*

A Conceptual Framework to Guide Aquatic Monitoring Program Design for Thermal Electric Power Plants. Presented at the American Society for Testing and Materials Symposium on Rationale for Sampling and Interpretation of Ecological Data in the Assessment of Freshwater Ecosystems; Philadelphia, Pennsylvania; November 1983 (prepared with J.S. Richey, and G.L. Thomas).

Panel Discussion. Public Forum: Perspectives on Cumulative Effects; Institute for Environmental Studies; University of Washington; Seattle, Washington; August 1983.

A Guide for Assessing the Water Quality Impacts of Highway Operations and Maintenance. Presented at the Transportation Research Board Annual Meeting; Washington, D.C.; January 1983 (prepared with B.W. Mar).

Assessment of Pollutant Loadings and Concentrations in Highway Stormwater Runoff. Presented at the Pacific Northwest Pollution Control Association Annual Meeting; Vancouver, British Columbia; November 1982 (prepared with B.W. Mar and L.M. Little).

Phosphorus and Velocity as Determinants of Nuisance Periphytic Biomass. Presented at the International Workshop on Freshwater Periphyton (SIL); Vaxjo, Sweden; September 1982 (prepared with E.B. Welch and R.B. Veenstra).*

The Development of Nuisance Periphytic Algae in Laboratory Streams in Relation to Enrichment and Velocity. Presented at the American Society of Limnology and Oceanography Annual Meeting; Raleigh, North Carolina; June 1982 (prepared with R.B. Veenstra and E.B. Welch).

A Predictive Model for Highway Runoff Pollutant Concentrations and Loadings. Presented at the Stormwater and Water Quality Model Users' Group Meeting; Alexandria, Virginia; March 1982 (prepared with B.W. Mar).

Stream Periphyton Development in Relation to Current Velocity and Nutrients. Presented at American Society of Limnology and Oceanography Winter Meeting; Corpus Christi, Texas; January 1979 (prepared with E.B. Welch).

A Comparison of Discrete Versus Composite Sampling of Storm Runoff. Presented at the Northwest Pollution Control Association Annual Meeting; Victoria, British Columbia; October 1978 (prepared with B.W. Mar and J.F. Ferguson).*

A Method of Defining Urban Ecosystem Relationships Through Consideration of Water Resources. Presented at UNESCO International Man and the Biosphere Project 11 Conference; Poznan, Poland; September 1977.

<u>GRADUATE AND UNDERGRADUATE COURSES TAUGHT</u> (University of Washington)

Civil and Environmental Engineering 552, Environmental Regulations; 8 quarters.

Landscape Architecture 590, Urban Water Resources Seminar; 3 quarters.

Landscape Architecture 522/523, Watershed Analysis and Design; 15 quarters.

Engineering 260, Thermodynamics; 1 quarter.

Engineering 210, Engineering Statics; 2 quarters.

Civil Engineering/Water and Air Resources 453, Water and Wastewater Treatment; 1 quarter.

Civil Engineering/Water and Air Resources 599, Analyzing Urbanizing Watersheds; 1 quarter.

CONTINUING EDUCATION SHORT COURSES TAUGHT (University of Washington; multiple offerings)

Infiltration Facilities for Stormwater Quality Control

Wetlands Ecology, Protection, and Restoration

Storm and Surface Water Monitoring

Fundamentals of Urban Surface Water Management

Applied Stormwater Pollution Prevention Planning Techniques

Construction Site Erosion and Pollution Control Problems and Planning

Construction Site Erosion and Pollution Control Practices

Construction Site Erosion and Sediment Control Inspector Training

Inspection and Maintenance of Permanent Stormwater Management Facilities

Biofiltration for Stormwater Runoff Quality Control

Constructed Wetlands for Stormwater Runoff Quality Control

LOCAL COMMITTEES

Stormwater Panel advising Puget Sound Partnership, 2007.

Technical Advisory Committee, City of Seattle Environmental Priorities Project, 1990-91.

Environmental Toxicology Graduate Program Planning Committee, University of Washington, 1990.

Habitat Modification Technical Work Group, Puget Sound Water Quality Authority, 1987.

Underground Injection Control of Stormwater Work Group, Washington State Department of Ecology, 1987.

Nonpoint Source Pollution Conference Advisory Committee, 1986-87.

Puget Sound Wetlands and Stormwater Management Research Committee, 1986-90.

Accreditation Review, University of Washington Department of Landscape Architecture, 1986.

Planning Committee for University of Washington Institute for Environmental Studies Forum on Perspectives on Cumulative Environmental Effects, 1983.

CONSULTING

Equity Legal Services, Inc., Fairview Heights, Illinois; Technical assistance in a legal case seeking injunctive relief and damages for repeated, widespread neighborhood flooding; 2023-2024.

U.S. Department of Justice; Technical assistance in Clean Water Act legal cases; 2017-2018 and 2022-2024.

Food and Water Watch, Washington, D.C.; development of a water quality monitoring program for confined animal feeding operations; 2022.

Brinnon Group, Brinnon, Washington; development of a water quality and aquatic ecological monitoring program for the local watershed and marine waters; 2021-2022.

Kampmeier & Knutsen PLLC, Portland, Oregon; Technical assistance in Clean Water Act legal cases; 2017 and 2021-2023.

Chesapeake Legal Alliance; Annapolis, Maryland; Assessment of and comment on Maryland's draft Municipal Separate Storm Sewer Discharge Permits and Accounting for Stormwater Wasteload Allocations and Impervious Acres Treated; 2020-2021.

Gonzaga University Legal Assistance; Spokane, Washington; Review of technical documents supporting a proposal for a PCB water quality variance for the Spokane River; 2020.

City of Monrovia, California; Recommendations for improving a watershed management plan; 2020.

Columbia Riverkeeper; Portland Oregon; Assessment of a port industrial development; 2020.

Columbia Riverkeeper and Northwest Environmental Defense Center; Portland Oregon; Assessment of Oregon Department of Environmental Quality's actions regarding setting Water Quality-Based Effluent Limits; 2020.

Coast Law Group, Encinitas, California; Technical assistance in Clean Water Act legal cases and assessments of submissions required by consent decrees; 2019-present.

Monterey County District Attorney, Monterey, California; Assessment of pollution issues at two construction company yards; 2019-2020.

Seneca Lake Guardian, Seneca Falls, New York; Assessment of potential water quality problems associated with an industrial plant; 2019.

Endangered Habitats League, Los Angeles, California; Assessment of stormwater management systems proposed for a large residential development; 2018-2019.

Ziontz Chestnut Law Firm, Seattle, Washington; Assistance with implementation of a court order on a settled case; 2018.

Black Warrior Riverkeeper, Birmingham, Alabama; Review and comment on a total maximum daily load assessment for the Black Warrior River; 2017.

King County, Washington, Seattle, Washington; Participant in a regional stormwater infrastructure assessment project; member of technical advisory committees for stormwater hydrologic and water quality modeling studies; 2012-present.

DeLano and DeLano, Escondido, California; Assessment of stormwater management systems proposed for residential and commercial developments; 2012-present.

Salmon-Safe, Inc.; assessment of sites for possible certification representing practices that protect salmon; 2004-present.

Puget Soundkeeper Alliance and Smith and Lowney, PLC, Seattle, Washington; Technical assistance in Clean Water Act legal cases and expert testimony; 1996, 2002-present.

Natural Resources Defense Council, Los Angeles, California; Technical and program analysis and expert testimony on legal cases involving municipal and industrial stormwater NPDES permit compliance and assistance in reacting to California municipal stormwater permits; 1993-present.

Santa Monica Baykeeper (now Los Angeles Waterkeeper); Technical and program analysis and expert testimony on legal cases involving municipal and industrial stormwater NPDES permit compliance; 1993-present.

Orange County Coastkeeper; Assistance with legal cases involving industrial and construction site pollution control and monitoring and expert testimony; 2001-present.

Lawyers for Clean Water and successor Sycamore Law; Assistance with legal cases involving stormwater discharges and expert testimony; 2004-present.

Earthjustice; Report and testimony regarding Washington state municipal stormwater permit before Pollution Control Hearing Board; 2008, 2013; assessment of Washington, DC combined sewer overflow control plan; 2015.

Tulane Environmental Law Clinic; Assessment and declaration on a legal case involving discharge under an industrial stormwater permit and expert testimony; 2015.

San Diego Coastkeeper, San Diego, California; Technical and program analysis and expert testimony on potential legal cases involving municipal and industrial stormwater NPDES permit compliance; liaison with City of San Diego; 1996-2011 and 2019-present.

Stillwater Science and Washington Department of Ecology; Water quality modeling for Puget Sound Characterization, Phase 2; 2010-2011.

City of Seattle Public Utilities; Analysis of technical aspects of stormwater management program; 2000-2008.

Ventura Coastkeeper; Technical and program analysis and expert testimony on legal cases involving municipal and industrial stormwater NPDES permit compliance; 2010-2015.

San Diego Airport Authority; Peer review of consultant products, training; 2004-2006.

U. S. Federal Court, Central District of California; Special master in Clean Water Act case; 2001-2002.

Storm Water Pollution Prevention Program, City of San Diego; Advising on response to municipal stormwater NPDES program; 2001-2002.

Kerr Wood Leidel, North Vancouver, B.C.; subconsultant for Stanley Park (Vancouver, B.C.) Stormwater Constructed Wetland Design; 1997-1998.

Clean South Bay, Palo Alto, California; Technical and program analysis and expert testimony on potential legal cases involving municipal and industrial stormwater NPDES permit compliance; 1996.

Resource Planning Associates, Seattle, Washington; Assistance with various aspects of monitoring under Seattle-Tacoma International Airport's stormwater NPDES permit; 1995-1997.

Watershed Management Institute, Crawfordsville, Florida; Writing certain chapters of guides for stormwater program development and implementation and maintenance of stormwater facilities; 1995-2003.

King County Roads Division, Seattle, Washington; Teaching two courses on construction erosion and sediment control; 1995.

Snohomish County Roads Division, Seattle, Washington; Teaching a course on construction erosion and sediment control; 1995.

Alaska Marine Lines, Seattle, Washington; Performance test of a sand filter stormwater treatment system; 1994-95.

Economic and Engineering Services, Inc., Bellevue, Washington; Assessment of the potential for water quality benefits through modifying existing stormwater ponds; technical advice on remedying operating problems at infiltration ponds; 1994-96.

Washington State Department of Transportation, Olympia, Washington; Teaching courses on construction erosion and sediment control; 1994.

City of Bellevue, Washington; Peer review of documents on potential erosion associated with a road project; analysis of stormwater quality data; 1993-95.

City of Kelowna, B. C., Canada; Teaching short courses on constructed wetlands and erosion and sediment control; 1993.

Oregon Department of Environmental Quality, Portland, Oregon; Technical review of Willamette River Basin Water Quality Study reports; 1992-93.

Whatcom County, Bellingham, Washington; Mediation on lakeshore development moratorium among county, water district, and local community representatives; 1993.

Boeing Commercial Airplane Company, Renton, Washington and Sverdrup Corporation, Kirkland, Washington (at request of City of Renton); Review of stormwater control system design; design of performance monitoring study for system; 1992-94.

Golder Associates, Redmond, Washington; Technical advisor for study of stormwater infiltration; 1992.

Smith, Smart, Hancock, Tabler, and Schwensen Attorneys, Seattle, Washington; Technical advice on a legal case involving a stormwater detention pond; 1992.

PIPE, Inc., Tacoma, Washington; Teaching a course on the stormwater NPDES permit; 1992.

CH2M-Hill, Inc., Bellevue, Washington and Portland, Oregon; Technical seminar on constructing wetlands for wastewater treatment; literature review on toxicant cycling in arid-region wetlands constructed for waterwater treatment; literature and data review on lake nutrient input reduction; expert panel on TMDL analysis for Chehalis River; 1989-1995.

Kramer, Chin and Mayo, Inc., Seattle, Washington; Watershed analysis in Washington County and Lake Oswego, Oregon; literature review in preparation for stormwater infiltration system design; literature review and contribution to design of constructed wetland for municipal wastewater treatment; 1989-1995.

Woodward-Clyde Consultants, Portland, Oregon and Oakland, California; Analysis of wetland capabilities for receiving urban stormwater; design of a constructed wetland for urban stormwater treatment; technical advisor on Washington Department of Ecology and City of Portland stormwater manual updates; 1989-1995.

R.W. Beck and Associates, Seattle, Washington; Assessment of pollutant loadings and their reduction for one master drainage planning and two watershed planning efforts; 1989-92.

Boeing Computer Services Corporation, Bellevue, Washington; mediation among Boeing, citizens' group, and City of Bellevue on stormwater control system design; 1990.

Parametrix, Inc., Bellevue, Washington; Review of Kitsap County Drainage Ordinance; 1990.

U.S. Environmental Protection Agency, Duluth Laboratory; Review of certain provisions of WET 2.0 wetland functional assessment model; 1989.

King County Council, Seattle, Washington; Review of King County Surface Water Design Manual; 1989.

Port of Tacoma, Washington; Assessment of stormwater control strategies; 1989.

Municipality of Metropolitan Seattle, Seattle, Washington; Assessment of land treatment systems for controlling urban storm runoff water quality; 1988-1992.

Impact Assessment, Inc., La Jolla, California (contractor to Washington State Department of Ecology); Socioeconomic impact assessment of the proposed high-level nuclear waste repository at Hanford, Washington; 1987.

Technical Resources, Inc., Rockville, Maryland (contractor to U. S. Environmental Protection Agency); assessment of water treatment waste disposal at pulp and paper plants; 1987-88.

Dames and Moore, Seattle, Washington; analysis of the consequences of a development to Martha Lake; 1987.

Harper-Owes, Seattle, Washington; project oversight, data analysis, and review of limnological aspects for Lake Chelan Water Quality Assessment Study; 1986-88.

URS Corporation, Seattle, Washington and Columbus, Ohio; presentation of a workshop on nonpoint source water pollution monitoring program design; analysis of innovative and alternative wastewater treatment for Columbus; development of a stormwater utility for Puyallup, Washington; watershed analysis for Edmonds, Washington; 1986-88.

Entranco Engineers, Bellevue, Washington; environmental impact assessment of proposed highway construction; technical review of Lake Sammamish watershed management project; technical review of Capital Lake wetland development; 1981-82; 1987-88; 1990.

Washington State Department of Ecology, Olympia, Washington; review of literature on wetland water quality, preparation of conference plenary paper, and leading discussion group at conference; analysis in preparation for a Shoreline Hearing Board case; 1986-87.

Richard C. Bain, Jr., Engineering Consultant, Vashon Island, Washington; analysis of watershed data and development of a policy for septic tank usage near Moses Lake, Washington; 1984-87.

University of Washington Friday Harbor Laboratory; analysis of adjacent port development and preparation of testimony for Shoreline Hearing Board; 1986.

Washington State Department of Transportation and Morrison-Knudsen Company, Inc./H.W. Lochner, Inc., Joint Venture, Mercer Island, Washington; environmental assessment of disposal of excavated material by capping a marine dredge spoil dumping site; 1984.

Foster, Pepper, and Riviera Attorneys, Seattle, Washington; analysis and testimony on provisions to reduce pollutants in stormwater runoff from a site proposed for development; 1983.

Williams, Lanza, Kastner, and Gibbs Attorneys, Seattle, Washington; collection and analysis of water quality data to support a legal case and preparation of testimony; 1982.

Herrera Environmental Consultants, Seattle, Washington; lake data analysis and report preparation; 1982-83.

Brown and Caldwell Engineers, Seattle, Washington; data collection and analysis for watershed study; 1982-83.

City of Marysville, Washington; environmental impact assessment of proposed bridge construction; 1982-83.

F.X. Browne Associates, Inc., Lansdale, Pennsylvania; contributions to manual on lake restoration for U.S. Environmental Protection Agency; preparation of funding proposals and permits for lake restoration; lake data analysis; literature reviews and analysis of septic tank contributions to lake nutrient loading and availability of different forms of nutrients; 1980-83.

Reston Division of Prentice-Hall, Inc., Reston, Virginia; review of and contributions to texts on environmental technology; 1978-79.

Butterfield, Joachim, Brodt, and Hemphill Attorneys, Bethlehem, Pennsylvania; analysis of environmental impact statements; expert witness; 1973.

Robby Eckroth

From: Jan Edelstein <jmeten@comcast.net>
Sent: Friday, May 2, 2025 2:10 PM
To: PDS comments
Subject: Public Comment - Critical Area Ordinance May 6 2025 Public Hearing
Attachments: FINAL Public Comment on Critical Areas Ordinance 5.2.2025 JME.pdf

Hello,

I attach the replacement comment, labelled FINAL, for the Tuesday Planning Commission Hearing on Critical Areas Ordinance Update.

Thanks for handling,
Jan Edelstein
208-720-0709

RE: Critical Area Ordinance Update

Supplement to Comments Dated May 2, 2025 with 2 attachments (Ecology CWA 303 Listing History for Big Lake/Total Phosphorous & Opinion of Dr. Richard Horner)

Submitted May 4, 2025 for May 6, 2025 Planning Commission Hearing.

Submitted By:

Jan M. Edelstein
17173 West Big Lake Blvd.
Mt. Vernon, WA 98274
208-720-0709
jmeten@comcast.net

Supplement: Revisions to Critical Area Ordinance – Best Available Science

Best Available Science demonstrates the failure of the Skagit County's development standards to protect anadromous fish habitat/critical areas, such as that provided by Big Lake, from the pollutants contained in stormwater runoff from individual new development activities and from the cumulative effects thereof. [See SCC 14.080 Standard critical areas review and site assessment procedures.]

SCC 14.24.080, as written and implemented, limits the County's requirement of the Applicant to provide a critical area site-assessment by a qualified professional to only off-site impacts on those critical areas that are within 200' of the boundary of the project.

Further, with respect to stormwater, the site-assessment requirement is for "consideration of impacts to drainage alterations." (c)(v). No information is required regarding the pollutant load to leave the site in the stormwater and to be discharged to the receiving "critical area" body of water.

Finally, Skagit County appears to believe that the functions and values of critical areas which receive stormwater runoff will be protected by mere compliance with Ecology's then current Stormwater Manual.

BAS 1: With Skagit County operating as described above, Big Lake water quality has deteriorated over the past 25 years of growing development around Big Lake. [Small cabins have been replaced with large homes with paved areas, treed lots around the lake have been cleared and 'filled in' with houses, and houses have 'marched up' the hillsides.]

As acknowledged by the Planning Commission over 20 years ago (O200300012), "Big Lake is located in a fragile watershed," with higher density residential development creating "the potential for an environmental and public health hazard regarding the Lake's water quality."

In 1999, Ecology had reported the Total Phosphorous reading as 18.7 ug/L and established a standard of 20 ug/L for TP. [See attached Ecology Water Quality Assessment Listing for Big Lake/Total Phosphorous.]

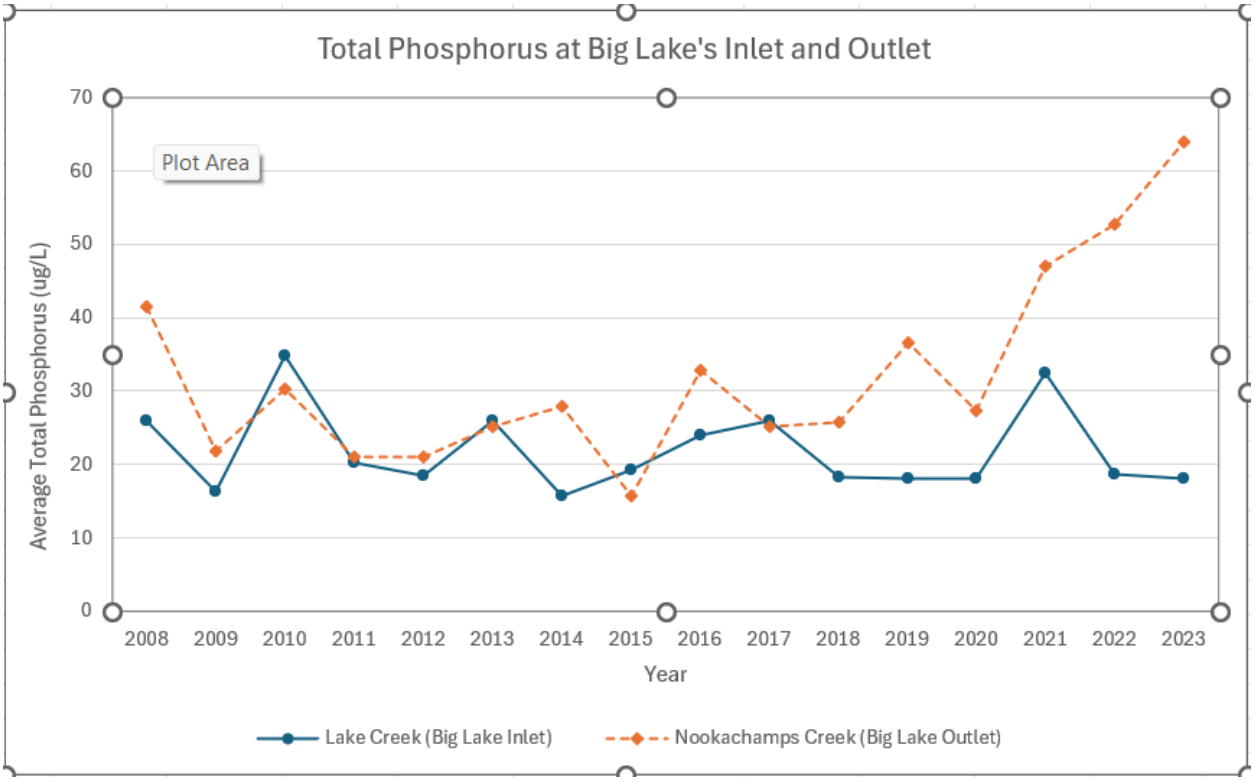
Ecology also reports: "According to O'Neal et al. (2001), shallow depths, dense residential development, and a location in a relatively large watershed may render Big Lake particularly susceptible to (and may have already caused) human-caused eutrophication. Future studies may likely recommend lowering the total phosphorus criterion."

In 2004, Ecology lists Big Lake as a "water of concern" for Total Phosphorous.

Since that time Ecology, receiving no new data, simply "carried forward" the "water of concern" listing.

During this time, Skagit County water quality monitoring program collected water quality data at the inlet and outlet of Big Lake. This data shows significant increases in Total Phosphorus to almost 3 times the water quality standard of 20ug/L.

Total Phosphorous drives algal blooms and growth of invasive aquatic plants, all of which is deleterious to fish population and human uses of the Lake.



Most recently, Richard R. Horner, Ph. D., professor emeritus of University of Washington and expert in stormwater runoff and surface water management, reports that Big Lake is in a

"relatively advanced in eutrophication and experiencing the elevated algal and aquatic plant growths characteristic of that state." [See Dr. Horner Opinion pg. 9]

BAS Example 2: A 100+ lot development on 100+ acres of hillside above Big Lake began development in 2006 with clearing of logs to convert to residential use. Over its almost 20- year history, this development has been subjected to 4 SEPA reviews for 4 separate permits, the last permit being approved in August, 2024.

With the stormwater discharge point on the project approximately 800 feet from Big Lake, at no time did the County ask for, nor did the Applicant provide, a critical areas site assessment regarding the project's impact on Big Lake.

The County conditioned the 4 permit approvals on compliance with the then current Ecology Stormwater Manual. This compliance goes only to using Best Management Practices to minimize flow and pollutants to Big Lake. At no time does it produce an analysis of the pollutants to remain in the runoff when it leaves the project site, or an analysis of those pollutants on Big Lake when discharged thereto.

To prepare for possible further appeals of the 4th permit, the citizen Appellants with Friends of Skagit County secured a critical areas site assessment from a qualified professional regarding the impact of the proposed project's stormwater runoff on Big Lake.

The assessment by Dr. Richard Horner is attached. His bio begins at page 28. As far as this writer knows, his analysis was the first of its kind to be submitted to Skagit County.

Dr. Horner's opinion includes an analysis of the type and amount pollutant loading expected in stormwater, how various Best Management Practices do and do not reduce the loading, the current state of Big Lake's aquatic habitat, and the expected impact of new pollutants loading on that habitat.

Dr. Horner's conclusions are clear – the proposed project's stormwater plan which had been approved four times does NOT protect the existing functions and values of Big Lake nor does it preserve or enhance anadromous fisheries. Instead, it would cause further degradation of those functions and values.

CONCLUSION: Best available science demonstrates that the County's current code is not up to the task of protecting critical areas from stormwater pollution.

To protect the functions and values of critical areas that provide anadromous fish habitat, the Skagit County Critical Areas Ordinance must be revised. Eliminate the 200'/300' restriction, and require the site assessment to identify the type and amount of pollutant loading in the stormwater and the impact of that loading on the critical area receiving body of water. Recognize that compliance with the Ecology Manual is not evidence that the functions and values of the receiving body of water will be protected.

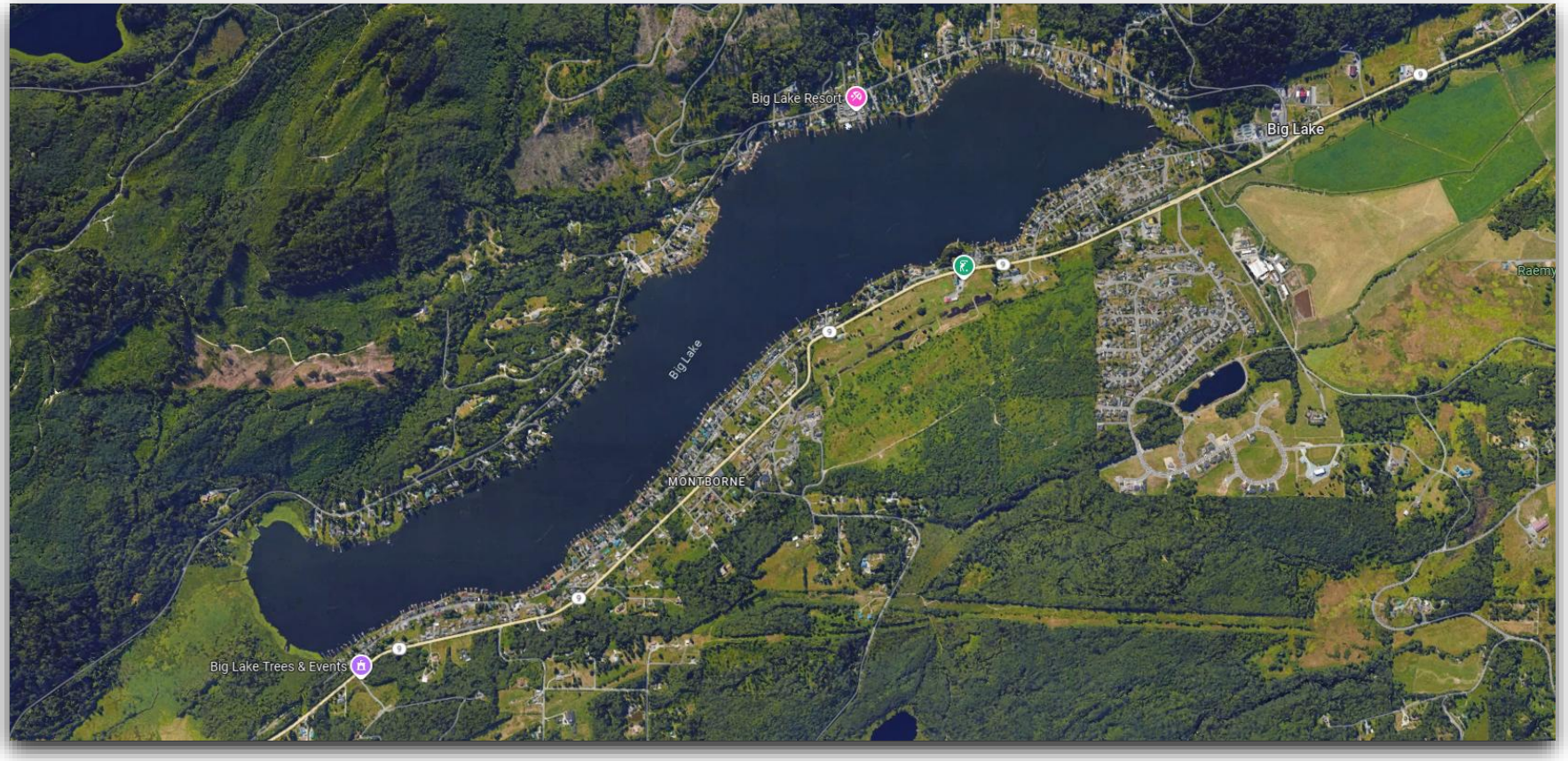
CRITICAL AREA ORDINANCE

REVISE TO PROTECT CRITICAL AREAS FROM STORMWATER POLLUTION

RCW 36.70A – Critical Areas

"…development regulations **must preserve the existing functions and values of critical areas …**

"shall give **special consideration** to conservation or protection measures necessary **to preserve or enhance anadromous fisheries.**



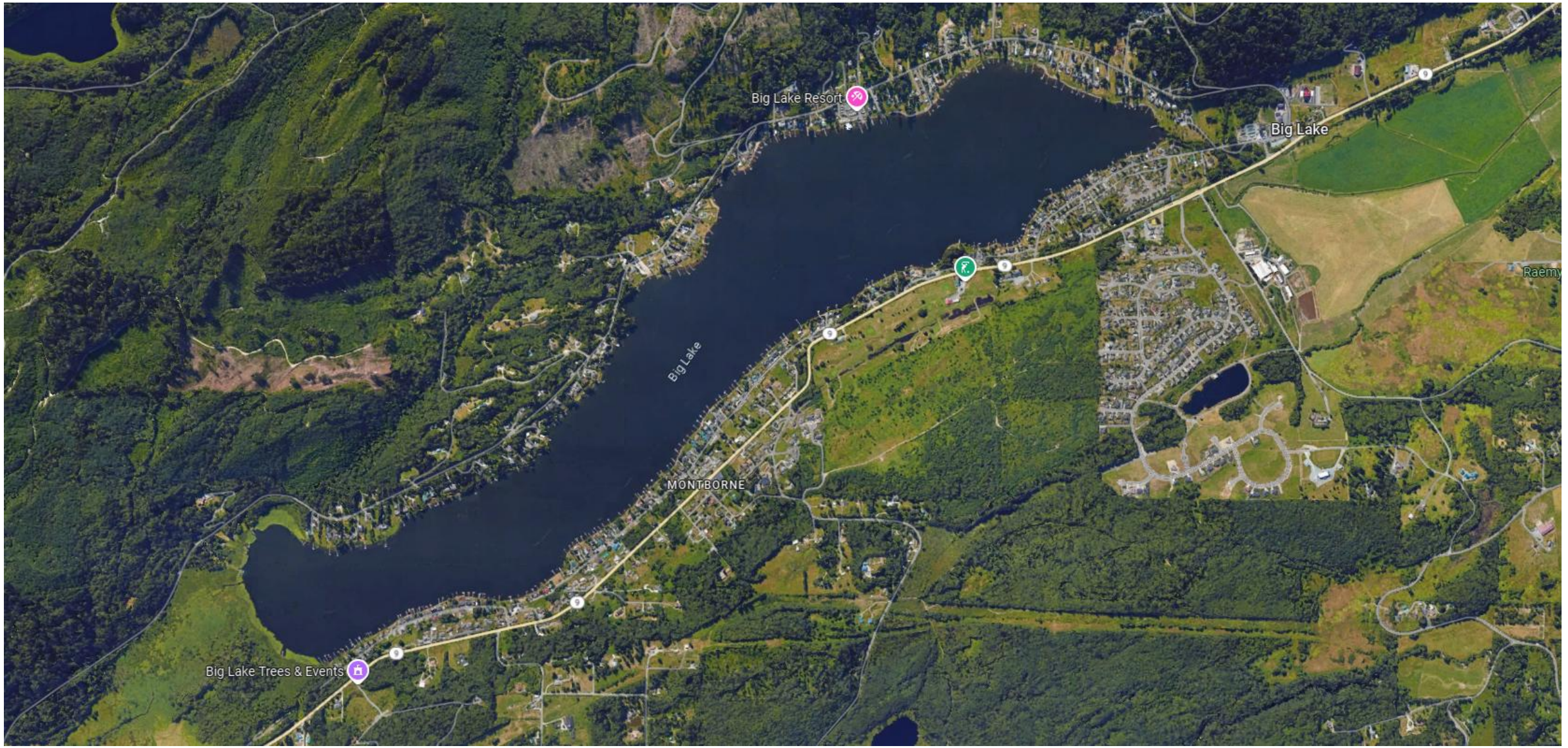


"Polluted stormwater runoff is the leading pollution threat to our lakes, rivers, streams, and Puget Sound."

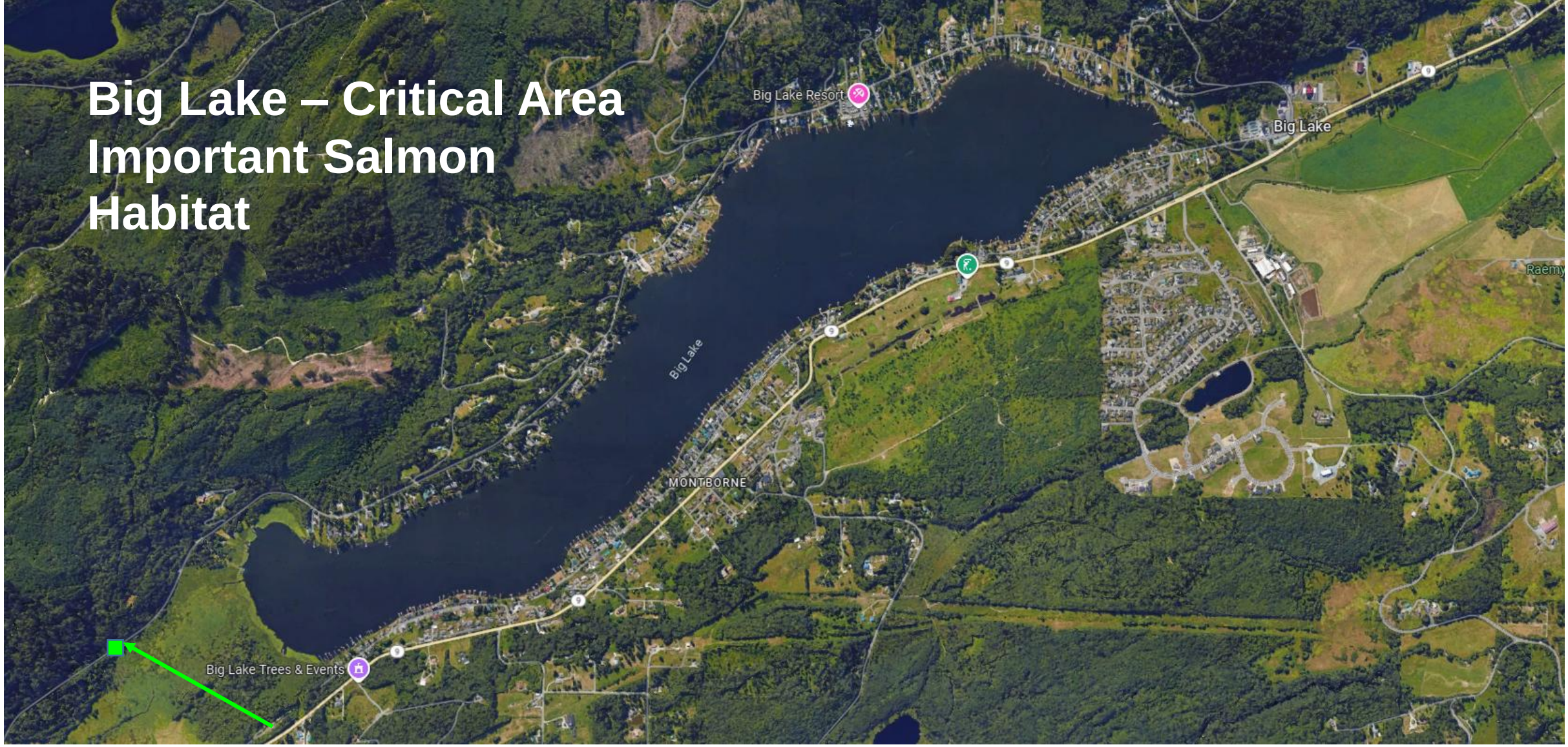
Department of Ecology, Washington State.

Newly recognized Threat to Fishery: 6PPD – tire chemical washed from roadways.

Big Lake Watershed -- 22 Square Miles

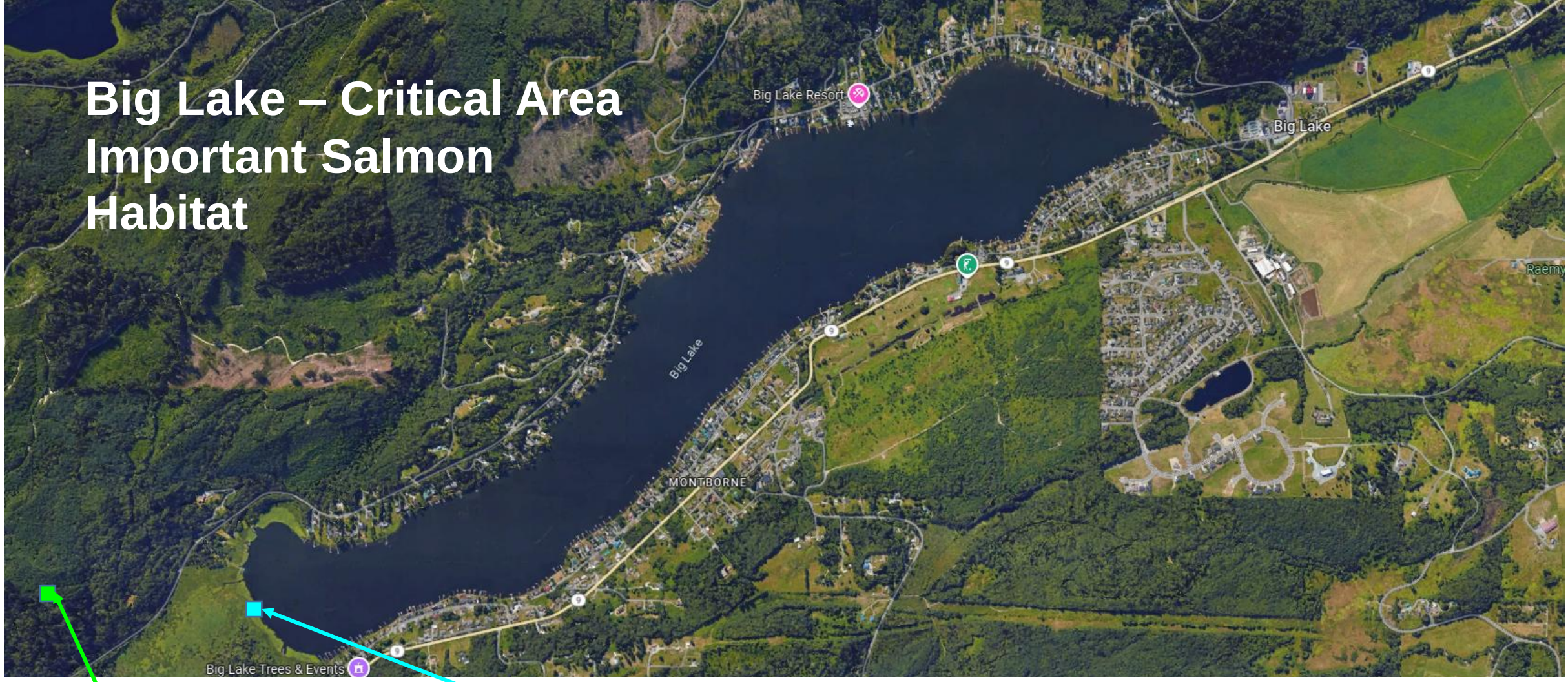


Big Lake – Critical Area Important Salmon Habitat



Lake Creek Fish Passage Improvement
https://srp.rco.wa.gov/project/280/11816
"Lake Creek connects two lakes in Skagit County, Big Lake to the north and Lake McMurray to the south. Lake Creek has a fantastic coho run."

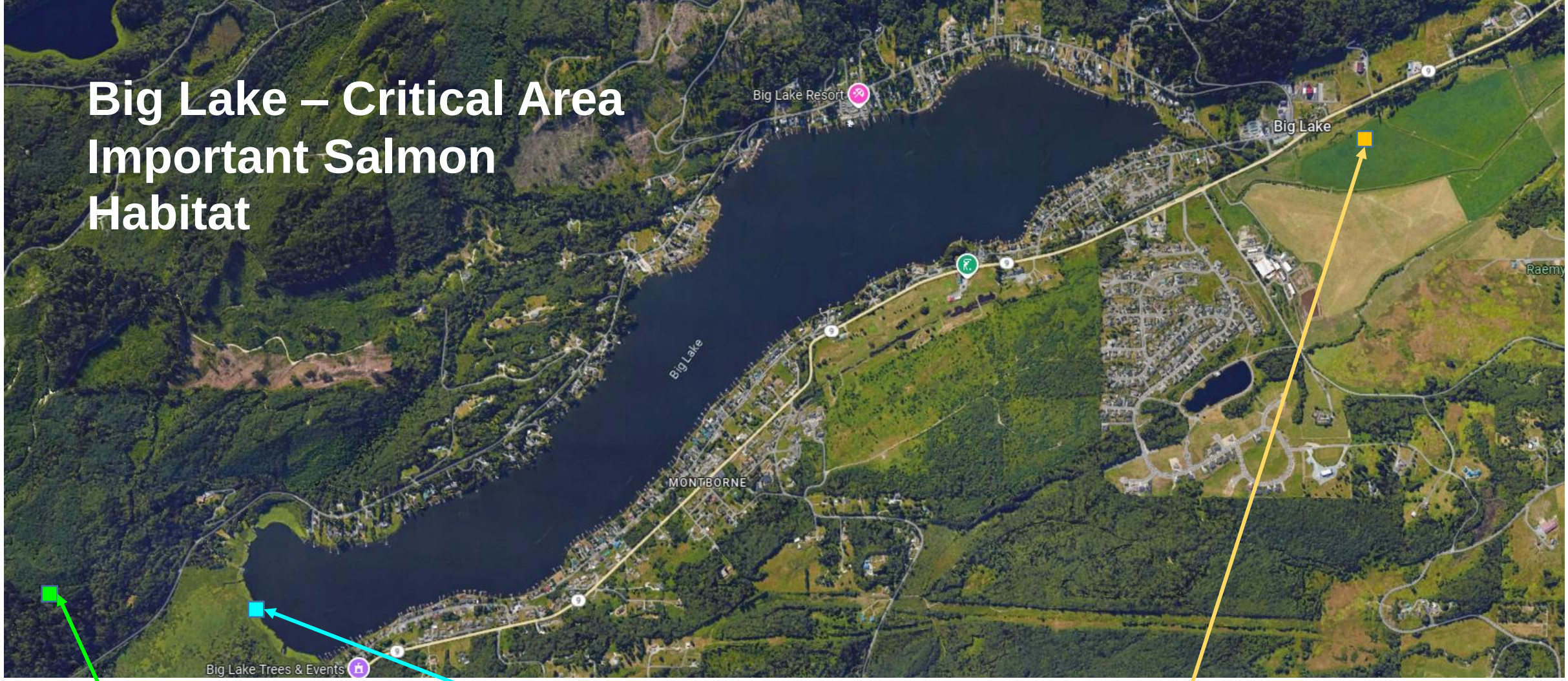
Big Lake – Critical Area Important Salmon Habitat



Lake Creek Fish Passage Improvement
https://srp.rco.wa.gov/project/280/11816
"Lake Creek connects two lakes in Skagit County, Big Lake to the north and Lake McMurray to the south. Lake Creek has a fantastic **coho run**."

Lake Creek Wetland Complex Protection
https://srp.rco.wa.gov/project/280/40070
"…permanently protect steelhead habitat on the West Fork of the Nookachamps River…steelhead spawning area just upstream of the project area… one of the largest intact functioning wetlands in this section of the west fork of the Nookachamps, and potentially **significant juvenile rearing habitat**." (67acres)

Big Lake – Critical Area Important Salmon Habitat



Lake Creek Fish Passage Improvement
https://srp.rco.wa.gov/project/280/11816
"Lake Creek connects two lakes in Skagit County, Big Lake to the north and Lake McMurray to the south. **Lake Creek has a fantastic coho run."**

Lake Creek Wetland Complex Protection
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"…permanently protect steelhead habitat on the West Fork of the Nookachamps River…**steelhead spawning** area just upstream of the project area… one of the largest intact functioning wetlands in this section of the west fork of the Nookachamps, and **potentially significant juvenile rearing habitat**."

Lanting - Gribble Cr - R18
https://srp.rco.wa.gov/project/280/87782
"A barrier culvert on Gribble Creek will be replaced with a fish passable structure, restoring access to 0.12 miles **of habitat for coho, steelhead, dolly varden/bull trout, and sea-run cutthroat trout."**

Planning & Development Services

Critical Areas Checklist

Pursuant to Skagit County Code 14.24.080

Section ____ Township ____ Range ____ Parcel Number _____ Related Permit: _____

Site Address: _____

Proposed uses: _____

Please answer the following questions concerning Critical Area indicators located on or within 300 feet of the project area.

Best Available Science - 1

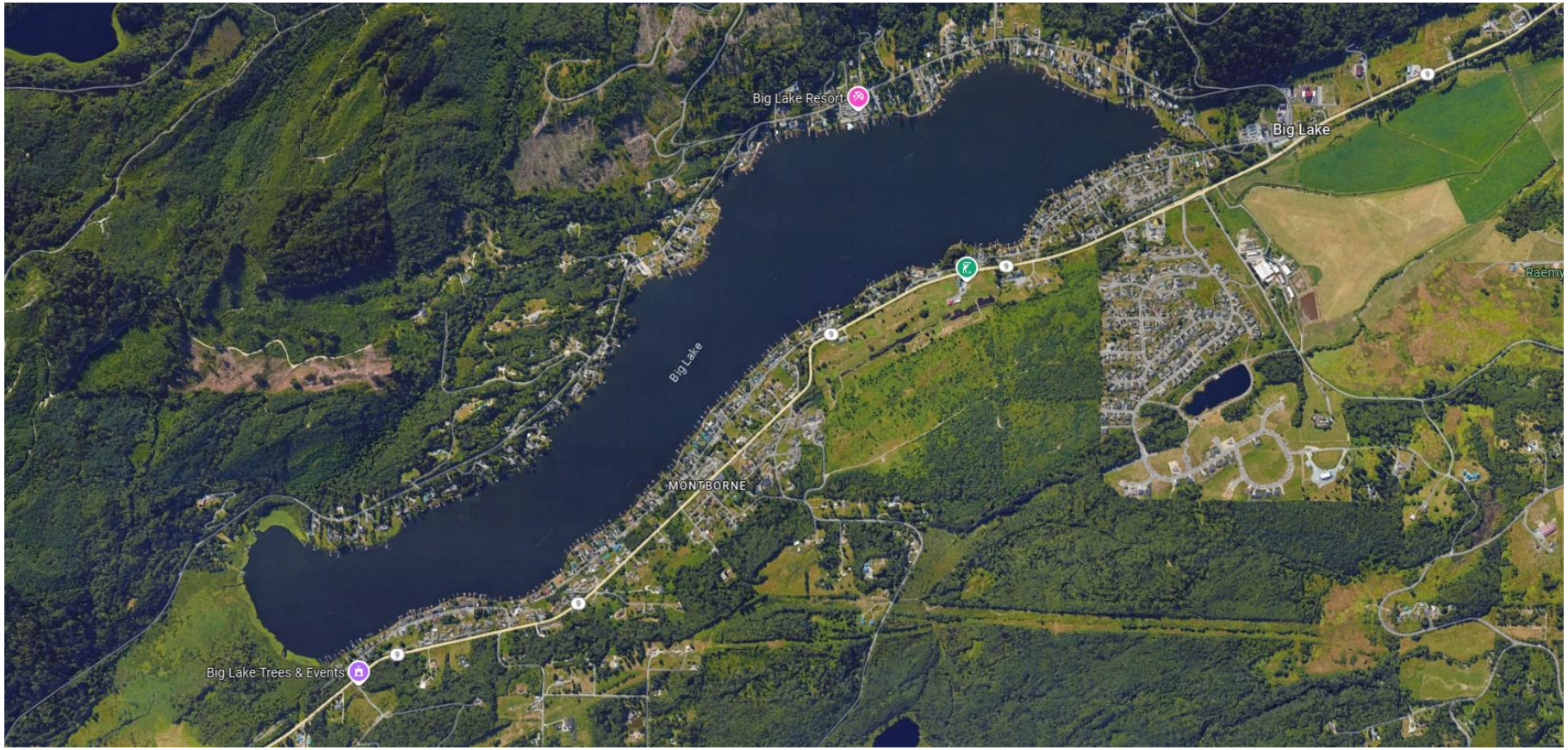
20 years of current review standards have failed to protect the functions and values of Big Lake, a critical area, from cumulative impact of development

TP* Standard 20ug/L

1999 - 18.7 ug/L

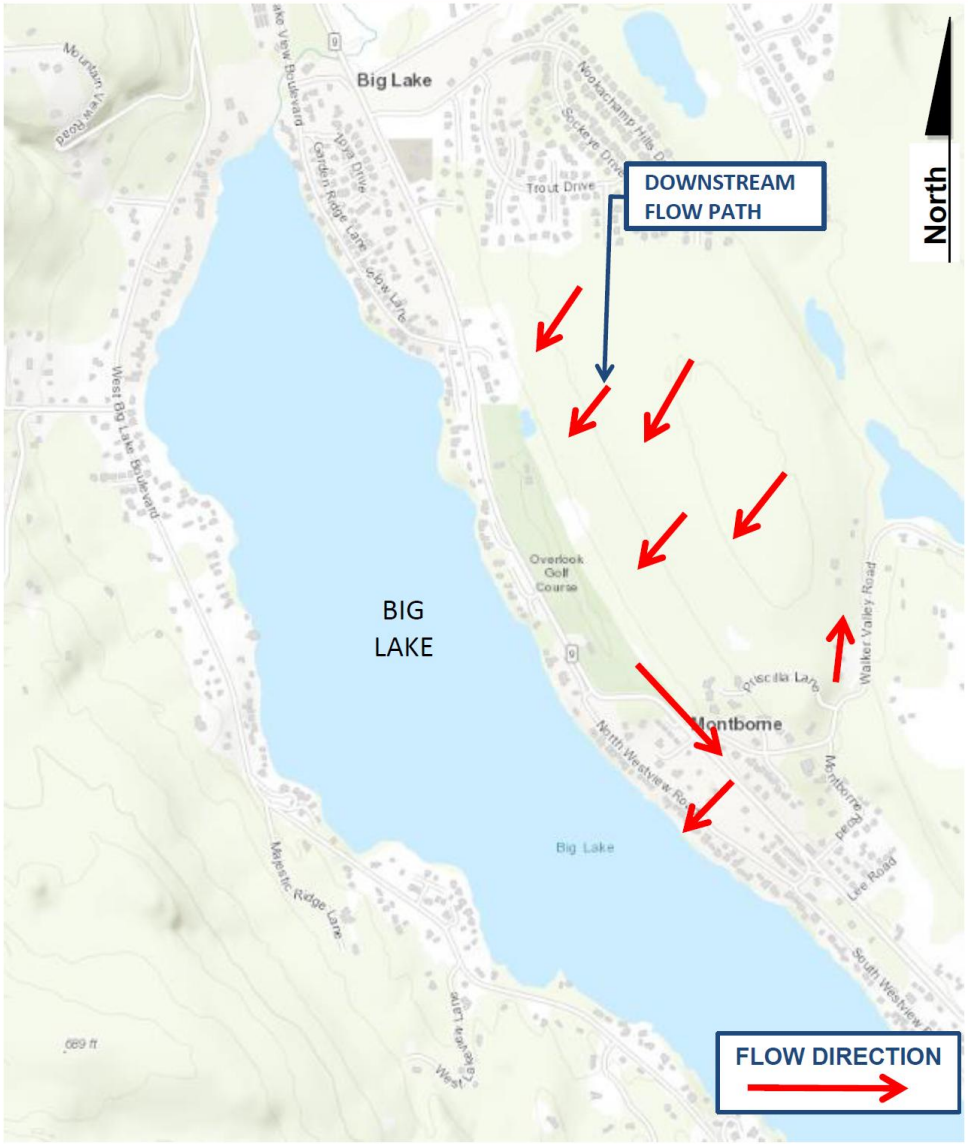
2021-2023 - 50-60 ug/L

Aug 2024: Sworn testimony of many users regarding degrading of swim/fish/aesthetic uses.



*Total Phosphorous

4 SEPA Reviews over 20 Years
No Assessment Impact of Stormwater Pollutants On Big Lake





Best Available Science - 2
Qualified Professional Opinion: Pollutants in Stormwater Runoff will degrade the functions and values of Big Lake, a critical area.

Opinion of Dr. Richard R. Horner dated November 19, 2024, pgs. 3-4:

Big Lake, [a critical area]…is in a eutrophic (relatively highly phosphorus-enriched) condition with excessive algal and aquatic plant growths degrading its beneficial uses.

Based on extensive data collected in the stormwater management field, the finished and occupied development [of 105 homes approximately 900' from Big Lake] will generate higher runoff volumes and concentrations and mass loadings of a number of water pollutants, some not previously of concern, compared to the current open land.

It is my opinion that the … development stormwater management plan as proposed will result in substantial increase in the discharge of phosphorous and other pollutants to, and degradation of, Big Lake.

Stevens County - Critical Areas Ordinance

2011 – Washington Appellate Court found Stevens County CAO did not protect Critical Areas. [Stevens County v. E. Wash. Growth Mgmt. Hearings Bd. 163 Wn. App. 680]

Stevens County Critical Areas Ordinance (2022):

Title 13: If the Administrator determines that the proposed project is within, adjacent to, or is likely to impact a critical area, the Administrator shall… require a critical area report…

Minimum report contents: …Sufficient information to assess potential stormwater effects, ….

Proposed Revision of SCC 14.24.080(4)(b)

…If a site inspection does not indicate a critical area on or within 200 feet of the subject property, no additional critical area assessment will be required.

Comment #3

Robby Eckroth

From: Jacob Koopmans <jacob.e.koopmans@gmail.com>
Sent: Monday, May 5, 2025 7:38 PM
To: PDS comments
Subject: Public Comment - Critical Area Ordinance May 6 2025 Public Hearing

Hello Planning Commission,

The critical area ordinance needs to be revised to ensure protection of critical areas from the pollutants in stormwater runoff.

Thank You,
Jake Koopmans

Comment #4

Robby Eckroth

From: Kim Sanford <kimsanford@msn.com>
Sent: Monday, May 5, 2025 8:19 PM
To: PDS comments
Cc: Jake Koopmans; Ellen Bynum; Greg Wittendorf; Jan Edelstein
Subject: Subject: Public Comment - Critical Area Ordinance May 6, 2025 Public Hearing

Hello Planning Commission,

The Critical Area Ordinance needs to be revised to ensure protection of the critical areas from the pollutants in stormwater runoff.

Thank you,

Kim Sanford
360-3914-4148
kimsanford@msn.com

Comment #5

Robby Eckroth

From: Jan Edelstein <jmeten@comcast.net>
Sent: Tuesday, May 6, 2025 11:06 AM
To: PDS comments
Subject: 2nd Supplemental Comment (Edelstein) for May 6, 2025 Hearing Critical Areas Ordinance Update
Attachments: 2nd Supplemental Comment Edelstein Critical Areas Ordinance 05.06.2025 .pdf

Hello,

I attach a second supplemental comment. This comment provides additional 'best available science' references to support my position that the County's limiting its review of off-site impacts to critical area to only a 200' buffer around the project site, rather than to whatever critical area may be adversely impacted, is not supported by 'best available science.'

Thank you,
Jan Edelstein
17173 West Big Lake Blvd.
Mt. Vernon WA
208-720-0709

Skagit County Code 14.24 Critical Areas
Amendments Needed to Protect Critical Areas
as required by the Washington Growth Management Act

May 6, 2025

SECOND SUPPLEMENTAL COMMENT: Public Comment – May 6, 2025 Planning Commission Hearing on Critical Areas Ordinance Update.

SUBMITTED BY:

Jan M. Edelstein
17173 West Big Lake Blvd.
Mt. Vernon, WA 98274
jmeten@comcast.net

More resources regarding "Best Available Science."

1. Ecology's 2024 Stormwater Management Manual for Western Washington in general and with particular focus on pollutants carried by stormwater, and generated by construction, in residential areas.
2. Washington State University Extension Study by Chaker-Scott: "Potential Contaminants in Residential Rain Barrel Water." https://rex.libraries.wsu.edu/esploro/outputs/report/Potential-contaminants-in-residential-rain-barrel/99900924141301842 and related studies.
3. Ecology's Focus on: Best Management Practices for 6PPD-q. https://apps.ecology.wa.gov/publications/documents/2310001.pdf and related studies.
4. Ecology's and others Puget Sound and related Watershed Management studies.
5. "Effects of Artificial Lighting at Night on Predator Density and Salmonid Predation" https://onlinelibrary.wiley.com/doi/10.1002/tafs.10286
6. USGS webpage on the adverse impact of Artificial Light at Night (ALAN) on salmon fisheries. Webpage lists a number of studies. https://www.usgs.gov/centers/western-fisheries-research-center/news/shedding-some-light-issue-investigating-how
    1. placing the word "may" with "shall" in the first sentence.

Comment #6

Robby Eckroth

From: Jan Edelstein <jmeten@comcast.net>
Sent: Tuesday, May 6, 2025 11:25 AM
To: PDS comments
Subject: Public Comment: 2025 Comp Plan Update: Please do not remove Section (7), the Big Lake Rural Village Special rule
Attachments: Dr.HornerOpinionBigLakeDegraded.pdf

Hello,

Section 7 of 14.16.310 protects Big Lake from pollution or degradation due to stormwater runoff from hillside development on over 180 acres. Please do not remove it.

But for this rule, the Overlook Crest project, with its addition of 18+acres of impervious area (14 NFL football fields) on this very 'erosive' hillside, would have been approved.

Dr. Richard Horner, an eminent expert in stormwater pollution and aquatic habitat, reviewed the then proposed project. He concluded very strongly, that if built, this project would result in further degradation of the Big Lake. His report has heretofore been submitted to Planning Department, but is attached for your convenience.

Best available science proves the critical nature of the Big Lake Rural Village Special rule. Please do not remove it.

Thank you,
Jan M. Edelstein

Comment #7

Robby Eckroth

From: Stephen Aghjayan <saseacom@mac.com>
Sent: Tuesday, May 6, 2025 12:33 PM
To: PDS comments
Subject: 2025 Skagit County Comprehensive Plan

Hello,
As a Skagit County citizen I am asking that original regulation 14.16.310 Section (7) be restored in the County's proposed development regulations (code) revisions.

Thank you.

Sent from my iPhone

Stephen Aghjayan
7344 Skagit View Drive
Concrete, WA98237

Comment #8

Robby Eckroth

From: motords@aol.com
Sent: Tuesday, May 6, 2025 2:21 PM
To: PDS comments
Subject: Possible Spam: Overlook Crest development

To: Skagit county commissioners

Regulation 14.16.310 Section (7) should be included in the 2025 development plan. Stormwater from the development should not go into Big Lake!

Regards,
Dean and Julie Seckel
Big Lake Residents since 2007

Sent from the all new AOL app for iOS

Comment #9

Robby Eckroth

From: Rosann Wuebbels <rwuebbels@yahoo.com>
Sent: Tuesday, May 6, 2025 4:09 PM
To: PDS comments
Subject: 2025 Skagit county comprehensive plan

I'm asking that original regulation 14.16.310 Section (7) be restored in the proposed development regulations (code) revisions. In regards to the proposed BIG LAKE development of 105 houses
Sincerely,
Rosanna Wuebbels
11134 O Ave.
Anacortes WA 98221

Yahoo Mail: Search, Organize, Conquer

Robby Eckroth

From: Sears, Tricia (DNR) <Tricia.Sears@dnr.wa.gov>
Sent: Tuesday, April 22, 2025 4:17 PM
To: Robby Eckroth
Cc: Sears, Tricia (DNR); Long, Lexine (COM)
Subject: Skagit County's Critical Areas Ordinance (2025-S-8322): WGS comments

Hello Robby,

In keeping with the interagency correspondence principles, I am providing you with comments on Skagit County's Critical Areas Ordinance (2025-S-8322).

For this proposal submitted via Planview, I looked at the proposal and focused on areas related to WGS work. Of note, but not limited to, I look for language around the geologically hazardous areas, mineral resource lands, mining, climate change, and natural hazards mitigation plans.

Specifically in this proposal, I reviewed the 2025_CAO Code_Draft 041525_PC. Thank you for updating your CAO! I have several comments and suggestions.

On page 58, the code states, "(2) Landslide hazards are areas potentially subject to landslides based on a combination of geologic, topographic and hydrologic factors. The following are known or suspected landslide hazards:…" and on page 59…" The Skagit County Code is current through Ordinance O20240001, passed January 29, 2024. published by the U.S. Geological Survey, the Geology and Earth Resources Division of the Washington Department of Natural Resources, or other documents authorized by government agencies." Please update your reference to say Washington Geological Survey instead of the Geology and Earth Resources Division of the Washington Department of Natural Resources. We are the Washington Geological Survey and we remain part of the DNR. Please update that in all applicable places.

On page 59, thank you for referring to the Washington Geologic Information Portal, "(a) Areas located within a high liquefaction susceptibility as indicated on the Washington Department of Natural Resources' Washington Geologic Information Portal."

On page 60 "Mine hazard areas as designated on the Department of Natural Resources Map: Coal Measures of Skagit County (1924) or within 200 feet of any other current or historic mine operations determined to be a suspect or known geologically hazardous area by the Administrative Official Director. (Ord. O20080014 (part))" It may be useful to also refer to the Washington Geologic Information Portal here too. This is the metadata description of the mines and mineral layer "All known digital data about mines and minerals in Washington State created by the Washington Geological Survey. This includes information on: coal, inactive and abandoned mine lands, metallic and nonmetallic minerals, hazardous minerals, and outlines of historical mining districts."

It states that PCAs must be recorded to the title of the property. Have you considered requiring the property to record to title a statement that there is a critical area on the property and the critical area is x, y, z. Recommend requiring that; many other jurisdictions have it.

The code provisions refer to qualified professional. There is a reference to 14.24.080, but that does not define the qualified professional for geologically hazardous areas. No other provisions in the CAO define the qualified professional for geologically hazardous areas. Recommend that it be clearly stated what a qualified profession is, and that it be a licensed geologist or engineer.

In 14.24.070 utilities are listed as not needing review when maintenance is done. Would they be allowed as new construction in geologically hazardous areas?

Below, I include our usual language for this and future endeavors.

Recognizing the limitations of the current proposals, I want to mention that it would be great for you to consider these in current or future work, be it in your comprehensive plan, development code, and SMP updates, and in your work in general:

- Consider adding a reference to the definition of geologically hazardous areas, WAC 365-190-120, in other areas besides the CAO. In addition, consider adding a reference to WAC 365-196-480 for natural resource lands.
- Consider adding a reference to the WGS Geologic Information Portal in other areas besides the CAO. If you have not checked our interactive database, the WGS Geologic Information Portal, lately, you may wish to do so. Geologic Information Portal | WA - DNR
- If you have not checked out our Geologic Planning page, you may wish to do so. Geologic Planning | WA - DNR

Thank you for considering our comments. If you have any questions or need additional information, please contact me. For your convenience, if there are no concerns or follow-up discussion, you may consider these comments to be final as of the 60-day comment deadline of 6/17/25.

Have a great day!

Cheerio,
Tricia

Tricia R. Sears (she/her/hers)
Geologic Planning Liaison
Washington Geological Survey (WGS)
Washington Department of Natural Resources (DNR)
Cell: 360-628-2867 | Email: tricia.sears@dnr.wa.gov

Robby Eckroth

From:	Jake Koopmans <jakekoopmansbl@gmail.com>
Sent:	Wednesday, May 7, 2025 9:10 PM
To:	PDS comments
Cc:	Kim Sanford; Greg Wittendorf
Subject:	Public Comment: Skagit County's Comprehensive Plan Draft Policies
Attachments:	2025_comprehensive-plan-comments_Sanford-Family.pdf

Please see attached public comment from our family.

Sincerely,
Kimberly Sanford
Danny Sanford
Jacob Koopmans
Greg Wittendorf

360-391-4146

PO BOX 839
Lyman WA 98263

May 7, 2025

TO:
Skagit County Planning & Development Services RE Planning Commission
1800 Continental Place
Mount Vernon, WA 98273

FROM:
Kimberly Sanford
Danny Sanford
Jake Koopmans
Greg Wittendorf
23904 N Westview Rd
Mount Vernon, WA 98274

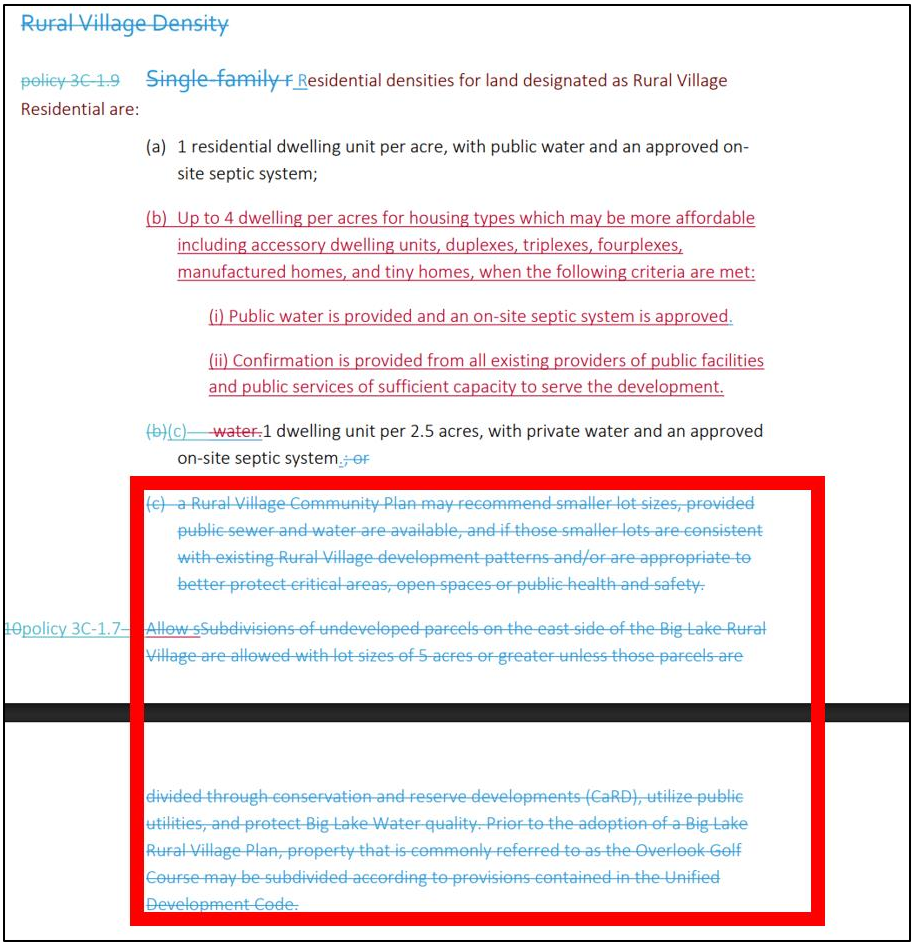
Mailing Address:
PO Box 839
Lyman, WA 98263

SUBJECT: Skagit County 2025 Comprehensive Plan Comment

We write to urge the Skagit County Planning Commission to retain the 2016 Comprehensive Plan verbiage regarding the protection of Big Lake water quality from the property commonly referred to as the Overlook Golf Course. Specifically, that the following text remain intact in the 2025 Comprehensive plan (denoted as Policy 3C-1.7 in the 2025 draft, and Policy 3C-1.10 in the 2016 Comprehensive Plan):

> Subdivisions of undeveloped parcels on the east side of the Big Lake Rural Village are allowed with lot sizes of 5 acres or greater unless those parcels are divided through conservation and reserve developments (CaRD), utilize public utilities, and protect Big Lake Water quality. Prior to the adoption of a Big Lake Rural Village Plan, property that is commonly referred to as the Overlook Golf Course may be subdivided according to provisions contained in the Unified Development Code.

The 2025 Comprehensive Plan draft uploaded to the County's 2025 Comprehensive Plan website, "CompPlan2025_WholeDocumentRedlines_V2.0.pdf", shows the following lined out of the draft policy:



Rural Village Density

policy 3C-1.9 Single-family r Residential densities for land designated as Rural Village Residential are:

(a) 1 residential dwelling unit per acre, with public water and an approved on-site septic system;

(b) Up to 4 dwelling per acres for housing types which may be more affordable including accessory dwelling units, duplexes, triplexes, fourplexes, manufactured homes, and tiny homes, when the following criteria are met:

(i) Public water is provided and an on-site septic system is approved.

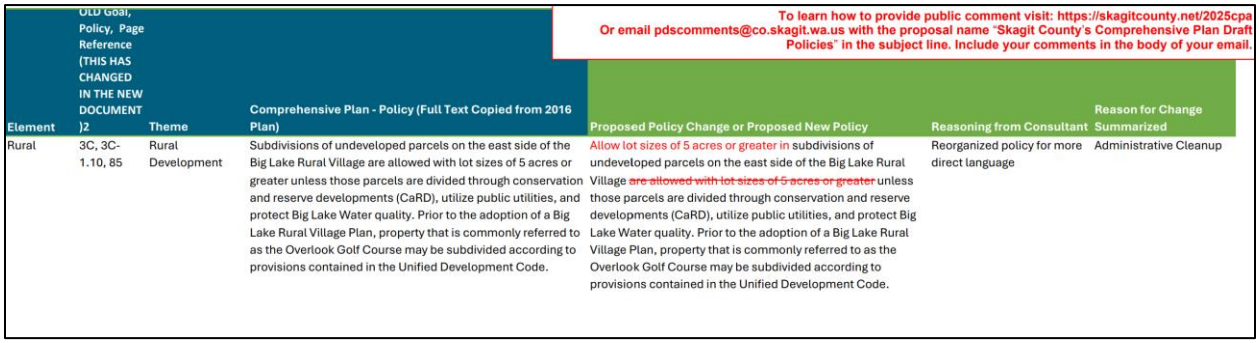
(ii) Confirmation is provided from all existing providers of public facilities and public services of sufficient capacity to serve the development.

(b)(c) water.1 dwelling unit per 2.5 acres, with private water and an approved on-site septic system.; or

(c) a Rural Village Community Plan may recommend smaller lot sizes, provided public sewer and water are available, and if those smaller lots are consistent with existing Rural Village development patterns and/or are appropriate to better protect critical areas, open spaces or public health and safety.

10policy 3C-1.7 Allow sSubdivisions of undeveloped parcels on the east side of the Big Lake Rural Village are allowed with lot sizes of 5 acres or greater unless those parcels are divided through conservation and reserve developments (CaRD), utilize public utilities, and protect Big Lake Water quality. Prior to the adoption of a Big Lake Rural Village Plan, property that is commonly referred to as the Overlook Golf Course may be subdivided according to provisions contained in the Unified Development Code.

The Rural element policy database, which is supposed to track reasons for updates in the 2025 policy, "SkagitCounty_PolicyDatabaseRural_0214.pdf", offers no description on why this policy is proposed to be deleted. Instead, the only proposed change is to reorganize the paragraph (administrative update, no policy change), not to delete the policy:



To learn how to provide public comment visit: https://skagitcounty.net/2025cpa
Or email pdscomments@co.skagit.wa.us with the proposal name "Skagit County's Comprehensive Plan Draft Policies" in the subject line. Include your comments in the body of your email.

Element	OLD Goal, Policy, Page Reference (THIS HAS CHANGED IN THE NEW DOCUMENT)2	Theme	Comprehensive Plan - Policy (Full Text Copied from 2016 Plan)	Proposed Policy Change or Proposed New Policy	Reasoning from Consultant	Reason for Change Summarized
Rural	3C, 3C-1.10, 85	Rural Development	Subdivisions of undeveloped parcels on the east side of the Big Lake Rural Village are allowed with lot sizes of 5 acres or greater unless those parcels are divided through conservation and reserve developments (CaRD), utilize public utilities, and protect Big Lake Water quality. Prior to the adoption of a Big Lake Rural Village Plan, property that is commonly referred to as the Overlook Golf Course may be subdivided according to provisions contained in the Unified Development Code.	Allow lot sizes of 5 acres or greater in subdivisions of undeveloped parcels on the east side of the Big Lake Rural Village ~~are allowed with lot sizes of 5 acres or greater~~ unless those parcels are divided through conservation and reserve developments (CaRD), utilize public utilities, and protect Big Lake Water quality. Prior to the adoption of a Big Lake Rural Village Plan, property that is commonly referred to as the Overlook Golf Course may be subdivided according to provisions contained in the Unified Development Code.	Reorganized policy for more direct language	Administrative Cleanup

Summary of why protecting Big Lake Water Quality from development on this parcel is Important.

The Skagit County Planning Commission made the following Findings of Fact in 2003 when adopting Ordinance #O20030012:

> *Big Lake is located in a fragile watershed. Although a majority of the 15,000 acres of the watershed basin is currently under forest management, a much smaller portion of the area includes existing, higher-density residential development around the Lake in which poor soil conditions and high water tables are characteristic. This unfortunate combination has created the potential for an environmental and public health hazard regarding the Lake's water quality. The proposed action attempts to balance the need to protect the environment while attempting to retain the long-standing, development investment expectations envisioned by the Overlook Golf Course property owner.*
>
> *It is generally understood that the Overlook Golf Course property includes larger undeveloped parcels which, due to their configuration, topography, view shed, proximity to the Lake, and other features, exhibit future development potential; provided, that it is done as a master-planned approach and in an environmentally sensitive manner. The proposed CP and development regulation language attempts to address these issues prior to the adoption of a Big Lake Rural Village (Joint Plan) community plan.*
>
> *AND*
>
> *The proposed action provides for sustainable growth and development at Big Lake while assuring that the Lake's environ is safeguarded.*

The Planning Commission in 2003 codified SCC 14.16.310(7)(b)(iv) to protect against the degradation of Big Lake as the result of development of the noted parcels.

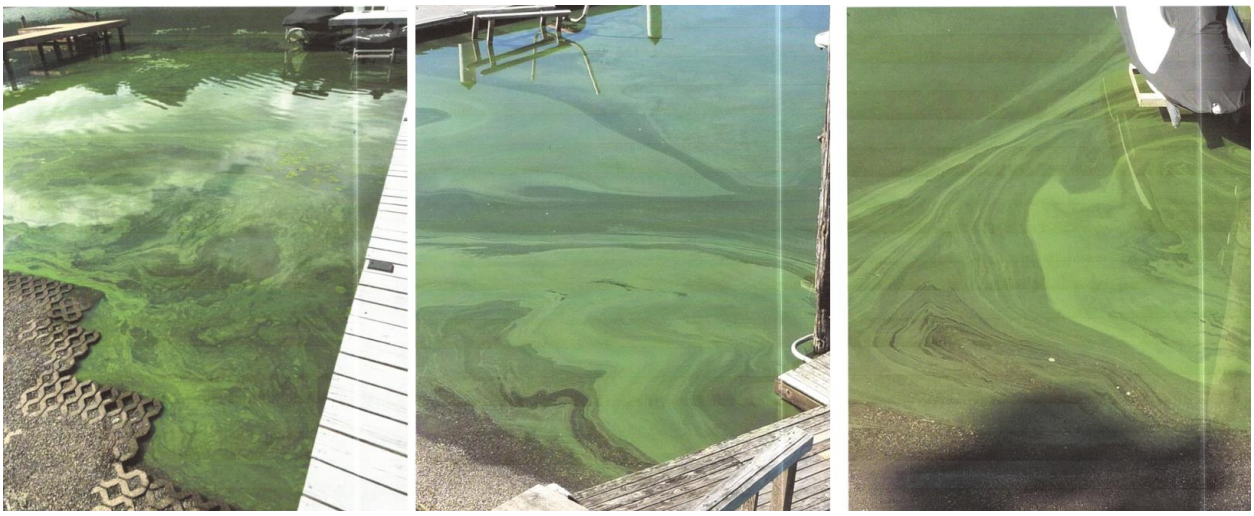
Big Lake is an impaired water body and is listed on Ecology's 303(d) list for:

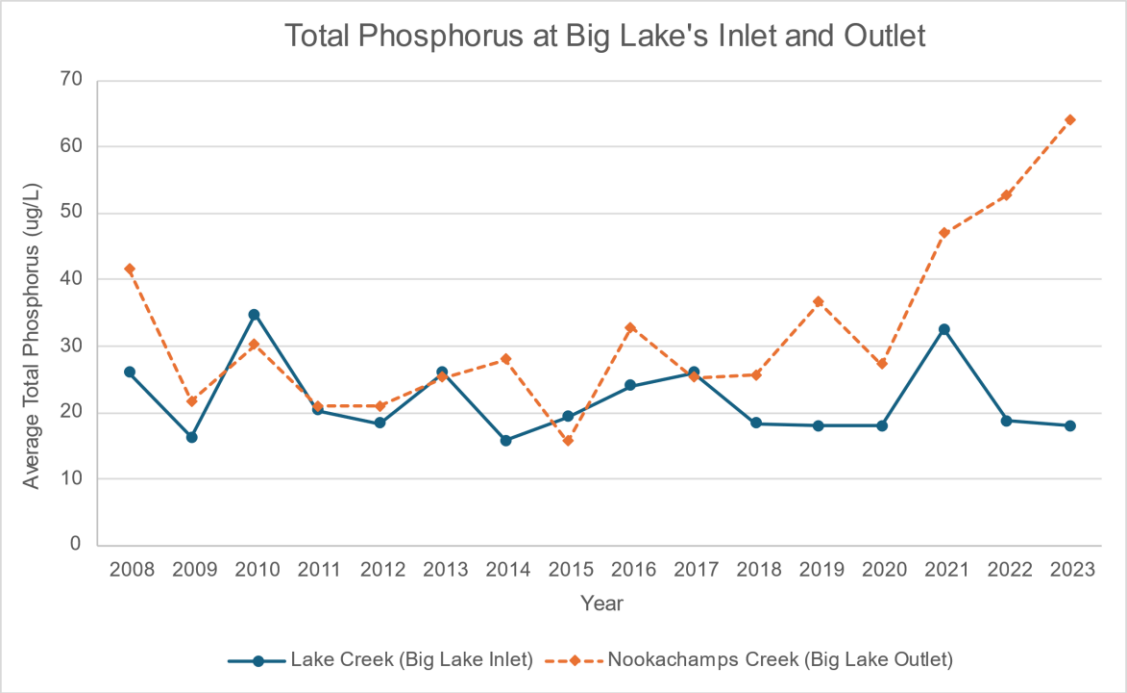
- Methyl Mercury (Category 5); Impaired since 2018
- 2,3,7,8-TCDD Dioxin (Category 5); Impaired since 2004
- Polychlorinated Biphenyls (Category 2); Impaired since 2004
- Hexachlorobenzene (Category 2); Impaired since 2004
- 4,4'-DDE (Category 2); Impaired since 2018
- Total Phosphorus (Category 2); Impaired since 2004

Phosphorus is a critical nutrient in fueling algae growth which:

- Impacts aesthetics and recreation
- Impacts total Dissolved Oxygen in the lake (aquatic life)
- Contributes to toxic blue-green algal blooms that threaten human, pet, and wildlife health

Skagit County's Water Quality Monitoring Program reported that the total phosphorus levels exceeded the Department of Ecology's maximum recommended average of 20 micrograms/L, especially in the last 3 years (see data in chart below), which correlates to the degraded condition that has been seen around the lake:





The detention ponds commonly used for developments has a *goal* of 50% total phosphorus removal per the 2019 Stormwater Management Manual for Western Washington (SMMWW) (Volume III, Chapter 1, Page 426), thereby further degrading Big Lake. 2019 SWMMWW makes it very clear that stormwater, even when BMPs are employed, can pollute and degrade impaired water bodies. (Volume I, Ch 2, Pg 74)

Skagit County Stormwater Management Program (SWMP) Plan, March 2022 states: It may be difficult to imagine stormwater runoff as being the biggest contributor to water pollution, but a small quantity of pollutants entering our streams, rivers, lakes and bays, thousands and thousands of times over, results in accumulation that is difficult to treat at a larger scale. Much of the pollution that finds its way into natural waters and aquatic food chains travels there unnoticed and is not quickly broken down or removed naturally.

Given the worsening condition of Big Lake and the 2003 Skagit County Planning Commission's finding of facts regarding the high likelihood of impacting Big Lake's water quality with developing the Overlook Golf Course parcels, why is it that the 2025 Skagit County Planning Commission proposes removing this policy with no justification on its potential impact to Big Lake? Is it odd that this specific policy is targeted for deletion as it is being developed and personally funded in part by Lisa Janicki who is also a County Commissioner?

Sincerely,

Kimberly Sanford

Danny Sanford

Jacob Koopmans

Greg Wittendorf

Comment #12

Robby Eckroth

From: Leslie Parks <lesliecrparks@gmail.com>
Sent: Thursday, May 8, 2025 11:26 AM
To: PDS comments
Subject: 2025 Skagit County Comprehensive Plan

Please restore the original regulation 14.16.310 Section (7) be restored in the proposed development regulations (code) revisions regarding "14.11.300 Rural Village Residential (RVR)
Based on existing SCC14.16.310. Existing subsection (7) regarding the Big Lake Rural Village Overlook Golf Course property has been deleted."
--
Leslie Parks

Robby Eckroth

From: Jenna Friebel <jfriebel@skagitdidc.org>
Sent: Thursday, May 8, 2025 11:54 AM
To: PDS comments
Cc: Andy Wargo; Allen Rozema; Robby Eckroth; Will W. Honea
Subject: Skagit County 2025 Comprehensive Plan Update - revised public comments and supporting documents
Attachments: 2025_CAO_Consortium_FNL 05082025_revised.docx; DFI Agreement_D14_Signed.pdf; Consolidated Dike, Drainage, and Irrigation District 22.pdf; Dike District 3.pdf; Dike, Drainage, and Irrigation District 5.pdf; Dike, Drainage, and Irrigation District 12.pdf; Dike, Drainage, and Irrigation District 25.pdf; Drainage and Irrigation District 14.pdf; Drainage and Irrigation District 15.pdf; Drainage and Irrigation District 16.pdf; Drainage and Irrigation District 17.pdf; Drainage and Irrigation District 18.pdf; Drainage and Irrigation District 19.pdf; Drainage and Irrigation District 22.pdf

Hi –

Please use the attached revised final comments on the CAO. In addition, I have attached the DFI maps referenced in these comments as well as an example of the recently updated DFI MOU.

Please let me know if you have any questions. Sorry for the earlier submittal.

Please confirm receipt given the large file sizes.

Jenna

Jenna Friebel, Executive Director

Skagit Drainage and Irrigation Districts Consortium LLC
2017 Continental Place Suite 4
Mount Vernon, WA 98273
360-708-0344

Skagit Drainage and Irrigation District Consortium, LLC
2017 Continental Place Suite 4
Mount Vernon, WA 98273
360.708.0344

May 8, 2025_Revised Final

Via email *(pdscomments@co.skagit.us)*

Skagit County Planning & Development Services
1800 Continental Place
Mount Vernon, WA 98273

RE: Comments to Skagit County's 2025 Draft Comprehensive Plan Update, Critical Areas Ordinance

Dear Planning Department,

The Skagit Drainage and Irrigation District Consortium, LLC ("Consortium") submits the following comments with respect to the redline version of the draft Skagit County Critical Area Ordinance Update and Critical Areas Ordinance Best Available Science (BAS) Review presented to the Skagit County Planning Commission on April 22, 2025.

As a general comment, the Consortium suggests that the Planning Department conduct the CAO update in two phases, as opposed to being conducted simultaneously, with the first phase comprised of editorial changes, so as to ensure there are no errors introduced through that process, followed by the second phase, which will include the proposed updates. As written, the COA was difficult to review. In order to incorporate the Consortium's comments, the text was copied from the April 22, 2025 document, the proposed Skagit County edits were accepted, and we then included the Consortium's comments in redline.

The Consortium's review and redline focuses on four central elements:

i. Addressing the regulatory redundancies between Skagit County and state and federal regulatory agencies pertaining to the maintenance of dike and drainage infrastructure;

ii. Updating references to the Tidegate Fish Initiative;

iii. Clarifying important differences between natural managed watercourses and artificial watercourses. This is particularly important in that the County's authority does not extend to artificial watercourses maintained by special purposes district formed under Title RCW 85. Accordingly, provisions related to critical areas should be consistent with both WAC 365-190-030, specifically (6a), related to fish and wildlife habitat conservation areas, and RCW 36.70A.030, specifically (11), which excepts from the definition of critical areas irrigation delivery systems, infrastructure, and drainage ditches within the boundaries of, and that are maintained by, an drainage and irrigation improvement district; and

iv. Proposing revisions intended to reflect Skagit County's regulatory responsibilities for drainage maintenance.

The Consortium appreciates this opportunity to provide public comment and welcomes an opportunity to meet with staff to provide additional context with respect to our comments and for the proposed redlines.

Sincerely,



Jenna Friebel
Executive Director, Skagit County Drainage and Irrigation District Consortium, LLC

Cc:

Skagit Dike District 3

Skagit Dike, Drainage and Irrigation Improvement District 5

Skagit Dike, Drainage and Irrigation Improvement District 12

Skagit Drainage and Irrigation Improvement District 14

Skagit Drainage and Irrigation Improvement District 15

Skagit Drainage and Irrigation Improvement District 16

Skagit Drainage and Irrigation Improvement District 17

Skagit Drainage and Irrigation Improvement District 18

Skagit Drainage and Irrigation Improvement District 19

Skagit Drainage and Irrigation Improvement District 22

Skagit Consolidated Dike, Drainage and Irrigation Improvement District 22

Skagit Dike, Drainage and Irrigation Improvement District 25

Comment #1

Pg 8/73. 14.24.070 Activities allowed without standard review sub-section (7)

~~Provided the requirements of SCC 14.24.120(4)(d) are met for ongoing agriculture, the lawful operation and maintenance of public and private diking and drainage systems which protect life and property along the Skagit and Samish Rivers and tidal estuaries in Skagit County~~This exemption applies to the lawful operation and maintenance of public and private diking, ~~and~~ drainage, and irrigation systems which protect life and property along the Skagit and Samish Rivers and tidal estuaries in Skagit County. ~~the existing structures and design prism of levees, dikes, and artificial watercourses 40 feet landward of the landward toe of the structure or facility and 40 feet waterward of the waterward toe of the structure, measured horizontally from the face of the levee, dike or bank of the artificial drainage structure toward the ordinary high water mark. The exempt area for operation and maintenance may be managed to meet Federal standards for funding assistance established by the United States Army Corps of Engineers under Public Law 84-99 or other laws and regulations adopted to guide the diking and drainage functions.~~ This exemption does not apply to public or private activities that expand the levee, dike, or drain beyond its design characteristics as of June 1, 1999, the time of adoption of this Subsection; nor activities that expand or create new facilities.

Comment #2

Pg 8/73. 14.24.070 Activities allowed without standard review sub-section (10)

Activities in or adjacent to ~~artificial~~ watercourses which ~~are~~ were constructed and are actively maintained for irrigation and drainage by ~~a~~ diking, ~~and~~ drainage, and irrigation improvement districts formed pursuant to Title RCW 85,~~;~~ provided, that any activity must comply with relevant state and federal regulations. ~~by securing written approval from the State Department of Fish and Wildlife; and provided further, that the activity must also comply with all applicable State and local drainage, erosion and sedimentation control requirements for water quality~~. ~~The operator must notify the Director in writing regarding the location and nature of anticipated activities a minimum of 14 days prior to commencing any such activity. Such notification will be a condition for allowance of this activity without standard review. This allowance only applies to activities not subject to SCC 14.24.120(4)(d).~~

Comment #3

Pg 18/73. 14.24.120 Ongoing Agriculture (1)

Purpose and Intent. The purpose of this Section is to address 2 mandates under the Growth Management Act (GMA): (a) to protect the existing functions and values of fish and wildlife habitat conservation areas (FWHCAs) in and adjacent to natural and~~,~~ ~~modified~~ managed watercourses with headwaters and natural watercourses without headwaters ~~natural, and artificial watercourses~~ as defined in SCC 14.04.020 ~~(collectively "watercourses")~~, and (b) to conserve and protect agricultural lands of long-term commercial significance, specifically those lands in ongoing agricultural activity as defined by SCC 14.04.020 that are located adjacent to these watercourses.

Comment #4

Pg 18/73. 14.24.120 Ongoing Agriculture (1.a. iii)

The ~~existing~~ riparian ~~buffer~~ vegetation characteristics and width, including but not limited to the ~~existing~~ amount of shade provided by the ~~existing~~ riparian ~~buffer~~vegetation at the time VSP was adopted.

Comment #5

Pg 20/73. 14.24.120 Ongoing Agriculture (4)

Required ~~Watercourse FWHCA~~ Protection Measures for Ongoing Agriculture in Fish and Wildlife Habitat Conservation Areas ("FWHCA"). Unless the emergency provisions of SCC 14.24.070(1) apply, the following watercourse protection measures are required:

Note: not all watercourses are FWHCAs.

Comment #6

Pg 21/73. 14.24.120 Ongoing Agriculture (4.c.iv)

V-ditching must not be constructed to drain into a natural watercourse~~ that also contains salmonids~~, unless the topography of the field is such that this is the only alternative to drain the field by gravity. ~~is to drain the V-ditch into a watercourse that does contain salmonids. When draining a V-ditch into a watercourse that does contain salmonids, appropriate~~ BMPs should be used to ~~avoid~~ minimize ~~contributing excess amounts of~~ sediment conveyed to the natural watercourse. For the purpose of determining ~~whether~~ a natural watercourse ~~contains salmonids,~~ the County will use:

~~Salmonid distribution based on the "limiting factors analysis" data compiled by the Washington State Conservation Commission; and~~

~~The Statewide Washington Integrated Fish Distribution database; and~~

~~Any other valid source of information which may confirm salmonid presence.~~

(A) Maps prepared by WDFW for the purposes of the Drainage Fish Initiative.

Comment #7

Pg 21&22/73. 14.24.120 Ongoing Agriculture (4.d)

Operation and Maintenance of Public and Private Agricultural Drainage Infrastructure. The following practices apply to any natural or any managed watercourse with headwaters that is part of a drainage ~~infrastructure~~system.~~, except those practices performed pursuant to a fully-executed Drainage Fish Initiative or Tidegate Fish Initiative agreement~~:

~~(i)~~ Regularly scheduled agricultural drainage infrastructure maintenance that includes dredging or removal of accumulated sediments in any ~~natural or~~ managed watercourse

with headwaters ~~watercourse must be conducted between June 15th and October 31st. If a Washington Department of Fish and Wildlife~~ or managed watercourse without headwaters must comply with WDFW issued hydraulics project approval ~~provides for a different~~ work windows~~, those requirements control~~. ~~If presence of fall or over winter crops prevents regularly scheduled maintenance during this time period, then the maintenance may be conducted outside this work window; provided, that the person or entity proposing to conduct the maintenance outside the work window can demonstrate that the presence of crops prevents maintenance within the work window and provided the maintenance is conducted using best management practices to minimize sediment or other impacts to water quality.~~

~~(ii)~~(i) ~~Owners or operators must consult with districts conducting drainage maintenance to schedule their crop rotations for crops that may still be in the field after October 31st so that, to the maximum extent possible, such drainage maintenance can occur in a year when the fall crops are not being raised in the field adjacent to the drainage infrastructure scheduled for drainage maintenance.~~

~~(iii) Unless there is no feasible alternative, regularly scheduled maintenance that includes dredging or removal of accumulated sediments in any watercourse should be conducted at those times when there is no or minimal water flow in the watercourse being maintained to minimize potential for distributing sediments to salmonid bearing waters.~~

~~(iv)~~(ii) Excavation spoils must be placed so as not to cause bank failures and so that ~~drainage~~ seepage from such spoils will not contribute sediment to the watercourse.

~~(v)~~(iii) Mowing or cutting of vegetation located within a managed watercourse with headwaters or managed watercourse without headwaters that is part of a drainage ~~infrastructure~~ system may be conducted at any time; provided, that the cutting is above the ground surface within the channel and in a manner that does not disturb the soil or sediments; and provided, that the cut vegetation does not block water flow. Watercourse bank vegetation must be preserved or allowed to reestablish as soon as practicable after drainage construction and maintenance are completed to stabilize earthen ditch banks.

~~(vi)~~(iv) Districts subject to this Section, operating pursuant to authority in RCW Title 85 or 86, which are conducting drainage activities must ~~complete and submit a~~maintain a drainage maintenance plan. ~~maintenance checklist to the County by June 1st of each year. The checklist must describe the intent of the district to comply with the drainage maintenance requirements of Subsection (4)(d) of this Section. The districts may seek assistance from NRCS, SCD and/or the County in completing the checklist or addressing the requirements of this Subsection. The checklist will be available from Skagit County Planning and Development Services, mailed to any entity conducting drainage activities, and must be submitted to Planning and Development Services when completed. The districts may submit modifications to the information in the checklist, if circumstances affecting district maintenance change after the initial submittal.~~

~~(A) The County must send a written notice to any district not submitting this completed checklist by June 1st of each year, stating that the County has not received the required checklist and that the district is not authorized to conduct drainage maintenance activity until the district has submitted the completed checklist evidencing intent to comply with this Subsection.~~

~~(B) Subsequent commencement of drainage maintenance work without submitting a completed checklist will be subject to enforcement pursuant to Chapter 14.44 SCC.~~

Comment #8

Best Avalable Science (BAS). Section 3. Frequently Flooded Areas. 3.2 Functions and Values p~~P~~age 10. The Consortium's comments with respect to BAS, Section 3, include the following:

A. Revisions to Section 3.2 ~~should be revised to discuss the differences~~differentiating between coast flooding, deltas, and river floodplains as they were each formed by different processes and function somewhat differently. In addition, the Consortium sees a need to revise the~~is~~ following sentence, included on ~~(~~page 10,~~)~~ as follows: ~~needs to be revised.~~

> ~~"~~Floodplains have been used for agriculture, residential development, and urbanization for centuries because the geographic locations tend to be well-suited for development during periods between floods.~~"~~

B. BAS supports the statement that Skagit County's floodplains ~~in Skagit County~~, ~~and~~ specifically those in the Skagit delta, ~~are~~have been, and continue to be, used for agricultural purposes because of the extremely high quality of the soils~~.~~ – s~~S~~oils of global significance. Soils are a natural resource, often associated with floodplains and deltas, and these~~is needs to~~significant attributes should be properly characterized.

C. In addition, the~~is~~ review of BAS should include references from ~~a~~ purely a hydrologic perspective, floodplains provide storage for water during floods – largely independent~~ce~~ of land ~~-~~use. By way of example, t~~T~~he Nookachamps, ~~– which is~~comprised of mostly agricultural land use, floods frequently, however, ~~but~~ little or no damage results from the~~is~~ flooding. Maintaining farmland in floodplain areas is a very sound policy objective~~.~~, A~~a~~s currently written, this BAS review does not adequately characterize the functions of floodplains, independent~~ce~~ of their land use.

SKAGIT DRAINAGE AND FISH INITIATIVE

Drainage Maintenance Agreement

By and Between the

WASHINGTON DEPARTMENT OF FISH AND WILDLIFE
and
SKAGIT COUNTY DRAINAGE AND IRRIGATION IMPROVEMENT District 14

This Agreement represents a commitment by the **WASHINGTON DEPARTMENT OF FISH AND WILDLIFE** (WDFW) and **SKAGIT COUNTY DRAINAGE AND IRRIGATION IMPROVEMENT DISTRICT 14 (District 14)** to acknowledge the critical interests and needs of each Party with regards to fish protection and the maintenance of drainage infrastructure within the established boundaries of said District. It also represents an acknowledgement by the SKAGIT RIVER SYSTEM COOPERATIVE (SRSC), representing the Swinomish Indian Tribal Community and the Sauk Suiattle Indian Tribe (collectively referred to as the Tribes), of a shared need to develop and maintain effective levels of communication and cooperation in recognition of the vital roles of agriculture and natural resources in sustaining the customs, culture and economic viability of Skagit County, its citizens and the Tribes and their members.

PART I: PURPOSE AND INTENT

This Agreement is predicated on the belief that the statutory duties, powers and responsibilities vested in the duly elected Commissioners of District 14 under Title 85 RCW and the statutory resource protection responsibilities of WDFW under Title 77 (RCW 77.55) reflect shared interests and needs of the State of Washington. The Parties to this agreement recognize and accept a clear and compelling need exists to reconcile these statutory responsibilities in a way that is both respectful and cognizant of each other's rights, obligations and interests.

The purpose and intent of this Agreement is to provide a mechanism through which each Party may achieve certainty in addressing their needs regarding agricultural drainage and fish protection. The specific goals and objectives of this Agreement are to:

1. Maintain a framework to cooperatively utilize a Drainage Maintenance Plan to ensure immediate and long terms interests and needs of each Party are identified and provided for with regards to drainage infrastructure behind tidegates and pump stations.
2. Defuse and avoid conflicts typically associated with sub-tidal drainage maintenance activities and fish protection efforts within the Skagit and Samish River deltas.
3. Provide a mechanism to resolve issues regarding jurisdictional authority involving drainage and fish protection.
4. Sustain open and constructive levels of communication and cooperation based on trust and mutual respect between each Party.
5. Improve working relationships and collaborative partnerships between each Party, stakeholder groups and government agencies.

PART II: PARTIES TO THIS AGREEMENT

The parties to this Agreement are the WASHINGTON DEPARTMENT OF FISH AND WILDLIFE (WDFW) and SKAGIT COUNTY DRAINAGE AND IRRIGATION IMPROVEMENT DISTRICT 14 (District 14) which controls lands historically subject to tidal influence within the Skagit delta, hereafter referred to as "WDFW" or "DISTRICT 14", respectively. This Agreement is limited to District 14's Drainage Maintenance Plan activities, which are the sole responsibility of District 14 and will not be applicable to other activities performed by District 14, or to individual landowners or any other party not signatory to this specific Drainage Maintenance Agreement.

PART III: FRAMEWORK FOR DEVELOPMENT AND IMPLEMENTATION OF THIS AGREEMENT

The primary component of this Agreement is a Drainage Maintenance Plan (see Addendum B), developed collaboratively and cooperatively between the duly elected Commissioners of District 14 and WDFW, in consultation with the Skagit River System Cooperative, consistent with the provisions of a Memorandum of Understanding (MOU) between the Washington Department of Fish and Wildlife and the Western Washington Agricultural Association, dated February 18, 2005.

PART III (A): Classification of Watercourses

The following definitions apply to those watercourses occurring within District 14, consistent with the aforementioned MOU and as further identified within the attached Drainage Maintenance Plan.

Natural Watercourses (Color Code: Blue):

Watercourses with headwaters that follow and/or replace a historic natural watercourse that has been altered, channelized, relocated, and/or constrained by dikes and that do not have flow control structures (tide gates, pump stations) at their confluence with marine waters. (Skagit River, Samish River, Skagit Bay, Samish Bay, Padilla Bay, Swinomish Channel)

Managed Watercourses with Headwaters (Color Code: Green):

Watercourses with headwaters that follow and/or replace a historic natural watercourse that has been significantly channelized, relocated, and/or constrained by dikes and that have flow control structures (tide gates, pump stations) at their confluence with marine waters (Turner Ditch, No Name Slough, Big Indian Slough, Big Ditch, Hill Ditch).

Managed Watercourses without Headwaters (Color Code: Magenta):

Watercourses without headwaters that follow and/or replace a historic natural watercourse that has been significantly channelized, relocated and/or constrained by dikes and that have flow control structures (tide gates, pump stations) at their confluence with marine waters (Wiley Slough, Dry Slough, Brown Slough, Hall Slough, Dodge Slough, Sullivan Slough, Joe Leary Slough).

Artificial Watercourses (Color Code: Yellow):

Watercourses without headwaters that are wholly built by humans and that do not follow or replace a historic natural watercourse, and are designed to convey water from local surface areas or subsurface drains for the purpose of removing excess water in order to improve conditions for agriculture.

PART III (B): Drainage Maintenance Activities

The following types of drainage maintenance activities are considered typical of work necessary to routinely maintain watercourses that comprise the drainage infrastructure

within the District. The Parties to this Agreement recognize that new maintenance activities and techniques may arise and may, by mutual consent, be incorporated into previously agreed upon Drainage Maintenance Agreements and related Drainage Maintenance Plans.

- Beaver dam removal
- Bridge repair, replacement
- Culvert repair, replacement
- Dike leveling and repair
- Dredging: Debris removal, channel maintenance
- Floodgate repair, replacement
- In-water mowing
- Out-of-water mowing
- Screwgate repair, replacement
- Tidegate minor repair
- Trash rack repair, replacement

For purposes of further clarifying established maintenance practices governed and controlled by the elected Commissioners of District 14, the construction and use of "V" ditches are considered the responsibility of individual landowners and, as such, are not addressed within the scope and intent of this District Agreement. Furthermore, the construction and use of water retention structures for irrigation purposes are also outside the scope of this Agreement.

PART III (C): Best Management Practices (BMP's)

It is the intent of this Agreement to identify and prescribe appropriate BMP's for drainage maintenance activities for each category of watercourse located within the boundaries of District 14 based on the need to manage water and protect fish and related habitats.

This Agreement seeks to ensure that these BMP's are recognized and accepted as being reasonable, necessary and prudent for meeting their stipulated purpose and are not intended to constitute an infringement or impediment with regards to the ability of the duly elected Commissioners of District 14 to exercise their lawful duties and responsibilities under Title 85 RCW or the ability of WDFW to exercise its lawful duties and responsibilities under the provisions of Title 77 RCW.

BMP's have been developed for use in conjunction with each of the drainage maintenance activities (outlined below) for green, magenta, and yellow watercourses. A detailed description of individual BMP's prescribed for each of the following maintenance activities and watercourses within District 14 is included as a separate addendum to this Agreement (see Addendum A).

- Beaver dam removal
- Bridge repair, replacement
- Culvert repair, replacement

- Dike leveling and repair
- Dredging
- Floodgate repair, replacement
- In-water mowing
- Out-of-water mowing
- Screwgate repair, replacement
- Tidegate minor repair
- Trash rack repair, replacement

In some instances, BMP's associated with the activities and watercourses listed above will warrant modification for use within this Agreement based on unique circumstances and characteristics that exist within this District. Deviation from the BMP's identified pursuant to this MOU will require mutual consent of both Parties and will be reflected in writing as a modification to this Agreement and related Hydraulic Project Approval conditions.

PART III (D): Resource Protection Measures

The Parties to this Agreement recognize and accept the need for safeguards and protocols to ensure the protection of fish, fish life and habitat in conjunction with maintenance of drainage infrastructure within District 14. It is acknowledged and agreed that the use of Hydraulic Project Approvals (HPA's), as provided for in RCW 77.55, constitutes the appropriate tool for implementing the BMPs identified pursuant to this Agreement and issued HPA conditions for drainage maintenance within District 14. It is further recognized that the use of BMP's alone shall constitute the appropriate tool for implementation of this Agreement in those watercourses classified as artificial. It is also recognized that in-water work within natural (blue) watercourses requires an individual HPA and that there are no blue watercourses within the easements of District 14.

WDFW will issue Hydraulic Project Approval's incorporating the BMPs identified in the Drainage Maintenance Plan for District 14 (see Addendum A) as resource protection measures for the maintenance activities listed in the previous section for green and magenta watercourses.

For purposes of implementing this Agreement, General Five-Year HPA's will be issued and shall apply only to the repair and maintenance of existing drainage infrastructure. The construction of new drainage infrastructure within District 14 will require an individual site specific HPA, consistent with the general provisions of RCW 77.55, as well as any other local, state and federal requirements that may apply.

WDFW agrees to expedite renewal of the above referenced General Five-Year Hydraulic Project Approvals developed in association with this Agreement.

PART III (E): Habitat Improvement Projects

The Parties to this Agreement acknowledge that some drainage maintenance activities may have varying degrees of direct and/or indirect impacts to fish life and habitat. For purposes of implementing this Agreement between WDFW and District 14, the goal and intent of each Party is to offset direct and/or indirect temporary impacts to fish and fish

habitat by incorporating BMP's as conditions associated with the HPA's issued for maintenance activities provided for as part of the Drainage Maintenance Plan for District 17 (see Addendum A).

In addition, the goals and objectives of implementing mutually agreed upon projects are identified in the attached Drainage Maintenance Plan for District 14 (see Addendum A). At established five-year periods, progress toward implementation of projects identified within the attached District Plan will be evaluated and considered during the revision and development of subsequent plans and in re-issuance of related permits. WDFW will work with partners to identify and lead habitat improvement projects. The District 14 commissioners will participate in the feasibility analysis and support feasible projects consistent with the written parameters established as part of this Agreement and the Drainage Maintenance Plan.

Projects Benefiting Both Drainage and Fish:

The highest priority in identifying and implementing projects pursuant to this Agreement will be projects that provide benefits for both drainage and fish. In such instances, District 14 agrees to commit resources (land, equipment, time, funding) to assist in implementing feasible habitat improvement projects identified within this Drainage Maintenance Agreement and Plan in cooperation with WDFW and other interested parties.

District 14 herein agrees to partner with WDFW and other interested parties to identify, pursue and obtain additional funding through available sources (grants, etc) sufficient to evaluate and implement habitat improvement projects identified within this District Agreement and Plan, and to do so within a mutually agreed upon timeframe for completion.

Projects Providing Benefits Primarily for Fish:

In instances where habitat improvement projects identified within this District Drainage Maintenance Agreement and Plan are determined to be beneficial primarily for fish, WDFW agrees to identify, pursue and acquire funding sufficient for implementation. The goals, objectives and obligations necessary to implement each of these mutually agreed upon projects are clearly identified within the attached Drainage Maintenance Plan (see Addendum A).

At established five-year periods, progress toward implementation of projects identified in this District Agreement and Plan will be reviewed, evaluated and considered in the revision and development of subsequent plans. Failure to participate in feasibility analysis and support feasible projects consistent with the written parameters established as part of this Agreement and Drainage Maintenance Plan may constitute grounds for voiding this Agreement.

PART III (F): Emergency Drainage Maintenance

The Parties to this Agreement recognize and acknowledge that exigent circumstances will arise as a result of weather or other factors influencing watercourse flows and the need

to convey water. Emergency drainage maintenance activities are typically the same as the routine maintenance activities identified elsewhere in this Agreement and Plan but may occur outside of designated work periods and/or require the use of action steps that differ or deviate from the BMP's prescribed for routine drainage maintenance activities by District 14. In the event of a drainage maintenance emergency, the following protocols will apply:

Natural Watercourses (blue)

Emergency approval by the WDFW is required for all emergency repair activities occurring in Natural Watercourses identified in a District Drainage Maintenance Agreement.

Managed Watercourses With Headwaters (green)

Emergency notification to the WDFW is required only in circumstances where emergency repair activities in a Managed Watercourse with Headwaters deviate from the timing restrictions and provisions identified in a District Drainage Maintenance Agreement and Plan.

Managed Watercourses Without Headwaters (magenta)

Emergency notification to WDFW is required only in circumstances where emergency repair activities in a Managed Watercourse without Headwaters deviates from the timing restrictions and provisions identified in a District Drainage Maintenance Agreement and Drainage Maintenance Plan.

Artificial Watercourses (yellow)

Notification to the WDFW is not required for emergency repair activities in artificial watercourses identified in a District Drainage Maintenance Agreement and Drainage Maintenance Plan.

The purpose of the emergency notification is to get concurrence from WDFW and establish appropriate permitting pathways.

PART III (G): Drainage Maintenance Activity Reporting

District 14 agrees to prepare and submit an annual report summarizing maintenance activities for the preceding calendar year using a format and timeline developed jointly between the WDFW and WWAA. The annual report will be forwarded to WWAA and WWAA will provide a copy of the report to WDFW for review and comment at the Annual Meeting.

PART III (H): Annual Drainage and Fish Review Meeting

The Parties to this Agreement agree to meet annually in February of each year at a time and place to be determined and established through mutual consent between WDFW, the District and WWAA. The purpose of this annual meeting will be to review and discuss drainage maintenance activities planned to occur during the coming year and to identify any relevant issues that may warrant the attention of the Parties in keeping with the spirit and intent of maintaining open and constructive channels of communication.

Participation at this meeting will also be open mutually accepted entities by Signatory Parties to this Agreement. Scheduled meetings may be modified or deferred by mutual consent.

PART IV: DRAINAGE MAINTENANCE PLANS

The Parties to this Agreement agree to work cooperatively to gather existing and pertinent information for the development and renewal of a District Drainage Maintenance Plan consistent with the following template. This template is not intended to be exhaustive or all-inclusive and is meant to serve as a guide for each Party in identifying relevant details for consideration in developing a Drainage Maintenance Plan as the primary component of this District Drainage Maintenance Agreement.

Drainage Maintenance Plan – Template

A. Drainage District Overview
    a. Location - map
    b. Drainage District boundaries - map
    c. Drainage District areas - acres
    d. Predominant land uses
    e. Watercourse types - map
        i. Artificial watercourses - miles (yellow)
        ii. Managed watercourses without headwaters - miles (magenta)
        iii. Managed watercourses with headwaters - miles (green)
        iv. Natural watercourses- miles (blue)
    f. Drainage infrastructure - map
        i. Water crossing structures - culverts
        ii. Pump stations
        iii. Tidegates
        iv. Other (siphon, screwgate)

B. Salmonids
    a. General salmonid distribution
    b. General salmonid habitat distribution
    c. General salmonid fish passage obstacles

C. Managed Watercourse with Headwaters (green)
    a. Reach Assessment
        i. Reach descriptions - map
        ii. Reach drainage infrastructure
        iii. Reach drainage maintenance activities
        iv. Reach habitat conditions
            1. Riparian characteristics

2. Fish passage barriers
3. Fish passage obstacles
4. Spawning habitat/substrate
5. Typical channel cross section
6. Reach gradient
7. Photos

b. Reach fish utilization
c. Reach fish habitat improvement opportunities

D. Habitat Improvement Projects

PART V: ISSUANCE OF HYDRAULIC PROJECT APPROVALS (HPA's)

Pertinent to this Agreement, WDFW agrees to issue appropriate HPA's as an Addendum to this District Drainage Maintenance Plan.

PART VI: DISPUTE RESOLUTION

The Parties recognize that a dispute or disagreement may arise in the course of furthering the purpose and intent of this Agreement, as well as in the development and implementation of a Drainage Maintenance Plan between WDFW and District 14 In the event of a dispute or disagreement involving the substance or intent of this Agreement, WDFW and the duly elected Commissioners of District 14 agree to communicate promptly and meet informally to seek a mutually satisfactory resolution. In the event of a dispute or disagreement involving the development or implementation of this District Agreement and Drainage Maintenance Plan, the Parties agree the following steps will be taken, in the order set forth below:

1. An attempt will be made to resolve the issue at the local level.
2. The Director of WDFW, or his designee, and a Commissioner of District 14 will meet in person.
3. The Parties will jointly engage and equitably fund the services of a mutually agreed upon facilitator to assist in resolving the dispute.
4. In the event resolution is not achieved using the previous steps, the Parties will be free to pursue other courses of formal action.

In the event of an alleged violation of the terms and provisions of a Hydraulic Project Approval issued in conjunction with this District Drainage Maintenance Agreement, WDFW will follow established Enforcement Program policy with regards to the investigation and handling of such incidents.

PART VII: DURATION AND SEVERABILITY

This Agreement shall become effective upon signature by both Parties and will remain in effect until such time as it is dissolved or otherwise revised by mutual consent of both

Parties. Either Party may terminate its participation thirty days after providing written notice to the other Party of its intent to do so.

The Parties to this Agreement recognize that each is operating as an independent entity pursuant to the powers, duties and responsibilities vested in each of them under the laws of the State of Washington. This Agreement and all related HPA's will be reviewed, revised as mutually agreed, and reissued as warranted at intervals of five (5) years from their date of origin. The Parties to this Agreement may mutually consent to reopen the Agreement for review, revision or cancellation at times more frequent than the established five-year intervals due to extenuating circumstances.

Examples of such circumstances are:

- Legislative acts altering the substance of this agreement
- Acts of nature
- Decisions of a Court
- Other factors mutually agreed upon (e.g. new technology, equipment, information)
- New information (e.g. changes in biological conditions that may result in damages to fisheries resources) not available during the development of a Drainage Maintenance Agreement and/or Drainage Maintenance Plan.

No agent, employee, or representative of either Party shall be deemed to be an agent, employee, or representative of any other Party for any purpose relative to this Agreement and each Party is solely and entirely responsible for the acts of its agents and employees during the period this Memorandum is in effect.

END OF AGREEMENT

ENTERED into this 03 day of MARCH, 2020 ~~2019~~ by BJB

BRENDAN BROKES, REGION 4 DIRECTOR
DEPARTMENT OF FISH AND WILDLIFE
STATE OF WASHINGTON

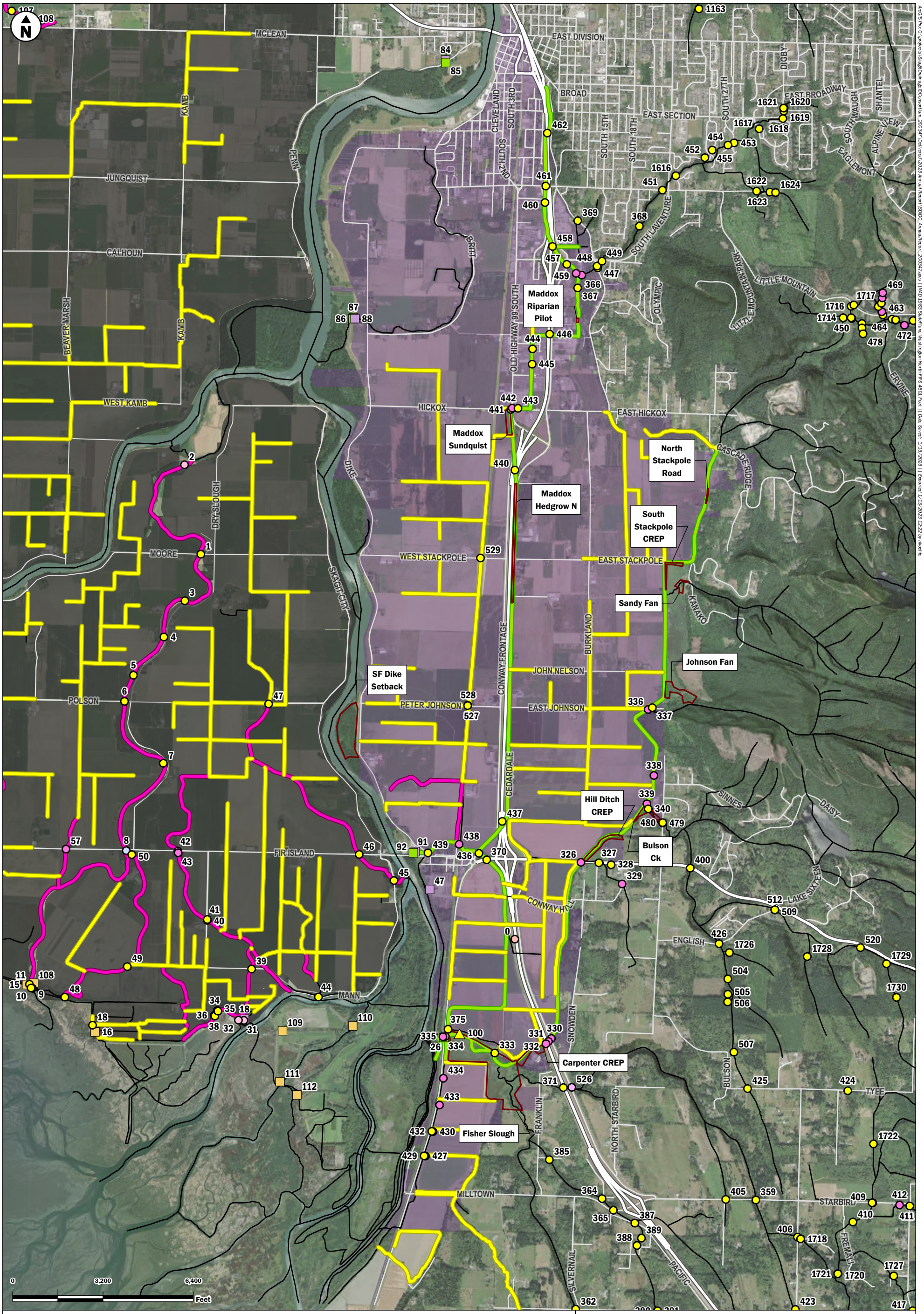
AND ON BEHALF OF DISTRICT 14

COMMISSIONER	COMMISSIONER	COMMISSIONER
18Feb21	2-24-21	
DATE	DATE	DATE

Addendum A: HPA Provisions

Addendum B: Drainage Maintenance Plan

Addendum C: Emergency Contacts



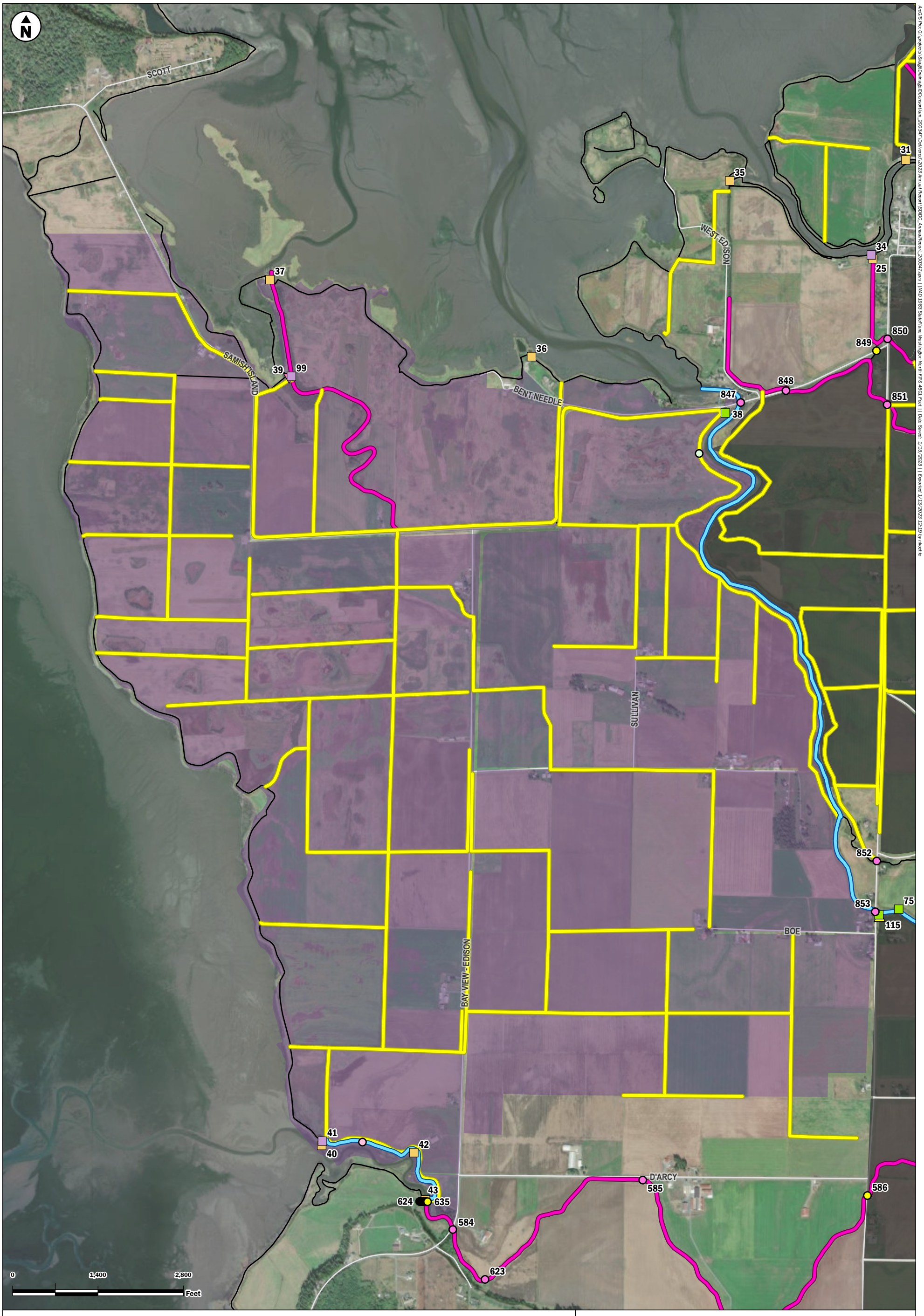
Dike District 3

2023 Annual Report
Skagit County Drainage and Irrigation District Consortium
Skagit County, Washington

Aspect Consulting	JAN-2023	BY: TDR / NLK	FIGURE NO. 1
	PROJECT NO. 200347	REVISED BY: ---/---	

Data source credits: None || Basemap Service Layer Credits: Esri, NASA, NGA, USGS, FEMA, Maxar

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Bridge
Culvert
Dike
Levee

FLOOD GATE
PUMP STATION
RETURN FLOOD GATE
TIDE GATE
TUBE

StR = Stream/River
ArtWA = Artifcial Watercourse
MW = Managed Watercourse without Headwaters
Other Lines Without DFI Attribute

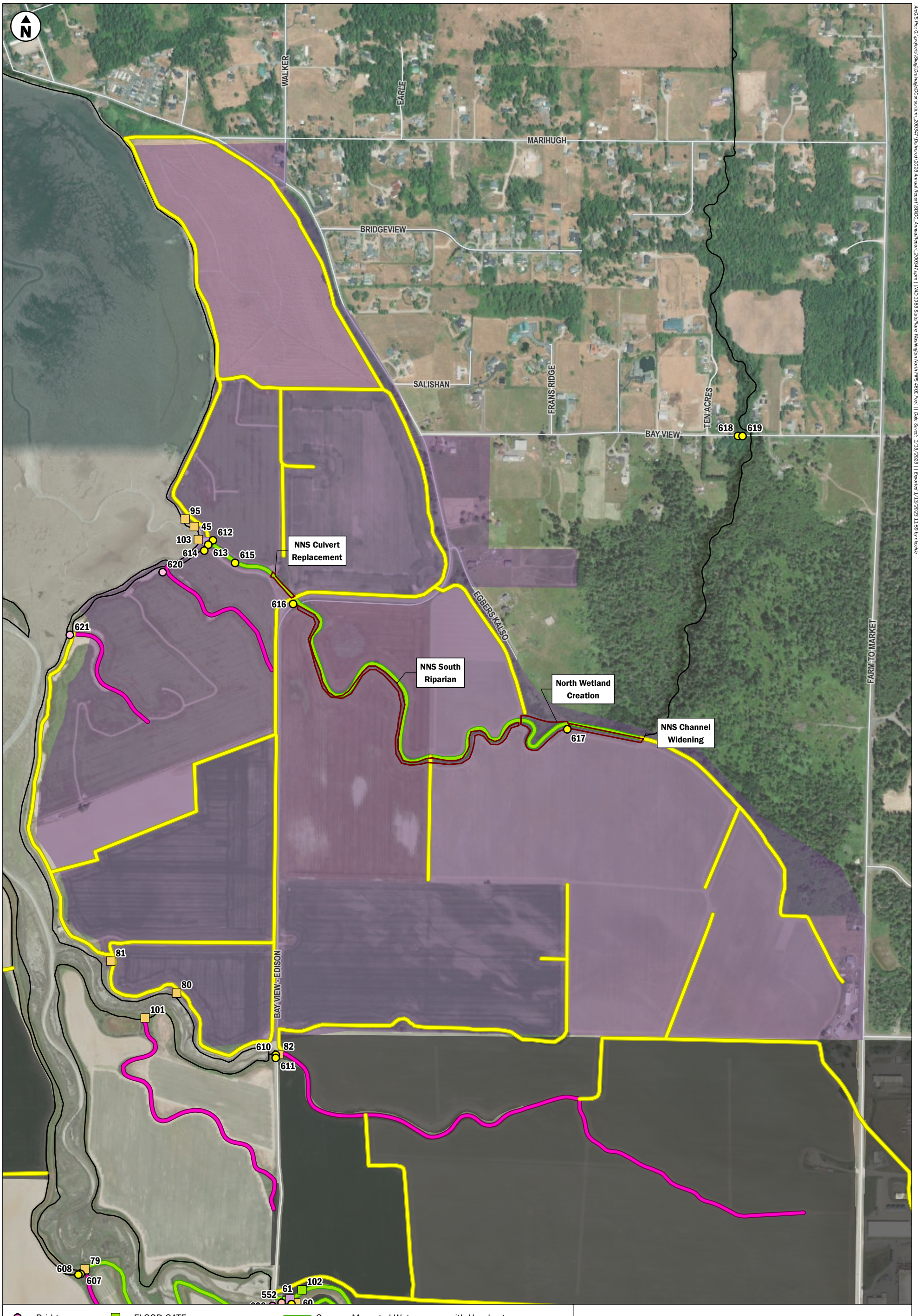
Dike, Drainage, and Irrigation District 5

2023 Annual Report
Skagit County Drainage and Irrigation District Consortium
Skagit County, Washington

Aspect CONSULTING	JAN-2023	BY: TDR / NLK	FIGURE NO. 1
	PROJECT NO. 200347	REVISED BY: ---/---	

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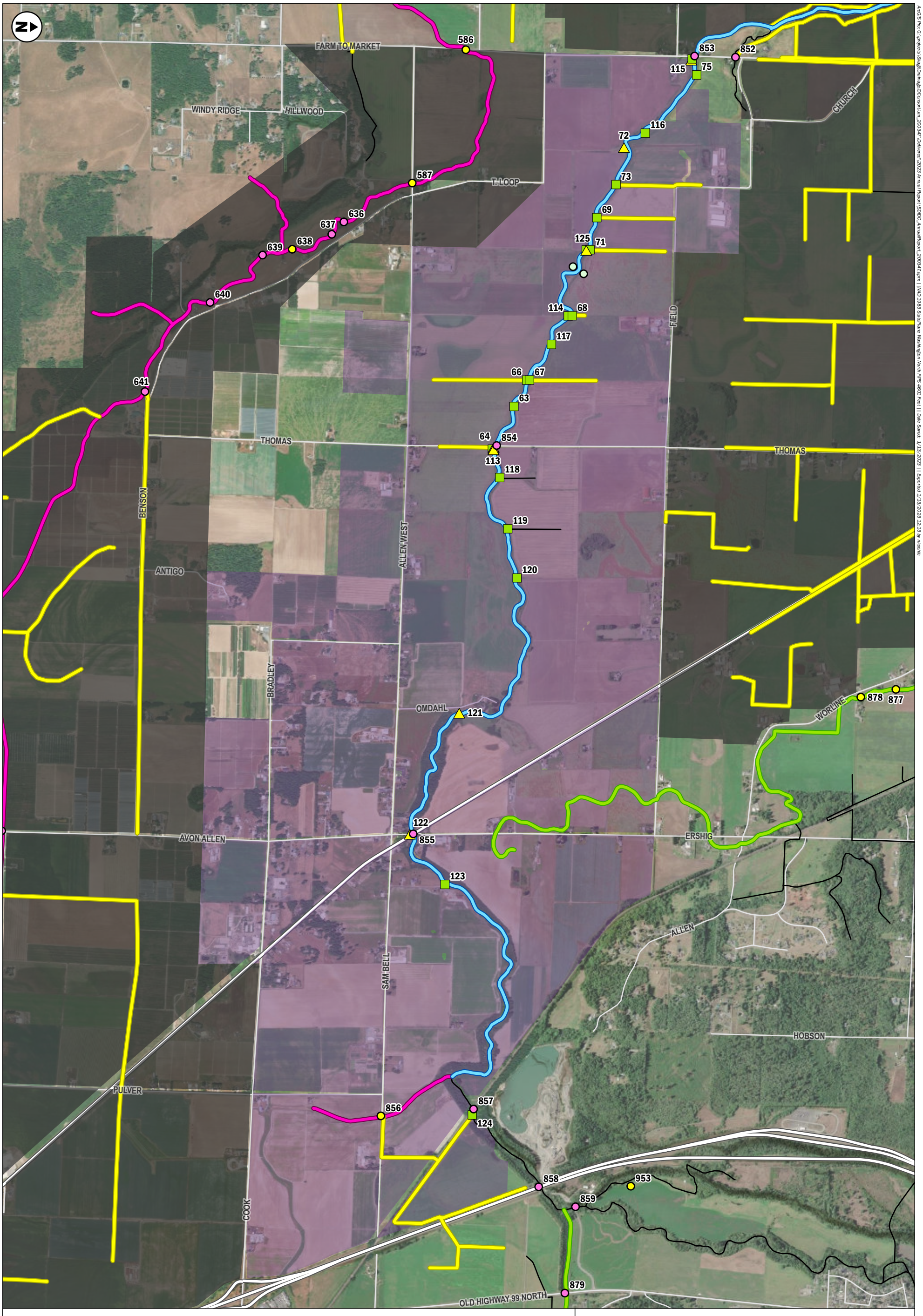
Dike, Drainage, and Irrigation District 12

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Skagit County Drainage and Irrigation District Consortium
Skagit County, Washington

Aspect Consulting	JAN-2023	BY: TDR / NLK	FIGURE NO. 1
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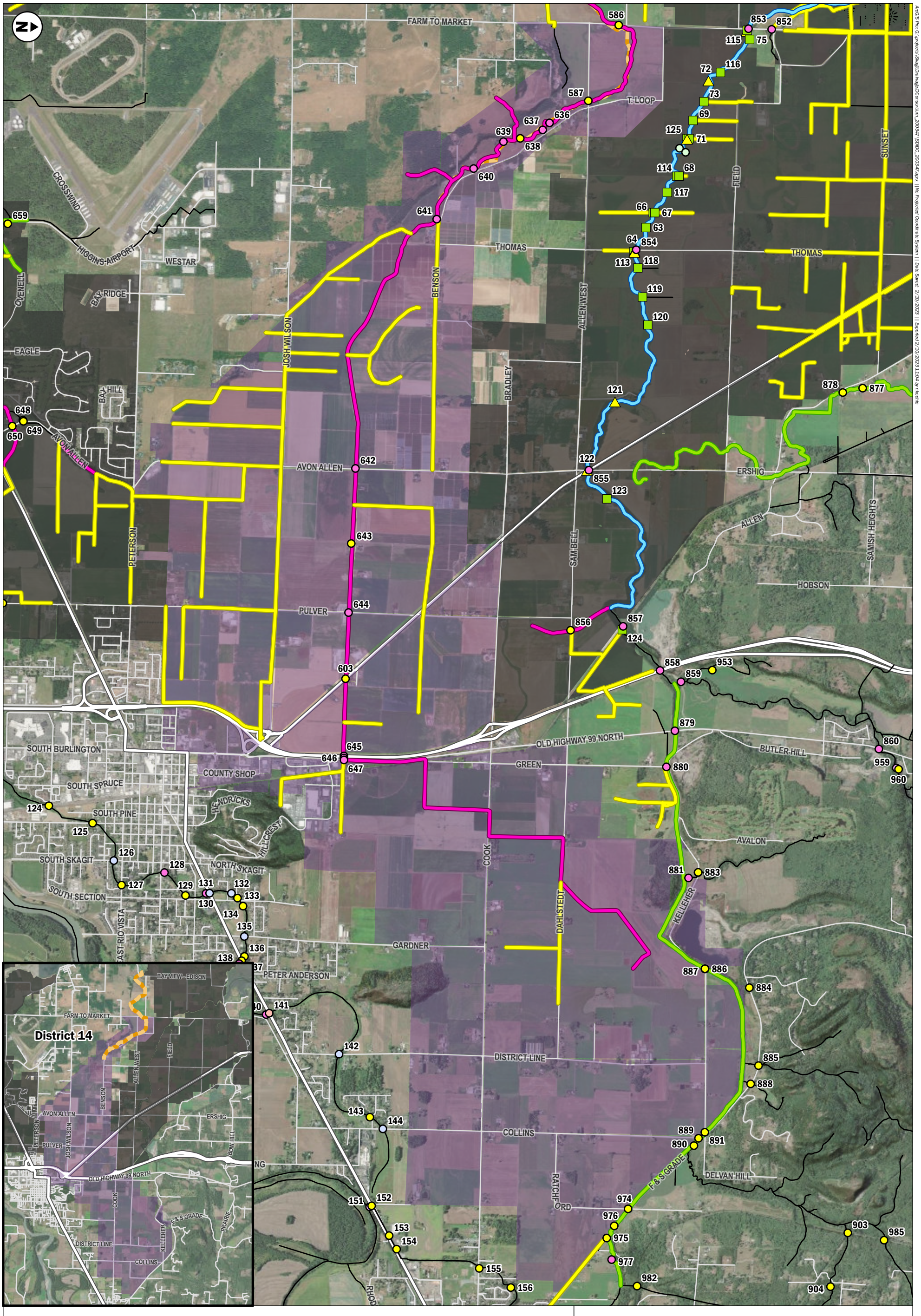
Dike, Drainage, and Irrigation District 25

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Skagit County Drainage and Irrigation District Consortium
Skagit County, Washington

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Bridge
Culvert
Fill
Fishway
Levee
Unknown
FLOOD GATE
OPEN TUBE
RETURN FLOOD GATE
StR = Stream/River
ArtWA = Artifcial Watercourse
Green = Managed Watercourse with Headwaters
MW = Managed Watercourse without Headwaters
Other Lines Without DFI Attribute
District 14 Easement

0 3,200 6,400 Feet

Drainage and Irrigation District 14

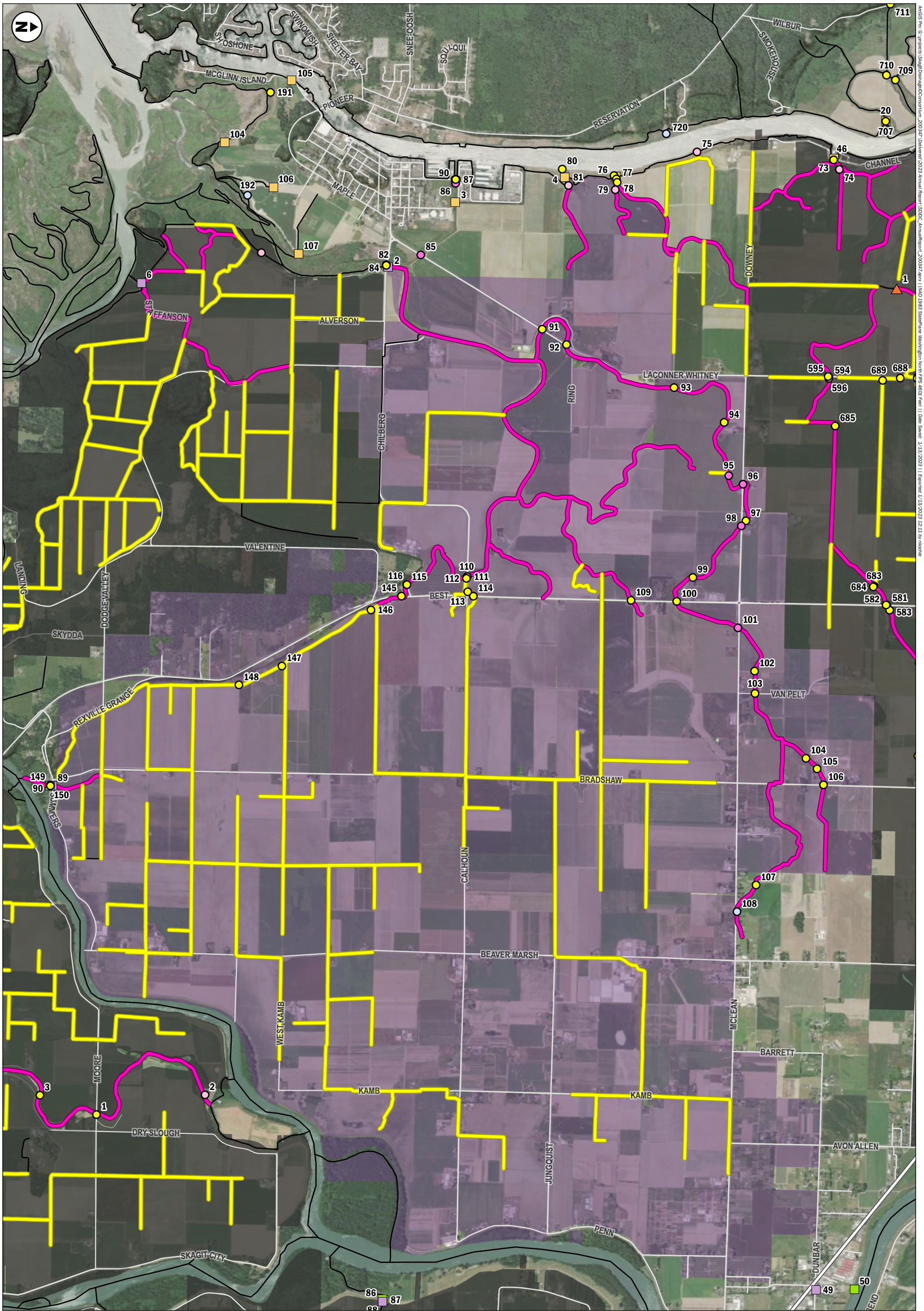
Skagit County Drainage and Irrigation District Consortium
Skagit County, Washington

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Bridge
Culvert
Dike
Fill

FLOOD GATE
OPEN TUBE
PUMP STATION
TIDE GATE

ArtWA = Artifcial Watercourse
MW = Managed Watercourse without Headwaters
Other Lines Without DFI Attribute

0 2,500 5,000 Feet

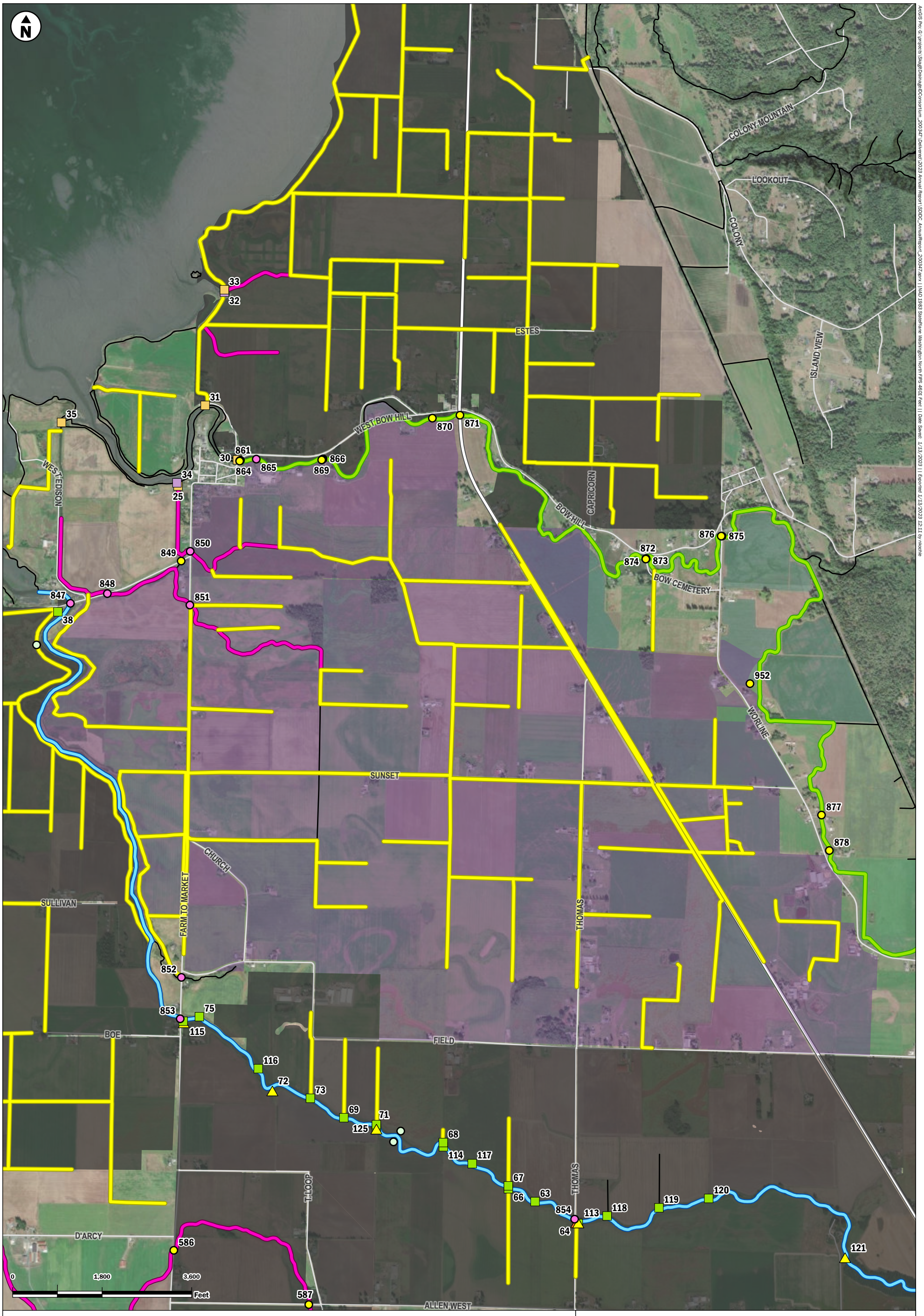
Drainage and Irrigation District 15

2023 Annual Report
Skagit County Drainage and Irrigation District Consortium
Skagit County, Washington

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Bridge
Culvert
Levee

FLOOD GATE
OPEN TUBE
PUMP STATION
RETURN FLOOD GATE
TIDE GATE

StR = Stream/River
ArtWA = Artifcial Watercourse
Green = Managed Watercourse with Headwaters
MW = Managed Watercourse without Headwaters
Other Lines Without DFI Attribute

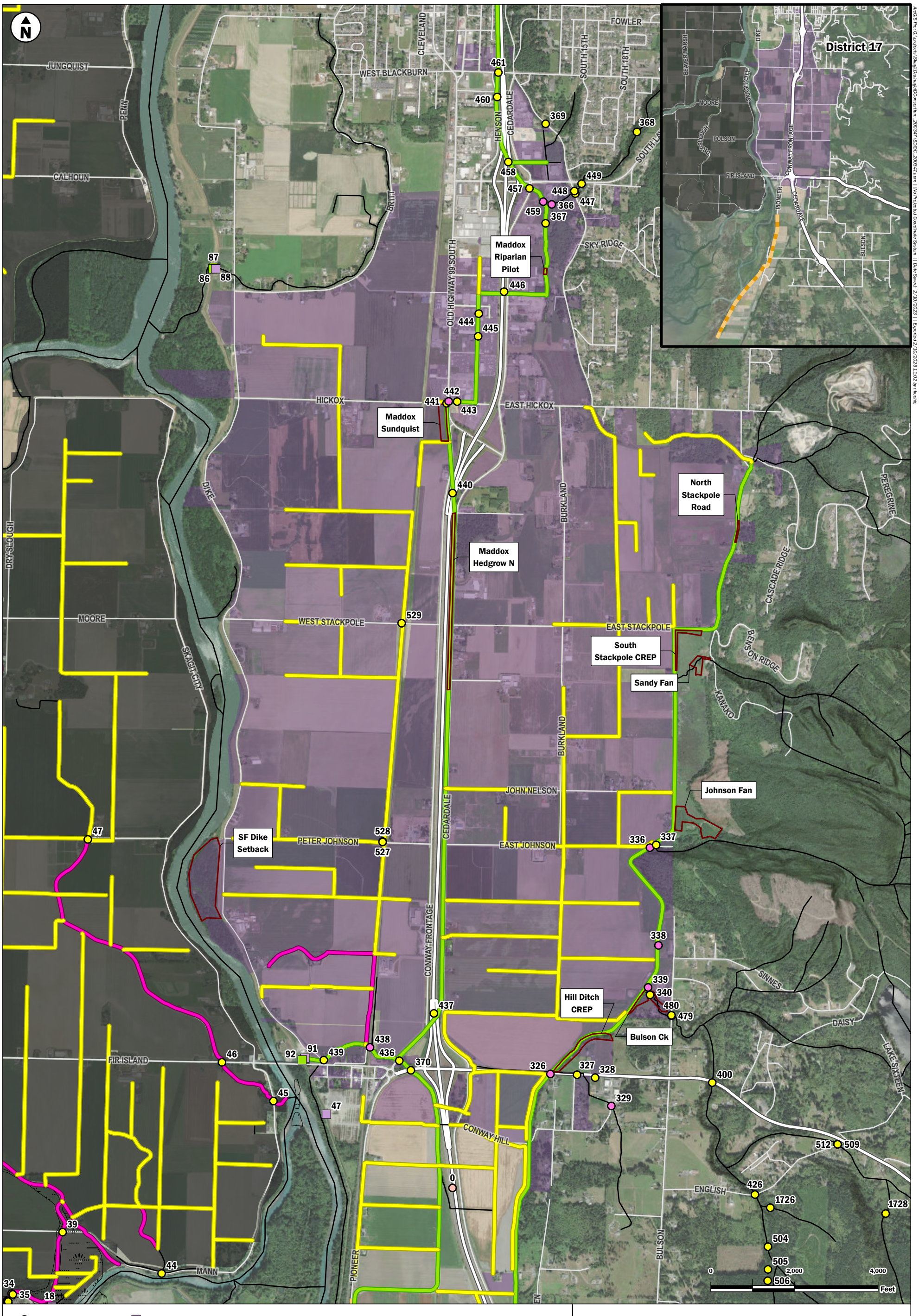
Drainage and Irrigation District 16

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Skagit County Drainage and Irrigation District Consortium
Skagit County, Washington

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Drainage and Irrigation District 17

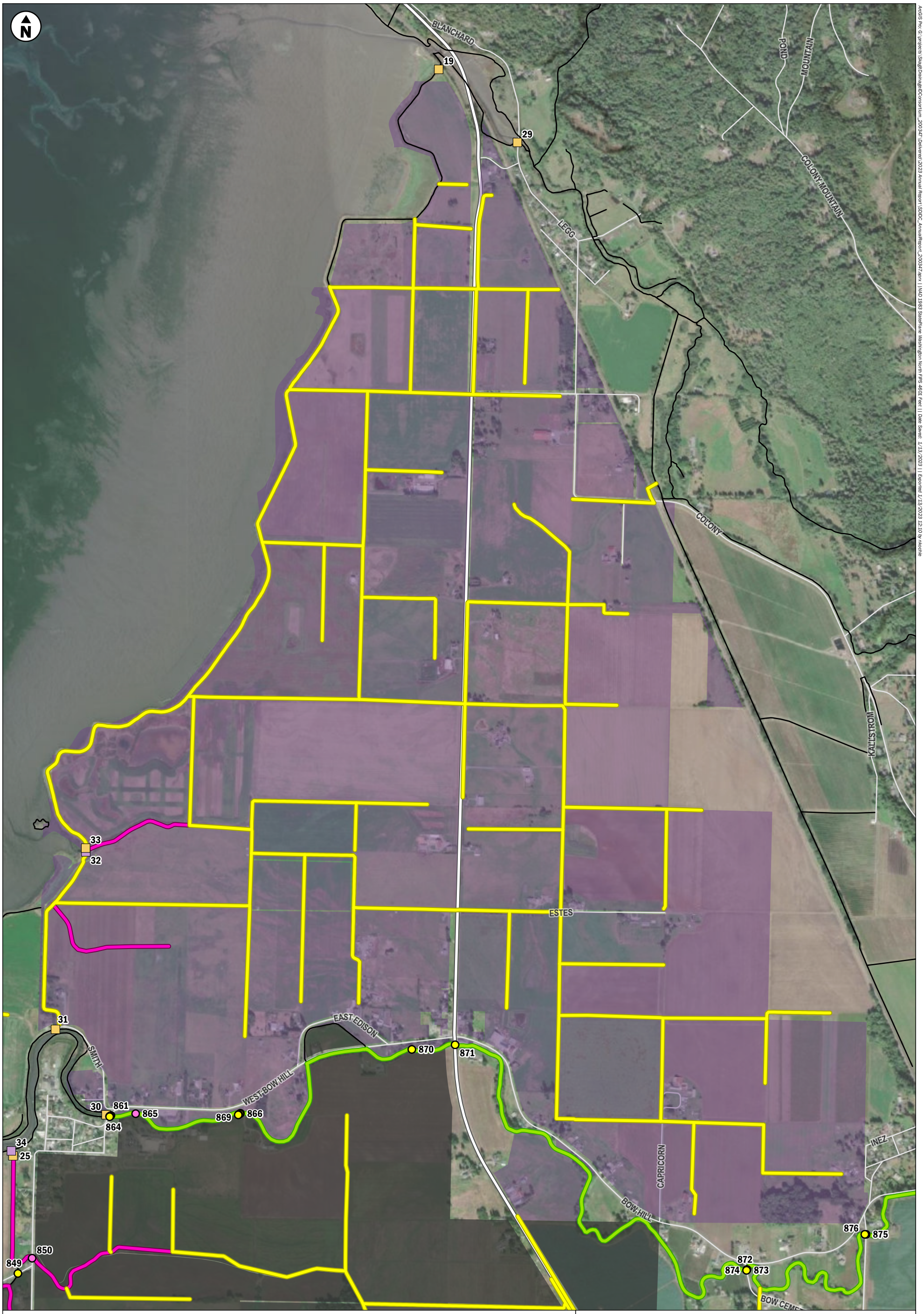
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Skagit County, Washington

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Bridge
Culvert
PUMP STATION
TIDE GATE

ArtWA = Artifcial Watercourse
Green = Managed Watercourse with Headwaters
MW = Managed Watercourse without Headwaters
Other Lines Without DFI Attribute

0 1,100 2,200 Feet

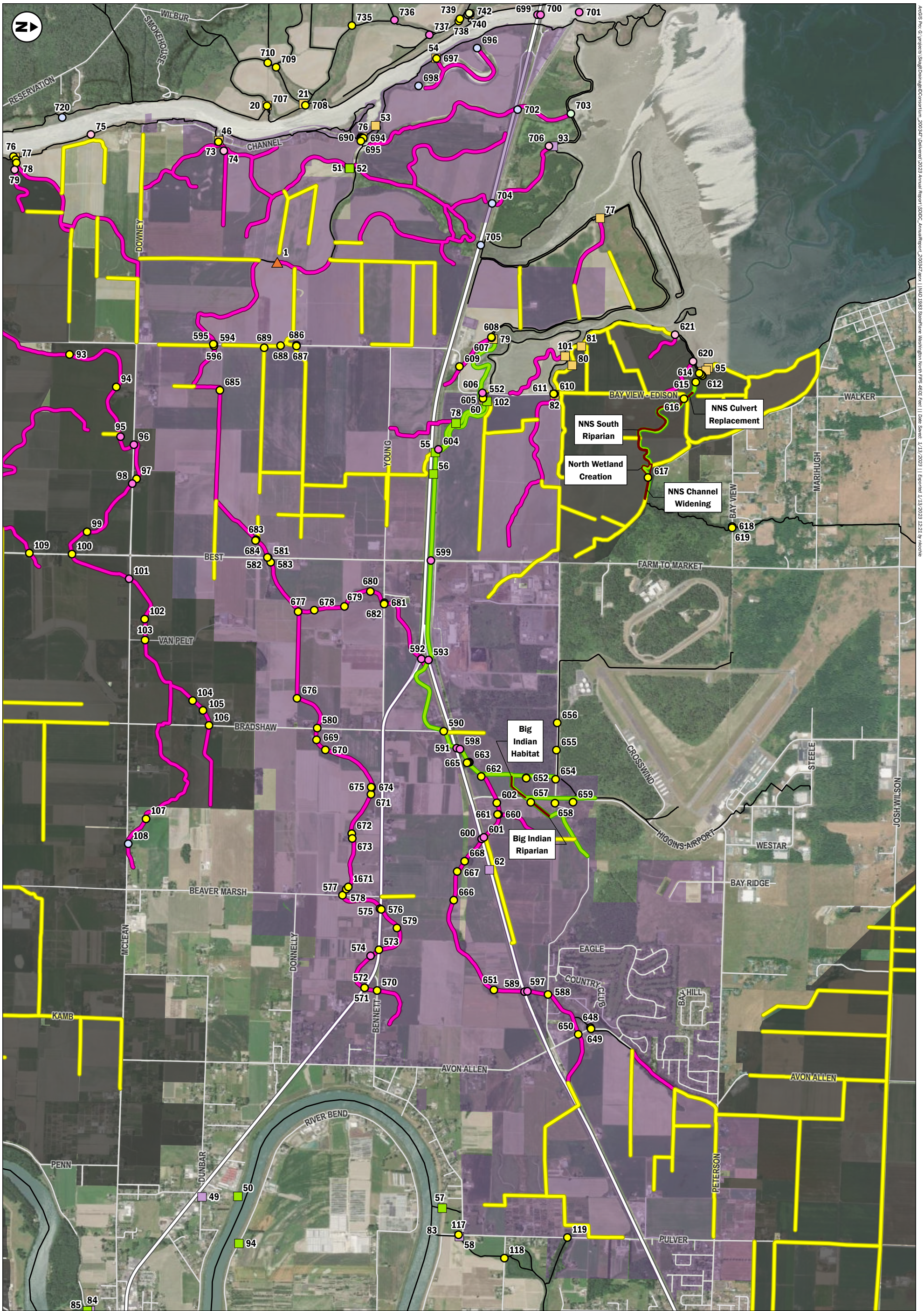
Drainage and Irrigation District 18

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Skagit County, Washington

Aspect CONSULTING	JAN-2023	BY: TDR / NLK	FIGURE NO. 1
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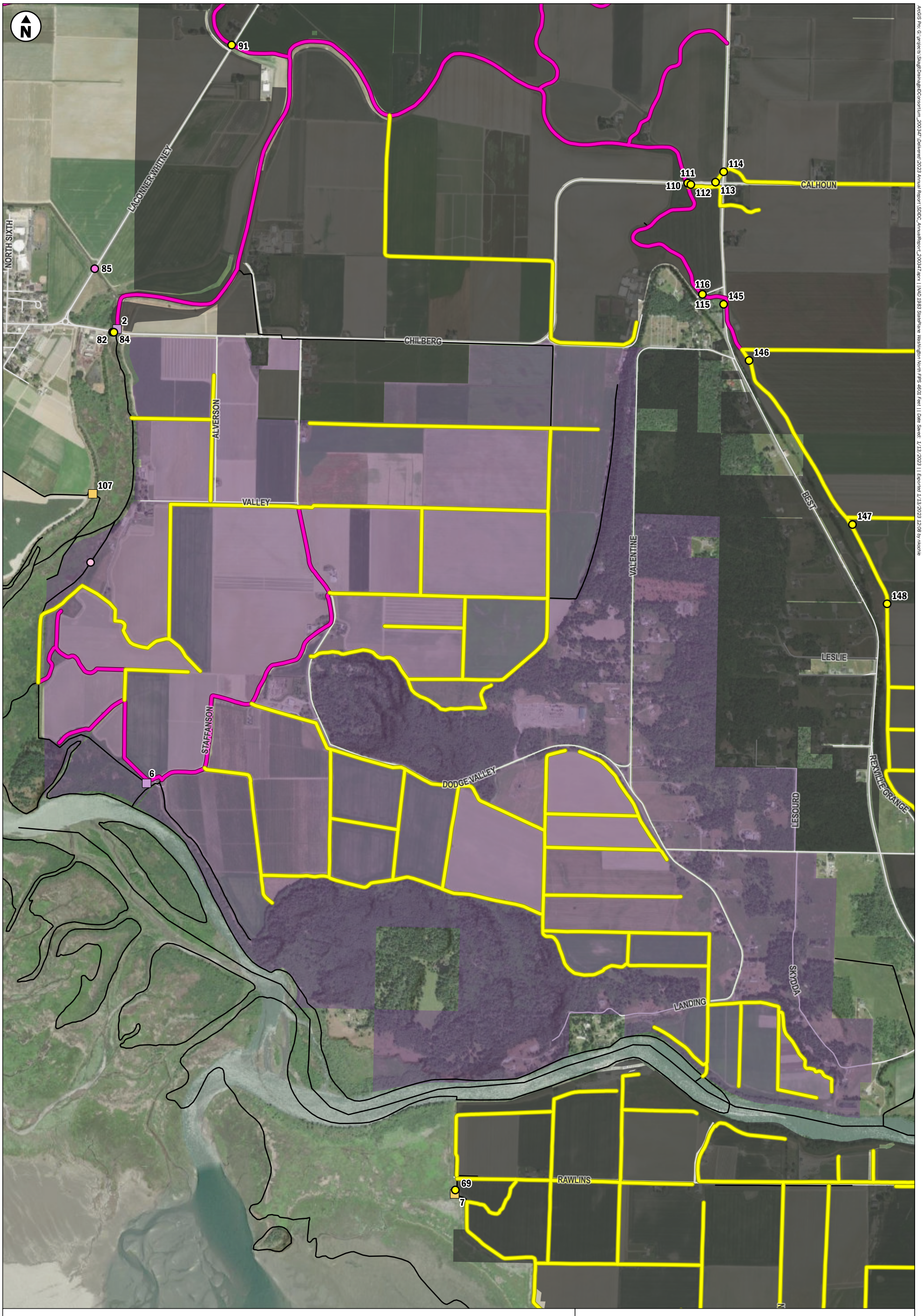
Drainage and Irrigation District 19

2023 Annual Report
Skagit County Drainage and Irrigation District Consortium
Skagit County, Washington

Aspect CONSULTING	JAN-2023	BY: TDR / NLK	FIGURE NO. 1
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Bridge

Culvert

Dike

PUMP STATION

TIDE GATE

ArtWA = Artifcial Watercourse

MW = Managed Watercourse without Headwaters

Other Lines Without DFI Attribute

0 1,400 2,800 Feet

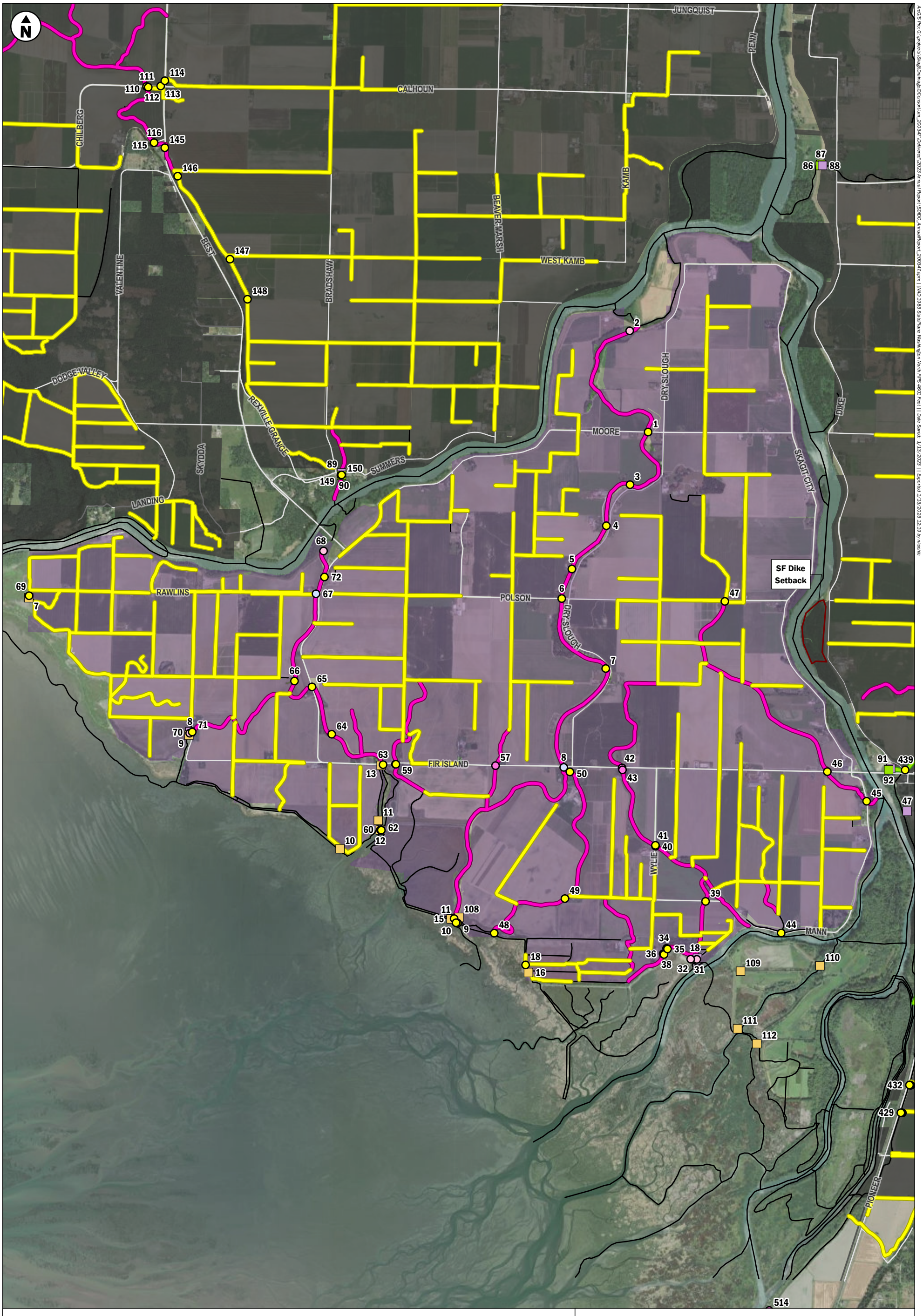
Drainage and Irrigation District 22

2023 Annual Report
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Skagit County, Washington

Aspect CONSULTING	JAN-2023	BY: TDR / NLK	FIGURE NO. 1
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Bridge
Culvert
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Fill

FLOOD GATE
PUMP STATION
TIDE GATE
ArtWA = Artifcial Watercourse

Green = Managed Watercourse with Headwaters
MW = Managed Watercourse without Headwaters
Other Lines Without DFI Attribute

0 2,800 5,600 Feet

Consolidated Dike, Drainage, and Irrigation District 22

2023 Annual Report
Skagit County Drainage and Irrigation District Consortium
Skagit County, Washington

Aspect CONSULTING	JAN-2023	BY: TDR / NLK	FIGURE NO. 1
	PROJECT NO. 200347	REVISED BY: ---/---	

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Comment #14

Robby Eckroth

From: Irene Derosier <iween@me.com>
Sent: Thursday, May 8, 2025 12:16 PM
To: PDS comments
Subject: Comment on environmental regulations

Greetings,

I am in full support for the following considerations:

The planning commission is also considering changes to zoning and development code, including allowing medium-density housing in rural village residential zones and increasing the number of allowed accessory dwelling units from one to two in urban growth area zones.

Concentrated development density makes perfect sense as there is so much upside to this policy. Maximizing and concentrating existing infrastructure development, building on taxable property values, generating more housing. It's a great opportunity for all.

Also, I think the increased buffers specific to wetlands is a good idea. It seems as though there are reasonable considerations for landowner use exceptions and the science behind this proposed change is clear. Please protect our wetlands and water quality!

Sincere regards,
Irene Derosier

11260 Bayview Edison Rd.
Mt Vernon 98273

Sent from my iPad

Robby Eckroth

From: Molly Doran <mollyd@skagitlandtrust.org>
Sent: Thursday, May 8, 2025 1:42 PM
To: PDS comments
Subject: 2025 Development Regulations and Critical Areas Ordinance Update, Skagit Land Trust

Submitted by Molly Doran
Skagit Land Trust, Executive Director
1020 S 3rd
Mount Vernon WA
98273

Thank you for the opportunity to comment on the proposed 2025 updates to the Development Regulations and the Critical Areas Ordinance.

Skagit Land Trust conserves wildlife habitat, working agricultural and forest lands, scenic open space, wetlands, and shorelines for the benefit of our community and as a legacy for future generations. Our organization has over 1,700 family and business supporters (members) and 500 active volunteers who work to protect the most important and beloved places in Skagit County. Today, the Trust protects more than 10,000 acres, including more than 48 miles of shoreline.

Our comments draw from this mission and seek to ensure that the Development Regulations and Critical Areas Ordinance support the Skagit County Comprehensive Plan and work to maintain the resilience of Skagit County's natural environment in the face of population growth and the impacts of climate change.

Development Regulations

- **We support the following amendment to SCC 14.08.060(3),** requiring that "*Site-specific proposals to de-designate natural resource lands must be deferred until a comprehensive countywide analysis is conducted*."

Site-specific de-designation requests are often submitted simply because a landowner seeks to gain additional development potential on their land, regardless of whether their parcel meets the Natural Resource Land designation criteria. It is very difficult and time-consuming for planners to consider such isolated de-designation requests separate from a more comprehensive review of the natural resource land base. On rare occasions a parcel may have been incorrectly designated as Natural Resource Land, but this should only be evaluated on a comprehensive basis when looking at the agricultural or forest land base as a whole.

The Comprehensive Plan update included a corresponding proposed change to policy 4A-1.1 (e): *"Site-specific proposals to de-designate natural resource lands must be deferred until a comprehensive countywide analysis is conducted*." However, this policy applied to Ag-NRL lands only. **This same provision should be applied to policy 4B-3.3 regarding forest lands of long-term commercial significance.** This would make the Comprehensive Plan fully consistent with the above proposed code amendment.

- **We support the following proposed amendment to SCC 14.08.060(4)(g),** requiring a climate impact analysis to be completed prior to expansion of an urban growth area:

Prior to altering urban growth areas, or as part of a periodic update, a climate impact analysis must be completed. The climate impact analysis shall evaluate the greenhouse gas (GHG) and vehicle miles traveled (VMT) impacts associated with the proposed change and consider climate vulnerability and resilience scenarios created by the change. The analysis shall also consider the GHG and VMT impacts associated with other feasible alternatives for accommodating projected growth. Preference shall be given to alternatives that reduce per capita VMT and GHG emissions and changes that increase climate resilience and protect vulnerable populations and overburdened communities.

There is a significant amount of infill potential within the existing urban growth areas in Skagit County, especially as cities show an increasing willingness – and face stronger state requirements – to increase densities and allow a wider range of "middle housing" options. Promoting more compact, walkable, and transit-oriented development within cities and their existing UGAs will significantly reduce GHG and VMT impacts associated with population growth compared to UGA expansions.

- Consistent with our comments on the Comprehensive Plan update, **we oppose allowing middle housing types in the Rural Village Residential zone**, including duplexes, triplexes, fourplexes and manufactured home parks, as is proposed in **Table 14.11.020-1 Allowed Uses in the Rural Mixed-Use Zones**.

As we noted in our comments on the Comprehensive Plan, the rural area accepted 24.6% of the County's growth from 2017-2022, compared to 75.4% for the urban areas. This reflects a movement in the wrong direction from the 2000 to 2010 period when rural area growth was 21% versus 79% for the urban area. **We strongly oppose any effort to create additional development potential in the rural area.**

With climate change, many of the factors that previously dictated where growth and development should go must be updated with greater emphasis on natural hazards and limited resources. Thus, things such as water supply, single source aquifers, flood plain hazards, forest fire hazards, erosion, landslides, and transportation routes in floodplains all need to be considered. We believe affordable housing and environment conservation goals are best served by targeting most new residential growth to the urban areas. **Allowing additional density in the rural area,** even for the important purpose of increasing affordable housing**, is moving in the wrong direction and will be harder for the county to support as environmental conditions change.**

- **We support the existing provision in code, SCC 14.76.200, allowing a one-acre segregation for agricultural land preservation in the Ag-NRL zone**. This provision allows the creation of a substandard one-acre lot containing an existing residence in Ag-NRL, in consideration for placing a conservation easement on the remainder of the parcel to permanently protect the agricultural land. Critical areas review is not required for the purposes of this segregation provided that no additional development is contemplated

SCC 14.76.200 makes great sense for the protection of Ag-Natural Resource Land. **We recommend that a similar process for a "Conservation Subdivision" should be offered in non-Ag-NRL zones**. This would allow an existing house to be separated from the remainder of a parcel which would then be conserved in perpetuity through a conservation easement allowing a variety of conservation purposes, including natural resource management, open space preservation, and habitat protection. As with the above provision available in Ag-NRL, the land division would not require critical areas review or other arduous and expensive procedures that are required when a land division is done for development purposes.

Critical Areas Ordinance

We appreciate the comprehensive review of the current Critical Areas Ordinance (CAO), based on Best Available Science (BAS), conducted by the consultants and Facet, titled "Gap Analysis". We support most of the recommendations and the rationale for them made in this report. Listed below are specific recommendations in the Gap Analysis that we feel are particularly important. Also noted are some discrepancies where it appears the consultant's recommendations may not have been fully incorporated into the new draft.

- **We strongly support the Gap Analysis recommendation to include new language in the CAO that requires "no net loss of ecological function" as a protection standard that applies to all critical areas. However, the Code must make clear that this requirement cannot be used to justify the substitution of mitigation for full protection of existing critical areas.**

- The new draft includes requirements for critical area assessment to consider direct and indirect impacts to critical areas and buffers. This is important:

14.24.080 Standard critical areas review and site assessment procedures.
….
(*5)(iv) An assessment of the probable direct and indirect impacts to the critical area(s) and buffer(s) as well as the cumulative impacts to critical areas resulting from the existing development of the site and the proposed development ….*

- **We support the updated references to new Department of Ecology wetland functional rating system and any future updates, together with all the changes that seek to reconcile the definitions in the County CAO with State definitions:**

14.24.210 Wetlands classifications
Wetlands will be rated according to the Washington State Wetland Rating System for Western Washington 2014 Update, Version 2.0 (Department of Ecology Publication No. 23-06-009) current or as amended. This document contains the definitions, methods and a rating form for determining the categorization of wetlands below

- **We support the new language regarding the condition of wetland buffers and the need for extra measures if the buffer is degraded:**

14.24.230 Wetland protection standards.
….
(4)(c) Vegetated buffer standards: All wetland buffer widths presume the buffer is densely vegetated with a native plant community appropriate for the ecoregion, consisting of an average of 80% native cover comprised of trees, shrubs and groundcover plants. If the existing buffer is sparsely vegetated or vegetated with invasive species, the buffer must either be enhanced through an approved mitigation plan or increased per SCC 14.24.240(1)(c) to ensure the buffer provides adequate functions.

- In Section **14.24.240 (Wetland performance-based buffer alternatives and mitigation standards),** we support the changes to buffer averaging and buffer reductions, particularly the deletion of paragraph (3) "Buffer width decreasing."

- We support similar changes to buffer requirements as cited above, made also in Section **14.24.540 Fish and wildlife habitat conservation area performance-based buffer alternatives**

and mitigation standards. In addition, in paragraph (g) of this Section, we support the requirement for a critical areas assessment if timber harvest is allowed in a riparian area buffer: "No net loss of ecological functions must be demonstrated through the critical area report process."

- We support the Gap Analysis recommendations for Section 14.24.230, regarding **protection of small wetlands**; **however, it doesn't appear the proposed changes to this section would necessarily accomplish what the Gap Analysis proposed. Page 12 of the Gap Analysis states:**

  14.24.230 (6)(a) provides a complete exemption for wetland standards for Category III and IV wetlands that are less than 1,000 square feet, when isolated and other criteria are met. Even small wetlands provide important functions so mitigation should be required to meet the stated goals of no net loss of ecological function, including hydrological function in areas with downgradient drainage issues. We would recommend that if Skagit County wishes to continue allowing impacts to small wetlands, that they, at a minimum, require full mitigation to ensure no net loss of ecological function. Furthermore, all wetlands are protected by Ecology under the Water Pollution Control Act and the Skagit County Water Pollution Code SCC 16.32, even when they are not considered jurisdictional by the Corps under Clean Water Act jurisdiction. To prevent circumstances where applicants circumvent or are unaware of state law, then state and federal approval should also be required when wetland fill is authorized by Skagit County. If the county wishes to maintain flexibility for Category III and IV wetlands less than 1,000 square feet, buffer reductions may be considered in lieu of full exemption from statutory requirements.

- **Species and Habitats of Local Importance Maps. We support the recommendation in the Gap Analysis (page 22, quoted below) that concerns mapping and identification of species and habitats of local importance. We were unable to find any update in the CAO that responds to this recommendation**:

  The SCC designates identified habitats and species of local importance according to an official map. We were unable to find this map through internet searches and it should be made more accessible to users. Additionally, we recommend that these protections apply to all species and habitats of local importance wherever found since no comprehensive inventory exists.

- **In addition, we support the recommendation in the Gap Analysis that habitat management plans also incorporate information from other agencies in addition to WDFW, including USFWS and NOAA. We do not find any changes in the CAO reflecting this recommendation.** Page 25 of the Gap Analysis states:

  "Other" FWHCAs such as listed species are protected on a case-by-case basis "by means of a habitat management plan based on the Washington State Priority Habitat and Species (PHS) program." We recommend updating the language of this section such that a habitat management plan (HMP) will implement WDFW management recommendations for PHS species. WDFW's management recommendations have not been developed for all regulated species and are not always applicable to site-scale management. We would recommend that this section be updated to also consider information from other sources such as USFWS, NOAA, other governments and agencies that have information on the species, peer-reviewed literature, and other BAS.

- **We support the addition to SCC 14.24.500, Fish and wildlife habitat conservation area designations, of the underlined language in 14.24.500 (1) (k):**

State priority habitats and areas associated with State priority species as defined in WAC 365190-080 or documented in the Washington State Department of Fish and Wildlife Priority Habitats and Species List.

- **We support the addition of the underlined language to 14.24.500 (4):**

  "The following species and habitats have been designated on a site-specific basis according to the official Washington Department of Fish and Wildlife Priority Habitats and Species List, 2023 or as amended, and/or the County's List of Habitats and Species of Local Importance Map: "

Skagit County lists Great Blue Heron nest sites as a habitat of local importance, SCC14.24.500 (4) (a). WDFW lists Great Blue Heron as a priority habitat and species and dedicates a chapter to the management of Great Blue Heron in WDFW's "Management Recommendations for Washington's Priority Habitats and Species".

March Point offers Great Blue Heron ideal nesting habitat with mature coastal forest able to support large nests high above the ground and nearby access to an abundance of forage fish to meet the caloric demands of rapidly growing heron young.

- **We ask that SCC recognize the importance of nearby foraging to the Great Blue Heron by adding to SCC14.24.500 (4) (a) the following underlined language: "Great blue heron nest sites and foraging areas".**

- Because Great Blue Heron eat a variety of forage fish, we also fully support the GAP Analysis recommendation that SCC 14.24.500 (1) (d) Forage Fish Spawning Habitat includes "other forage fish spawning areas" in addition to the herring and smelt spawning areas currently identified.

- In its management recommendations for Great Blue Heron, WDFW notes that protection of great blue heron habitat is needed because with increasing development this nesting habitat is becoming rare, and "A single event involving human disturbance can lead an entire colony to terminate a nesting attempt". With over 500 nests, the March Point colony is the largest colony in the Salish Sea and the reproductive center for Pacific Great Blue Heron.

- **We would like to take this opportunity to recommend that the CAO provide stronger protection for heronries, especially the March Point heronry**. This could be done by making the County CAO consistent with the Anacortes CAO regarding Great Blue Herons. Three parcels on which the March Point heronry stands are under the County's jurisdiction. The Anacortes CAO provisions, shown below, are based on WDFW's priority species habitat recommendations for management of herons, so adding them to Skagit County's CAO would make it consistent with the requirement for following Best Available Science.

  March Point Heronry
  a. Purpose. *Because Skagit County is home to the greatest concentration of nesting great blue heron in the Salish Sea, March Point being the largest, the city has identified the March Point Heronry as a habitat of local importance.*
  b. Proposed development activities within 1,000 feet, or that are likely to impact the colony, must provide a critical areas assessment report and habitat management plan that follows at a minimum the guidelines provided by WDFW's Management Recommendations for Washington's Priority Species (March 2012) https://wdfw.wa.gov/sites/default/files/publications/01371/wdfw01371.pdf.

c. Buffers will be implemented as described in the buffer section below.
d. Colony protection is required for minimum 10 years after abandonment.
[Buffer provisions]
c. Great Blue Heron Nesting and Breeding Areas. Development near a verified heron breeding habitat including nesting colony areas, former nesting colonies:
i. A year-round urban buffer of 197 feet;
ii. For unusually loud activities that occur during breeding season (February through September) a seasonal buffer of 656 feet, and a blasting buffer of 1,320 feet;
iii. For properties without an existing and approved management plan, a management plan developed by a qualified professional to follow, at a minimum, WDFW's Management Recommendations for Washington's Priority Species (March 2012) and that identifies the nesting and breeding site as well as prenesting staging area, and breeding season foraging habitat;
iv. For the March Point colony, given the observed and documented sensitivity of this mega-colony to human intrusion and the fact that the colony is in a rare, isolated, but tight location, a year-round buffer of 984 feet. (Ord. 4025 § 2 (Att. A), 2022; Ord. 3064 § 2 (Att. A), 2021)

Another option would be to work with City of Anacortes to annex the three parcels on which the March Point heronry stands, placing the entire heronry under the Anacortes CAO provisions.

- **We support the addition of underlined language about habitat corridors rather than a "nonriparian buffer" to 14.24.540**, Fish and wildlife habitat conservation area performance-based buffer alternatives and mitigation standards:

  Buffer Width Increasing. The Administrative Official Director may require the standard buffer width to be increased or to establish a nonriparian buffer habitat corridors, when such buffers are necessary for 1 of the following: (a) To protect priority fish or wildlife using the HCA."

General Observations

- **The term "corridor" appears just once and "connectivity" 4 times (all 4 with reference to wetlands). It is important that the CAO provide more support for improving habitat connectivity both in wetlands, riparian areas and elsewhere.**

- **Explicit measures to adapt to climate change are absent in the CAO. Page 58 of the consultant's Best Available Science Review (Skagit County BAS 2.24.2025 - FINAL.pdf) has a list of "Strategies to manage climate change impacts to FWHCAs" (Fish & Wildlife Habitat Conservation Areas) that the County should incorporate wherever possible into the CAO.**

Alluvial Fans

- We appreciate the specification of **alluvial fans as a known or suspected landslide hazard in SCC 14.24.400 (2)(i).**

Similar to the GAP analysis recommendation for improved mapping and data bases for mine hazards (GAP analysis Table 4), **we recommend Skagit County update its mapping of alluvial fans, including mapping of potential run-out areas on alluvial fan maps.**

In early 2021 the Washington State Legislature passed and funded Washington State Bill "SB5088-Landslide Hazard Mapping and Inventory," that will improve understanding of landslide and other geological hazards. The Washington Geological Survey published an updated deep-seated landslide and alluvial fan mapping product in 2020 (WGS Report of Investigations 42, February 2020).

To reduce the risk of property damage associated with alluvial fans, we recommend the following language from Whatcom County Code 16.16.345(C) be added to the Skagit County CAO:

> *Permanent residential structures and commercial developments shall be allowed in alluvial fan hazard areas only if the fan has undergone a county-approved study to assess potential hazards, determine risks, and identify mitigation measures and is deemed suitable for development. The technical administrator shall make this determination based on a detailed assessment by a qualified professional that identifies the risks associated with a 500-year return period debris flow or the maximum credible event that could impact the alluvial fan*.

Thank you for the opportunity to comment

Skagit Land Trust

Comment #16

Robby Eckroth

From: Heather Spore <hspore@swinomish.nsn.us>
Sent: Thursday, May 8, 2025 2:35 PM
To: Robby Eckroth; PDS comments
Cc: Angela.SanFilippo@commerce.wa.gov
Subject: 2025 Development Regulations and Critical Areas Ordinance Update
Attachments: SITC_Ltr2County_CAO comment_05082025-final.pdf

Hello Planning and Development Services,

The Swinomish Indian Tribal Community submits the below comments, also described in the attached PDF with footnotes, on the proposed changes to the Skagit County Critical Areas Ordinance. The Tribe strongly urges Skagit County to incorporate the suggested revisions in order to meet its legal and moral obligations to protect and enhance the vast critical areas within the Skagit County boundary.

May 8, 2025

Robby Eckroth, Senior Planner
Skagit County Planning and Development Services
1800 Continental Place
Mount Vernon, Washington 98273

Sent electronically via email to: pdscomments@co.skagit.wa.us

RE: Skagit County Critical Areas Ordinance Open for Public Comment

Dear Mr. Eckroth,

The Swinomish Indian Tribal Community ("Swinomish Tribe" or the "Tribe") is submitting these comments on the draft Skagit County Critical Areas Ordinance ("Draft CAO") that will be included as part of the County's 2025 Comprehensive Plan update. In summary, the Swinomish Tribe has numerous concerns and objections with the Draft CAO because it is inconsistent, confusing and fails to meet the County's obligation to give special consideration to conservation and protection measures necessary to preserve or enhance anadromous fisheries.

Background and setting for our objections and concerns

The Swinomish Indian Tribal Community is a federally recognized Indian tribe and political successor in interest to certain tribes and bands that signed the 1855 Treaty of Point Elliott, which among other things reserved fishing, hunting and gathering rights and established the Swinomish Reservation on Fidalgo Island in Skagit County, Washington. The Swinomish Reservation sits at the mouth of the Skagit River, the largest river system draining to Puget Sound and the only river in the Lower 48 states that still has all species of wild Pacific salmon and steelhead spawning in its waters. Since time immemorial, the Swinomish Tribe and its predecessors have occupied and utilized vast areas of land and water in the northern Salish Sea up to the Canadian border to support the Swinomish Tribe's cultural and traditional lifeways.

Swinomish is the primary guardian of the Skagit and Samish River basins and surrounding coastal areas. The Tribe is and adjudicated co-manager of Washington fisheries along with the Washington Department of Fish and Wildlife (WDFW) and have worked with WDFW and NOAA Fisheries for decades in this capacity to ensure protection and restoration of fishery resources in the Skagit and Samish basins, as well as shellfish resources in Washington's coastal zone. Coastal zones and critical areas serve as vital nursery grounds, feeding areas, and migration routes for salmon and steelhead, including ESA-listed stocks. Past and current degradation of coastal habitat, critical areas and water quality due to human development, agriculture, and habitat destruction and modification are significant barriers to recovery of salmon and shellfish stocks, and therefore a key factor impacting the Tribe's treaty-reserved resources. Climate change-related impacts to shorelines such as sea level rise, ocean acidification, erosion, and intensified weather patterns further exacerbate these issues and threaten resources and the cultural lifeways of coastal tribes.

The Tribe submits the following specific comments on the draft Critical Areas Ordinance.

Incorrect Citation to "Critical Areas" definition in Introductory Section
The Introduction of the CAO in SCC 14.24.010 provides a definition of "critical areas" but then provides a code reference (RCW 36.70A.030(6)) for 'Agricultural Land'. This citation should be corrected to RCW 36.70A.030(11).

Buffer enhancement activities allowed without standard review
Buffer enhancement activities are included in SCC 14.24.070(12-13) as activities allowed without standard review. However, the added language to subsection (12) actually makes riparian buffer enhancement activities more difficult to implement due to unnecessary requirements such as a review and approval by the Planning Director. Buffer enhancement activities include activities such as noxious weed management and installation and maintenance of native plant species. These activities should be streamlined for implementation rather than adding cumbersome procedural hurdles. As a result, **the Tribe objects** to SCC 14.24.070(12) as written, and request that SCC 14.24.070(12)(b) be removed from the code.

In addition, we request that SCC 14.24.070(12)(a) be modified to remove the first sentence, which restricts buffer enhancement activities to handheld equipment. Across Skagit County, the vast majority of riparian enhancement activities conducted by entities such as the Skagit Conservation District, the Skagit Land Trust, the USFS, the Tribes, and others includes the use of a dingo-mounted auger and tractors for mowing between rows of installed trees until the trees are tall enough to shade competing grasses. The dingo-mounted auger is essential for the mental and physical well-being of the staff and volunteers who complete this work, as handheld augers result in high rates of injury and job dissatisfaction. Without this tool, the work becomes untenable. Tractor mowing planting areas is a mechanical management tool to control competing and/or non-native species and limits the use of sprayed herbicides that can achieve similar results. Tractor mowing is much preferred and without the ability to use this tool, the proposed code changes limit the ability to accomplish this work.

Skagit County's own BAS review[1] demonstrates the importance of healthy, functioning buffers to key critical areas, including wetlands, geologic hazard areas, and fish and wildlife habitat conservation areas. The BAS review recommends that the County "Promote buffers of adequate width to support wildlife guilds in adjacent habitat" (Ficetola et al. 2008; Semlitsch and Bodie 2003; Crawford and Semlitsch 2007), and to encourage stewardship on a parcel-by-parcel and county-wide scale.

Further, the Gap Analysis[2] provides a clear recommendation to the County for this section of code. The Gap Analysis suggests that the County "incentivize restoration and reduce potential permitting barriers". This special consideration for enhancement of fish and wildlife habitat conservation areas is directed by the Growth Management Act directly in RCW 36.70A.172(1), which states that: "counties shall give special consideration to conservation or protection measures necessary to preserve or enhance anadromous fisheries".

The Tribe objects to SCC 14.24.070(12) as currently drafted. We request that SCC 14.24.070(12)(b) be removed altogether, and substitute language suggested in the Gap Analysis that allows buffer enhancement without review "as long as the project is consistent with the chapter and does not harm critical areas or their buffers." We request that SCC 14.24.070(12)(a) be modified to remove the first sentence, which restricts enhancement activities to handheld equipment. We do not support the threshold of a 500 square foot riparian enhancement area being the threshold for no review as recommended in the Gap Analysis, since there is no basis for this limitation and the Standard Buffer Widths table in SCC 14.24.530.(1)(c), which includes buffer widths of 100-200 feet. Limiting a "no review" threshold to enhancement areas of 500 square feet or less would result in riparian buffer enhancement activities being only allowed on 2.5 to 5 feet of stream length without Director review, which is unreasonable and useless. This places an unnecessary review burden on projects intended to achieve meaningful riparian function. Any minimum threshold for projects that would not require Director review should be consistent with the chapter and ensure the project does not harm critical areas or their buffers.

Inconsistent Functions and Values of FWHCAs in Agricultural Lands Must be Corrected
The stated intent of the Ongoing Agriculture section (SCC 14.24.120) includes protection of Fish and Wildlife Habitat Conservation Areas ("FWHCAs") adjacent to watercourses. First, this excludes a number of FWHCAs described in SCC 14.24.500.1(a)-(l) that receive consideration in the current Skagit County critical areas code. The language in SCC 14.24.120 must be revised to be inclusive of all FWHCAs.

Further, SCC 14.24.120(1)(a) provides an incomplete list of the values and functions that are relevant to the Ongoing Agriculture section. It is unclear why the functions and values of interest in Agricultural Lands is limited to water quality, large woody debris, buffers characteristics and shade, and channel morphology, but in the FWHCAs other functions and values are included, such as bank integrity, runoff pollutant removal, wildlife habitat, microclimate, and nutrient input. These must be evaluated consistently. As a result, SCC 14.24.120(1)(a) must be revised to align and be consistent with the functions and values of other FWHCAs.

Critical Areas Report Requirements Confuse Existing and New Impacts
The drafted language for SCC 14.24.080(5)(c)(iv) requires that a critical areas report must include "an assessment of the probable direct and indirect impacts to the critical area(s) and buffer(s) as well as the cumulative impacts to the critical area resulting from the existing and proposed development." This inappropriately lumps existing impacts together with new impacts, which will create confusion and difficulty in assessing the impacts of a development under review. The existing impacts must be detailed and assessed separate from the proposed development and anticipated impacts that would not occur but for its approval and implementation.

Under SEPA rules, threshold determinations and probable adverse impacts of a proposed action are considered. If impacts from the proposed action are comingled with the impacts of the existing developments, there is no way to qualitatively or quantitively understand the scope and magnitude of the impacts of each action, make a threshold determination, or to establish appropriate mitigation for the proposed action. To address this concern, we recommend that SCC 14.24.080(5)(c)(iv) be reworded to read: "an assessment of the probable direct and indirect impacts to the critical area(s) and buffer(s) resulting from the proposed development; and, an assessment of the cumulative impacts to the critical area resulting from the existing and proposed development".

Critical Areas Report Language Consistence
SCC 14.24.080.5(b) requires that the critical area report 'must be completed as follows', but then the subsequent bullets all refer to a "site assessment". We suggest replacing "site assessment" with "critical areas report" for clarity and consistency.

PCA Tract Ownership Unnecessarily Restricted

Development proposals proximal to critical areas may result in the designation of a Protected Critical Area (PCA), in some cases resulting in the PCA being placed in a separate ownership tract (SCC 14.24.090(5)(b). The code specifies that ownership may then be "transferred to the County, homeowners' association, or land trust." A tract may be a fully separate parcel (RCW 84.04.130). This drafted language specificity undermines the rights of a property owner to select the best or most financially advantageous owner for their PCA tract. There are other options for PCA ownership that are not listed, such as a Tribal government, an electrical utility, an adjacent City, or an interested neighbor. It is unfair and without any basis to limit the financial options and personal interests of the property owner of the PCA to just these specific ownership scenarios. The essential component of any ownership of a PCA must be to uphold the terms and conditions of the PCA agreement, and it is unnecessary for the County to weigh in on any other relationship. If the County feels strongly about providing example ownership arrangements within this code, we suggest adding the language "for example" or "such as."

Inconsistent Use of FWHCA and HCA throughout CAO

There is a mix of references to Fish and Wildlife Habitat Conservation Areas, Fish and Wildlife HCAs, FWHCAs, and simply HCAs. All are used interchangeably. For accuracy and consistency, these are not all interchangeable. The Tribe has particular concern about referring simply to a 'HCA'. This section should be revised for consistency and accuracy.

Incomplete Critical Areas Report Evaluation Procedures, Failure to Require Completeness and Accuracy

In SCC 14.24.100, there is no description of how or on what criteria Skagit County might review a completed Critical Areas Report or how and on what basis the County might make its determination of approval or disapproval. These are fundamental components that are simply missing. There is also no assurance that an interested party can submit best science and technical information into the record where a critical areas report is incomplete. There should be a statement that the County will review "**the critical areas assessment report for completeness and accuracy using best available science and shall consider the recommendations and conclusions of the critical areas assessment report, and other credible technical information submitted to the record by an interested party, to assist the County in making administrative decisions concerning approval, conditional approval, or denial of the subject project and to resolve issues concerning critical areas jurisdiction and appropriate mitigation and protective measures."** Without this type of statement, there is no regulatory certainty for project proponents about how a critical areas report will be evaluated, and seemingly limits Skagit County or an interested party from asking for any changes or additions to a Critical Areas Report. This conflicts with SCC 14.24.050 which directs that the County "will utilize data from natural resource agencies as a source of best available science when reviewing sites and critical areas reports." This direction, as well as ensuring that the best science and technical information can submitted to the record should be brought forward into SCC 14.24.100 in order to actually allow the County to utilize the best science and technical information submitted to the record from natural resources agencies and interested parties.[3] Only then can critical areas be assured complete and accurate protection.

Obsolete Reference to Rescinded Permit Programmatic

SCC 14.24.120(4)(d) refers to the Tidegate-Fish Initiative, which was an agreement signed by participating Drainage, Diking and Irrigation Districts, Western Washington Agriculture Association (WWAA), the Washington Department of Fish and Wildlife (WDFW), the National Marine Fisheries Service (NMFS), and the US Fish and Wildlife Service (USFWS). The intent of the agreement was to provide delta-wide coverage for districts to comply with federal permitting through the US Army Corps of Engineers (USACE), comply ESA consultation requirements, and ensure estuary habitat restoration occurred in the Skagit and Samish deltas at a pace to help achieve Skagit Chinook Recovery Plan habitat goals. In 2010 a supporting ESA Section 7 biological opinion was written and signed by NMFS. The programmatic permit coverage through the USACE was revoked in 2021. Districts are in negotiations to develop a new program for regulatory permit coverage, but none is in place at this time. Meanwhile, tidegates are being federally permitted on an individual basis. Please remove the reference to the "Tidegate Fish Initiative".

Issuance of a Reasonable Use Exception Must Result in No Net Loss of Critical Areas
An essential criteria for approval of a Reasonable Use Exception (RUE) is that the proposed development results in No Net Loss of Critical Areas ecological functions and values. Proposed language in SCC 14.24.140(6) describes the Decision Criteria, and the No Net Loss requirement must be clearly stated as a requirement of RUE approval. The provided language includes statements like "limiting disturbance", "less impact" on critical areas, "minimize impacts to priority habitats and species". But when it comes to mitigating for all remaining impacts, this is only indirectly required in the Review Criteria. **Unless and until an REU proposal can fully demonstrate that it will achieve no net loss through avoidance, minimization or mitigation (in that order as required by WAC 197-11-768) of any impacts to the critical area then the RUE cannot be granted.**

Further, SCC 14.24.140(6)(a) limits the consideration to "impacts on wetlands, fish and wildlife habitat conservation areas, or buffers", but the County must consider all critical areas and their buffers (wetlands, CARAs, FFAs, geologically hazardous areas, and FWHCAs) for RUE proposals to achieve the no net loss standard.
The Gap Analysis is in agreement with this concern, stating on page 14 that, "we recommend that the reasonable use exception require no net loss of ecological function." Since "No Net Loss" of ecological functions and values is an essential requirement of the CAO, we believe that this criteria should be explicit in the Review Criteria, and request its inclusion at SCC 14.24.140(6)(e).

Variance Requirements Relation to RUE Application
SCC 14.24.150(3) describes the elements of Hearing Examiner (HE) decision making for a Variance request. All elements (a)-(g) must have an HE finding, and as such, the word "and" needs to be added at the end of (f) to make it clear that (a)-(g) each require the finding.

Protected Critical Areas and Density Area Calculations
For "Protected Critical Areas (PCA) Designations for New Land Divisions" under SCC 14.24.090(5)(a), the drafted code indicates that the "Areas within a PCA can be included in the total acreage for development purposes and may be used in lot area or density calculations."

And under SCC 14.24.190(1)(c) the County proposes a Density Credit for residential uses from the area of the property containing the critical area to areas without critical areas, provided that this "does not create a density greater than that allowed under SCC 14.18.310(2)". We are concerned that this added statement is overly focused on Conservation and Reserve Development (CaRD) lots but ignores densities on other types of lots.

SCC 14.18.310(2) describes the allowable densities for "Maximum Residential Densities with a CaRD" and provides some limited exceptions regarding septic and water requirements. However, this should also include the general residential densities across zoning types which are described in SCC 14.16.030. Any increase in density must ensure that it has a legally allowable and adequate source of water. This language should be revised to read "Does not create a density greater than that allowed under SCC 14.18.310(2) or SCC 14.16.030".

Measures to Minimize Land Use Impacts Must Result in No Net Loss
High intensity land uses may need a broad buffer to protect the functions and values of wetlands. Examples of high intensity land uses are described in Table 8C-3 (Appendix 8-C of modified Ecology Publication 05-06-008[4]) include commercial, industrial, dense residential, and dairies. The drafted code language suggests in SCC 14.24.230(1)(d) that a high impact land use may apply moderate impact land use buffers if "measures to minimize impacts to wetlands from high impact land uses are implemented." But **this is not what the Best Available Science indicates**.

The BAS resource "Department of Ecology Publication No. 05-06-008, Wetlands in Washington State, Volume 2" – already cited in the proposed code – provides "Special Conditions for a Possible Reduction in Buffer Widths". The buffer reductions suggested in the draft language **must result in no net loss**. The BAS[5] suggesting the possibility for a buffer reduction based on land use states that:

> ***Condition 1: Reduction in Buffer Width Based on Reducing the Intensity of Impacts from Proposed Land Uses***
> *The buffer widths recommended for proposed land uses with high-intensity impacts to wetlands can be reduced to those recommended for moderate-intensity impacts under the following conditions:*
> 1) *For wetlands that score moderate or high for habitat (6 points or more for the habitat functions), the width of the buffer can be reduced if both of the following criteria are met:*
>   a. *A relatively undisturbed, vegetated corridor at least 100-feet wide is protected between the wetland and any other Priority Habitats as defined by the Washington State Department of Fish and Wildlife. The latest definitions of priority habitats and their locations are available on the WDFW web site at: http://wdfw.wa.gov/hab/phshabs.htm). The corridor must be protected for the entire distance between the wetland and the Priority Habitat by some type of legal protection such as a conservation easement.*
> 2) *Measures to minimize the impacts of different land uses on wetlands, such as the examples summarized in Table 8C-8, are applied. For wetlands that score less than 6 points for habitat, the buffer width can be reduced to that required for moderate land-use impacts by applying measures to minimize the impacts of the proposed land uses (see examples in Table 8C-8).*

The essential component when considering a reduction in the buffer widths based upon land use is the no net loss requirement for impacts to habitat functions and values. This section must be revised to refer more directly to the wetland guidance language in its entirety, and to specify that any "measures to minimize impacts" must be evaluated to ensure that they will fully achieve no net loss to habitat functions and values.

Forage Fish are indicators of Fish and Wildlife Habitat Conservation Area
The CAO fails to designate forage fish spawning areas as a FWHCA. This is counter to the BAS, does not adopt the Gap Analysis recommendations, and is conflict with WAC and RCW.

The Gap Analysis (p. 22) acknowledged the role of sand lance and other common forage fish, stating "we recommend including other forage fish spawning areas to maintain consistency with the GMA and provide protection for these habitats." Further, WAC 365-190-130(2)(d) requires that in addition to herring and smelt spawning areas, other forage fish spawning areas must be considered for classification and designation. Because of the requirement in RCW 36.70A.172(1) where "counties shall give special consideration to conservation or protection measures necessary to preserve or enhance anadromous fisheries", and because of the role of forage fish in supporting the marine foodweb, which supports ESA-threatened anadromous fish as well as ESA-endangered Southern Resident Killer Whales, the language in SCC 14.24.500 must be revised to designate "forage fish spawning areas" as a critical area.

FWHCA Water Type Classifications Mis-Represent State Criteria
The FWHCA regulations provide an overview of the Type S, F, Ns, Np stream classification structure and refer to WAC 222-16-030. Unfortunately, the summary statements about each stream type used in the draft SCC fail to capture details that are essential to appropriate application of the stream types. The Tribe is seriously concerned the lack of clarity in the Draft CAO will lead to mis-application of rules and protections as written.

These stream classifications are ubiquitous across state[6][7], and even Federal[8] regulations. However, the language shown in draft SCC 14.24.510 does not represent the factual use of those classifications for Type S, F, Ns, Np streams. For Type S, the definition is for 20 cubic feet per second (cfs) of mean annual flow and not 'averaging'. Additionally, WAC 222-16-030 states that Type S waters include associated wetlands. This detail is important because many Type S waters contain abundant floodplain off-channel wetlands that provide critical habitat functions for salmon and other wildlife.

Much more concerning, however, is the description for the Type F stream. The WAC is referenced in SCC 14.24.510, but in practice, the Department of Natural Resources (DNR) implements the rule using the Forest Practices Board Manual, which directs that:

> **"Waters meeting the physical characteristics for Type F streams described in this rule are presumed to have fish use unless a protocol survey or ID Team has verified otherwise."**[9]

The methods for determining fish use commonly understood across natural resources specialists and are delineated in the Forest Practices Board Manual 13[10], which essentially presumes fish presence if the stream meets the physical criteria unless proven otherwise. The description in the SCC for Type F waters is concerning, because the WAC reference does not include important DNR Board Manual Methodology and DNR Policies that are essential to the application of the WAC. Experience indicates that a lay audience is not very good at assessing fish use, and this must not be left to property owners, or even consultants who visit the site at a single moment in time. In particular, anadromous fish deserve special consideration by the County under RCW 36.70A.172(1), and so are defined by their migratory life history. One observation of a lack of fish presence absolutely does not indicate that a stream is Type N.

In addition, in the coming weeks (June 6, 2025) the Forest Practices Board is expected to vote to ratify a permanent water typing rule[11] containing changes to the water typing system that are relevant to Skagit County code. The Tribe recommends that the County delay approving changes to the CAO code until after June 6 to adequately incorporate the expected changes to WAC 222-16-030.

Several important changes to this rule are expected that are relevant to County FWHCA:

- A new section of WAC is expected to be added (222-16-0301) 'Verification of fish habitat and break between Type F and Type N water'. In this section, a new component of the water typing system is established that is highly relevant to county regulations. The new component is called the Anadromous Fish Floor (AFF), which is a portion of the landscape that is assumed to contain fish whether or not fish are present on any particular day. Low gradient streams, wetlands and sloughs may provide important habitat for salmon even if salmon are not present during the typical water typing survey window. The AFF provides regulatory certainty for landowners by defining where protocol water typing surveys and default physical criteria for fish habitat may be utilized. The Tribe urges the County to incorporate this important concept into the CAO to reduce the chances of erroneously missing fish habitat.
- The new water typing system, including delineation of the AFF and implementation of field-based water typing surveys, will rely on a new Board Manual (section 23) for technical guidance. The Tribe recommends that the County require use of Board Manual 23 for determining water types.
- The new rule codifies the inclusion of off-channel habitat as Type F water. Off-channel habitats form important rearing areas for threatened and other species and must be protected as critical components of Type F water. If the county chooses to repeat water typing definitions from 222-30-30, important details such as off-channel habitat should not be neglected.

Additionally, it is our understanding that Skagit County Forest Advisory Board (FAB) Chair has submitted comments in support of these proposed water typing rule changes on behalf of Skagit County[12]. The Tribe suggests coordinating with FAB to ensure current references are incorporated into the CAO and that the County remains consistent in its recommendations and implementation of stream water practices.

In order to address these concerns, the Tribe suggests that the SCC simply follow WAC 222-16-030 and not summarize its language. If SCC does wish to summarize, then the Draft CAO language should be revised to include the important role of wetlands in Type F waters and emphasize the guidance which evaluates a stream's physical characteristics for the Type F designation.

BAS for Riparian Areas is Incomplete

The BAS document[13] provided as a companion to this CAO update refers frequently to the WDFW guidance Riparian Ecosystems, Volume 2: Management Recommendations, compiled by Terra Rentz, et al. This document uses this citation (Rentz et al. 2020) in at least 7 locations. The Gap Analysis puts forward recommendations made in this document. But the WDFW Vol. 2 document – nor the WDFW Volume 1 Riparian Ecosystems that is peer-reviewed best science on riparian habitat buffer widths - are not included in the References list of the BAS that begins on page 59. The Tribe requests that these important technical documents are incorporated into the Best Available Science for the Critical Areas update and included in the Reference list of the BAS.

Proposed Buffers on Streams Do Not Follow BAS

The draft language in SCC 14.24.530.(1)(c) describe the Standard Buffer Widths proposed by the County in this CAO update, but these widths do not represent the best available science on the topic. Seeing that many of the waterbodies that these codes would be applied to are essential spawning, migration, or rearing habitat for anadromous fish, the County must give special consideration to conservation or protection measures necessary for these habitats (RCW 36.70A.172(1)).

As the BAS review describes, WDFW guidance[14] describes a shift from stream buffers to riparian management zones (RMZ) and recommends the RMZ is regulated as a FWHCA to protect its fundamental value, rather than as a buffer for a river or stream. Buffers do not provide full riparian function or a close approximation of it. Rather, WDFW recommends that "RMZs be considered a delineable, regulatory critical area and the guidance be applied to all streams and rivers, regardless of size and type." The WDFW recommendations provide a web-based mapping tool[15] for determining the site potential tree height for a given locale. Importantly, the WDFW recommends that the RMZ width is measured from the outer edge of the channel migration zone (if present) or the ordinary high-water mark, whichever is most landward.

The Tribe objects to the approach to riparian zone delineation that the Draft CAO has proposed because it provides sub-standard conservation and protection for streams associated with anadromous salmon. The Tribe recommends that the County revise its CAO to fully incorporate the WDFW recommendations for RMZs.

Buffer Width Enhancement Should Address Sub-standard Buffer Conditions

In SCC 14.24.530(1)(c)(i), the Draft CAO states that a "Standard Riparian Buffer Width" presumes that the buffer is in good and functioning condition, and provides performance standards for determining eligibility for a standard buffer width. The Draft CAO also indicates that if the existing buffer does not presently meet the performance standards in that item, that enhancement and/or increased width must be required. This is an important opportunity to codify that buffer width increase, and should be incorporated into SCC 14.24.540 by adding SCC 14.24.540(1)(c) and describes that scenario presented in SCC 14.24.530(1)(c)(i).

Summary and Conclusion

The Swinomish Tribe has identified numerous objections and concerns primarily because of inconsistent, confusing language and the County's failure to meet its obligation to give special consideration to conservation or protection measures necessary to preserve or enhance anadromous fisheries. The Tribe strongly urges Skagit County to incorporate the suggested revisions in order to meet its legal and moral obligations to protect and enhance the vast critical areas within the Skagit County boundary.

Thank you for consideration of our comments.

Sincerely,



Heather Spore, Environmental Policy Manager
Swinomish Indian Tribal Community

Cc: Angela.SanFilippo@commerce.wa.gov

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[1]https://www.skagitcounty.net/PlanningAndPermit/Documents/compplan2025/Skagit%20County%20BAS%202.24.2025%20-%20FINAL.pdf

[2]https://www.skagitcounty.net/PlanningAndPermit/Documents/compplan2025/Skagit%20CAO%20Gap%20Analysis%202025.02%20-%20FINAL.pdf

[3] If this agency data exists, and is accepted as the best available science, but was excluded from the Critical Areas Report, the County needs a means to ensure that data is brought to the proposal and assessment to ensure protection of critical areas and safety. For example, if an applicant proposes a development on an unstable slope, but the Critical Areas Report fails to utilize available information from DNR Landslide Mapping that demonstrates a potential risk, the County or an interested party should be able to review and determine a need for further assessment.

[4] Washington Department of Ecology (ECY). (2018). Appendix 8-C: Guidance on buffers and ratios for Western Washington wetlands in Washington State volume 2 – Protecting and managing wetlands. https://apps.ecology.wa.gov/publications/parts/0506008part3.pdf

[5] Washington Department of Ecology (ECY). (2018). Appendix 8-C: Guidance on buffers and ratios for Western Washington wetlands in Washington State volume 2 – Protecting and managing wetlands. https://apps.ecology.wa.gov/publications/parts/0506008part3.pdf

[6] https://app.leg.wa.gov/waC/default.aspx?cite=222-16-030

[7] https://app.leg.wa.gov/WAC/default.aspx/default.aspx?cite=220-660

[8] https://ecology.wa.gov/getattachment/56d82d6b-5a68-411e-97d5-5a432aec30c1/NFIP_Puget-Sound_Biological_Opinion_w_Errata_2008.pdf in Appendix 4

[9] https://www.dnr.wa.gov/forest-practices-water-typing#:~:text=Type%20%22F%22%20%3D%20Fish,may%20be%20perennial%20or%20seasonal.
[10] https://www.dnr.wa.gov/publications/fp_board_manual_section13.pdf
[11] https://www.dnr.wa.gov/publications/bc_fpb_wts_rm_20250514.pdf
[12] https://www.dnr.wa.gov/publications/bc_fpb_wts_rm_20250514.pdf
[13]https://www.skagitcounty.net/PlanningAndPermit/Documents/compplan2025/Skagit%20County%20BAS%202.24.2025%20-%20FINAL.pdf
[14] Rentz, R., A. Windrope, K. Folkerts, and J. Azerrad. 2020. Riparian Ecosystems, Volume 2: Management Recommendations. Habitat Program, Washington Department of Fish and Wildlife, Olympia. 80 pp
[15] https://wdfw.maps.arcgis.com/apps/MapJournal/index.html?appid=35b39e40a2af447b9556ef1314a5622d

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Swinomish Indian Tribal Community

A Federally Recognized Indian Tribe Organized Pursuant to 25 U.S.C. § 476
* 11404 Moorage Way * La Conner, Washington 98257 *

May 8, 2025

Robby Eckroth, Senior Planner
Skagit County Planning and Development Services
1800 Continental Place
Mount Vernon, Washington 98273

Sent electronically via email to: pdscomments@co.skagit.wa.us

RE: Skagit County Critical Areas Ordinance Open for Public Comment

Dear Mr. Eckroth,

The Swinomish Indian Tribal Community ("Swinomish Tribe" or the "Tribe") is submitting these comments on the draft Skagit County Critical Areas Ordinance ("Draft CAO") that will be included as part of the County's 2025 Comprehensive Plan update. In summary, the Swinomish Tribe has numerous concerns and objections with the Draft CAO because it is inconsistent, confusing and fails to meet the County's obligation to give special consideration to conservation and protection measures necessary to preserve or enhance anadromous fisheries.

Background and setting for our objections and concerns

The Swinomish Indian Tribal Community is a federally recognized Indian tribe and political successor in interest to certain tribes and bands that signed the 1855 Treaty of Point Elliott, which among other things reserved fishing, hunting and gathering rights and established the Swinomish Reservation on Fidalgo Island in Skagit County, Washington. The Swinomish Reservation sits at the mouth of the Skagit River, the largest river system draining to Puget Sound and the only river in the Lower 48 states that still has all species of wild Pacific salmon and steelhead spawning in its waters. Since time immemorial, the Swinomish Tribe and its predecessors have occupied and utilized vast areas of land and water in the northern Salish Sea up to the Canadian border to support the Swinomish Tribe's cultural and traditional lifeways.

Swinomish is the primary guardian of the Skagit and Samish River basins and surrounding coastal areas. The Tribe is and adjudicated co-manager of Washington fisheries along with the

Washington Department of Fish and Wildlife (WDFW) and have worked with WDFW and NOAA Fisheries for decades in this capacity to ensure protection and restoration of fishery resources in the Skagit and Samish basins, as well as shellfish resources in Washington's coastal zone. Coastal zones and critical areas serve as vital nursery grounds, feeding areas, and migration routes for salmon and steelhead, including ESA-listed stocks. Past and current degradation of coastal habitat, critical areas and water quality due to human development, agriculture, and habitat destruction and modification are significant barriers to recovery of salmon and shellfish stocks, and therefore a key factor impacting the Tribe's treaty-reserved resources. Climate change-related impacts to shorelines such as sea level rise, ocean acidification, erosion, and intensified weather patterns further exacerbate these issues and threaten resources and the cultural lifeways of coastal tribes.

The Tribe submits the following specific comments on the draft Critical Areas Ordinance.

Incorrect Citation to "Critical Areas" definition in Introductory Section
The Introduction of the CAO in SCC 14.24.010 provides a definition of "critical areas" but then provides a code reference (RCW 36.70A.030(6)) for 'Agricultural Land'. This citation should be corrected to RCW 36.70A.030(11).

Buffer enhancement activities allowed without standard review
Buffer enhancement activities are included in SCC 14.24.070(12-13) as activities allowed without standard review. However, the added language to subsection (12) actually makes riparian buffer enhancement activities more difficult to implement due to unnecessary requirements such as a review and approval by the Planning Director. Buffer enhancement activities include activities such as noxious weed management and installation and maintenance of native plant species. These activities should be streamlined for implementation rather than adding cumbersome procedural hurdles. As a result, **the Tribe objects** to SCC 14.24.070(12) as written, and request that SCC 14.24.070(12)(b) be removed from the code.

In addition, we request that SCC 14.24.070(12)(a) be modified to remove the first sentence, which restricts buffer enhancement activities to handheld equipment. Across Skagit County, the vast majority of riparian enhancement activities conducted by entities such as the Skagit Conservation District, the Skagit Land Trust, the USFS, the Tribes, and others includes the use of a dingo-mounted auger and tractors for mowing between rows of installed trees until the trees are tall enough to shade competing grasses. The dingo-mounted auger is essential for the mental and physical well-being of the staff and volunteers who complete this work, as handheld augers result in high rates of injury and job dissatisfaction. Without this tool, the work becomes untenable. Tractor mowing planting areas is a mechanical management tool to control competing and/or non-native species and limits the use of sprayed herbicides that can achieve similar

results. Tractor mowing is much preferred and without the ability to use this tool, the proposed code changes limit the ability to accomplish this work.

Skagit County's own BAS review[1] demonstrates the importance of healthy, functioning buffers to key critical areas, including wetlands, geologic hazard areas, and fish and wildlife habitat conservation areas. The BAS review recommends that the County "Promote buffers of adequate width to support wildlife guilds in adjacent habitat" (Ficetola et al. 2008; Semlitsch and Bodie 2003; Crawford and Semlitsch 2007), and to encourage stewardship on a parcel-by-parcel and county-wide scale.

Further, the Gap Analysis[2] provides a clear recommendation to the County for this section of code. The Gap Analysis suggests that the County "incentivize restoration and reduce potential permitting barriers". This special consideration for enhancement of fish and wildlife habitat conservation areas is directed by the Growth Management Act directly in RCW 36.70A.172(1), which states that: "counties shall give special consideration to conservation or protection measures necessary to preserve or enhance anadromous fisheries".

The Tribe objects to SCC 14.24.070(12) as currently drafted. We request that SCC 14.24.070(12)(b) be removed altogether, and substitute language suggested in the Gap Analysis that allows buffer enhancement without review "as long as the project is consistent with the chapter and does not harm critical areas or their buffers." We request that SCC 14.24.070(12)(a) be modified to remove the first sentence, which restricts enhancement activities to handheld equipment. We do not support the threshold of a 500 square foot riparian enhancement area being the threshold for no review as recommended in the Gap Analysis, since there is no basis for this limitation and the Standard Buffer Widths table in SCC 14.24.530.(1)(c), which includes buffer widths of 100-200 feet. Limiting a "no review" threshold to enhancement areas of 500 square feet or less would result in riparian buffer enhancement activities being only allowed on 2.5 to 5 feet of stream length without Director review, which is unreasonable and useless. This places an unnecessary review burden on projects intended to achieve meaningful riparian function. Any minimum threshold for projects that would not require Director review should be consistent with the chapter and ensure the project does not harm critical areas or their buffers.

Inconsistent Functions and Values of FWHCAs in Agricultural Lands Must be Corrected
The stated intent of the Ongoing Agriculture section (SCC 14.24.120) includes protection of Fish and Wildlife Habitat Conservation Areas ("FWHCAs") adjacent to watercourses. First, this excludes a number of FWHCAs described in SCC 14.24.500.1(a)-(l) that receive consideration

[1]https://www.skagitcounty.net/PlanningAndPermit/Documents/compplan2025/Skagit%20County%20BAS%202.24.2025%20-%20FINAL.pdf
[2]https://www.skagitcounty.net/PlanningAndPermit/Documents/compplan2025/Skagit%20CAO%20Gap%20Analysis%202025.02%20-%20FINAL.pdf

in the current Skagit County critical areas code. The language in SCC 14.24.120 must be revised to be inclusive of all FWHCAs.

Further, SCC 14.24.120(1)(a) provides an incomplete list of the values and functions that are relevant to the Ongoing Agriculture section. It is unclear why the functions and values of interest in Agricultural Lands is limited to water quality, large woody debris, buffers characteristics and shade, and channel morphology, but in the FWHCAs other functions and values are included, such as bank integrity, runoff pollutant removal, wildlife habitat, microclimate, and nutrient input. These must be evaluated consistently. As a result, SCC 14.24.120(1)(a) must be revised to align and be consistent with the functions and values of other FWHCAs.

Critical Areas Report Requirements Confuse Existing and New Impacts

The drafted language for SCC 14.24.080(5)(c)(iv) requires that a critical areas report must include "an assessment of the probable direct and indirect impacts to the critical area(s) and buffer(s) as well as the cumulative impacts to the critical area resulting from the existing and proposed development." This inappropriately lumps existing impacts together with new impacts, which will create confusion and difficulty in assessing the impacts of a development under review. The existing impacts must be detailed and assessed separate from the proposed development and anticipated impacts that would not occur but for its approval and implementation.

Under SEPA rules, threshold determinations and probable adverse impacts of a proposed action are considered. If impacts from the proposed action are comingled with the impacts of the existing developments, there is no way to qualitatively or quantitively understand the scope and magnitude of the impacts of each action, make a threshold determination, or to establish appropriate mitigation for the proposed action. To address this concern, we recommend that SCC 14.24.080(5)(c)(iv) be reworded to read: "an assessment of the probable direct and indirect impacts to the critical area(s) and buffer(s) resulting from the proposed development; and, an assessment of the cumulative impacts to the critical area resulting from the existing and proposed development".

Critical Areas Report Language Consistence

SCC 14.24.080.5(b) requires that the critical area report 'must be completed as follows', but then the subsequent bullets all refer to a "site assessment". We suggest replacing "site assessment" with "critical areas report" for clarity and consistency.

PCA Tract Ownership Unnecessarily Restricted

Development proposals proximal to critical areas may result in the designation of a Protected Critical Area (PCA), in some cases resulting in the PCA being placed in a separate ownership tract (SCC 14.24.090(5)(b). The code specifies that ownership may then be "transferred to the

County, homeowners' association, or land trust." A tract may be a fully separate parcel (RCW 84.04.130). This drafted language specificity undermines the rights of a property owner to select the best or most financially advantageous owner for their PCA tract. There are other options for PCA ownership that are not listed, such as a Tribal government, an electrical utility, an adjacent City, or an interested neighbor. It is unfair and without any basis to limit the financial options and personal interests of the property owner of the PCA to just these specific ownership scenarios. The essential component of any ownership of a PCA must be to uphold the terms and conditions of the PCA agreement, and it is unnecessary for the County to weigh in on any other relationship. If the County feels strongly about providing example ownership arrangements within this code, we suggest adding the language "for example" or "such as."

Inconsistent Use of FWHCA and HCA throughout CAO

There is a mix of references to Fish and Wildlife Habitat Conservation Areas, Fish and Wildlife HCAs, FWHCAs, and simply HCAs. All are used interchangeably. For accuracy and consistency, these are not all interchangeable. The Tribe has particular concern about referring simply to a 'HCA'. This section should be revised for consistency and accuracy.

Incomplete Critical Areas Report Evaluation Procedures, Failure to Require Completeness and Accuracy

In SCC 14.24.100, there is no description of how or on what criteria Skagit County might review a completed Critical Areas Report or how and on what basis the County might make its determination of approval or disapproval. These are fundamental components that are simply missing. There is also no assurance that an interested party can submit best science and technical information into the record where a critical areas report is incomplete. There should be a statement that the County will review "**the critical areas assessment report for completeness and accuracy using best available science and shall consider the recommendations and conclusions of the critical areas assessment report, and other credible technical information submitted to the record by an interested party, to assist the County in making administrative decisions concerning approval, conditional approval, or denial of the subject project and to resolve issues concerning critical areas jurisdiction and appropriate mitigation and protective measures."** Without this type of statement, there is no regulatory certainty for project proponents about how a critical areas report will be evaluated, and seemingly limits Skagit County or an interested party from asking for any changes or additions to a Critical Areas Report. This conflicts with SCC 14.24.050 which directs that the County "will utilize data from natural resource agencies as a source of best available science when reviewing sites and critical areas reports." This direction, as well as ensuring that the best science and technical information can submitted to the record should be brought forward into SCC 14.24.100 in order to actually allow the County to utilize the best science and technical information

submitted to the record from natural resources agencies and interested parties.[3] Only then can critical areas be assured complete and accurate protection.

Obsolete Reference to Rescinded Permit Programmatic

SCC 14.24.120(4)(d) refers to the Tidegate-Fish Initiative, which was an agreement signed by participating Drainage, Diking and Irrigation Districts, Western Washington Agriculture Association (WWAA), the Washington Department of Fish and Wildlife (WDFW), the National Marine Fisheries Service (NMFS), and the US Fish and Wildlife Service (USFWS). The intent of the agreement was to provide delta-wide coverage for districts to comply with federal permitting through the US Army Corps of Engineers (USACE), comply ESA consultation requirements, and ensure estuary habitat restoration occurred in the Skagit and Samish deltas at a pace to help achieve Skagit Chinook Recovery Plan habitat goals. In 2010 a supporting ESA Section 7 biological opinion was written and signed by NMFS. The programmatic permit coverage through the USACE was revoked in 2021. Districts are in negotiations to develop a new program for regulatory permit coverage, but none is in place at this time. Meanwhile, tidegates are being federally permitted on an individual basis. Please remove the reference to the "Tidegate Fish Initiative".

Issuance of a Reasonable Use Exception Must Result in No Net Loss of Critical Areas

An essential criteria for approval of a Reasonable Use Exception (RUE) is that the proposed development results in No Net Loss of Critical Areas ecological functions and values. Proposed language in SCC 14.24.140(6) describes the Decision Criteria, and the No Net Loss requirement must be clearly stated as a requirement of RUE approval. The provided language includes statements like "limiting disturbance", "less impact" on critical areas, "minimize impacts to priority habitats and species". But when it comes to mitigating for all remaining impacts, this is only indirectly required in the Review Criteria. **Unless and until an REU proposal can fully demonstrate that it will achieve no net loss through avoidance, minimization or mitigation (in that order as required by WAC 197-11-768) of any impacts to the critical area then the RUE cannot be granted.**

Further, SCC 14.24.140(6)(a) limits the consideration to "impacts on wetlands, fish and wildlife habitat conservation areas, or buffers", but the County must consider <u>all</u> critical areas and their buffers (wetlands, CARAs, FFAs, geologically hazardous areas, and FWHCAs) for RUE proposals to achieve the no net loss standard.

[3] If this agency data exists, and is accepted as the best available science, but was excluded from the Critical Areas Report, the County needs a means to ensure that data is brought to the proposal and assessment to ensure protection of critical areas and safety. For example, if an applicant proposes a development on an unstable slope, but the Critical Areas Report fails to utilize available information from DNR Landslide Mapping that demonstrates a potential risk, the County or an interested party should be able to review and determine a need for further assessment.

The Gap Analysis is in agreement with this concern, stating on page 14 that, "we recommend that the reasonable use exception require no net loss of ecological function." Since "No Net Loss" of ecological functions and values is an essential requirement of the CAO, we believe that this criteria should be explicit in the Review Criteria, and request its inclusion at SCC 14.24.140(6)(e).

Variance Requirements Relation to RUE Application

SCC 14.24.150(3) describes the elements of Hearing Examiner (HE) decision making for a Variance request. All elements (a)-(g) must have an HE finding, and as such, the word "and" needs to be added at the end of (f) to make it clear that (a)-(g) each require the finding.

Protected Critical Areas and Density Area Calculations

For "Protected Critical Areas (PCA) Designations for New Land Divisions" under SCC 14.24.090(5)(a), the drafted code indicates that the "Areas within a PCA can be included in the total acreage for development purposes and may be used in lot area or density calculations."

And under SCC 14.24.190(1)(c) the County proposes a Density Credit for residential uses from the area of the property containing the critical area to areas without critical areas, provided that this "does not create a density greater than that allowed under SCC 14.18.310(2)". We are concerned that this added statement is overly focused on Conservation and Reserve Development (CaRD) lots but ignores densities on other types of lots.

SCC 14.18.310(2) describes the allowable densities for "Maximum Residential Densities with a CaRD" and provides some limited exceptions regarding septic and water requirements. However, this should also include the general residential densities across zoning types which are described in SCC 14.16.030. Any increase in density must ensure that it has a legally allowable and adequate source of water. This language should be revised to read "Does not create a density greater than that allowed under SCC 14.18.310(2) or SCC 14.16.030".

Measures to Minimize Land Use Impacts Must Result in No Net Loss

High intensity land uses may need a broad buffer to protect the functions and values of wetlands. Examples of high intensity land uses are described in Table 8C-3 (Appendix 8-C of modified Ecology Publication 05-06-008[4]) include commercial, industrial, dense residential, and dairies. The drafted code language suggests in SCC 14.24.230(1)(d) that a high impact land use may apply moderate impact land use buffers if "measures to minimize impacts to wetlands from high impact land uses are implemented." But **this is not what the Best Available Science indicates**.

[4] Washington Department of Ecology (ECY). (2018). Appendix 8-C: Guidance on buffers and ratios for Western Washington wetlands in Washington State volume 2 – Protecting and managing wetlands. https://apps.ecology.wa.gov/publications/parts/0506008part3.pdf

The BAS resource "Department of Ecology Publication No. 05-06-008, Wetlands in Washington State, Volume 2" – already cited in the proposed code – provides "Special Conditions for a Possible Reduction in Buffer Widths". The buffer reductions suggested in the draft language **must result in no net loss**. The BAS[5] suggesting the possibility for a buffer reduction based on land use states that:

> ***Condition 1: Reduction in Buffer Width Based on Reducing the Intensity of Impacts from Proposed Land Uses***
> *The buffer widths recommended for proposed land uses with high-intensity impacts to wetlands can be reduced to those recommended for moderate-intensity impacts under the following conditions:*
>
> 1) *For wetlands that score moderate or high for habitat (6 points or more for the habitat functions), the width of the buffer can be reduced if both of the following criteria are met:*
>   a. *A relatively undisturbed, vegetated corridor at least 100-feet wide is protected between the wetland and any other Priority Habitats as defined by the Washington State Department of Fish and Wildlife. The latest definitions of priority habitats and their locations are available on the WDFW web site at: http://wdfw.wa.gov/hab/phshabs.htm). The corridor must be protected for the entire distance between the wetland and the Priority Habitat by some type of legal protection such as a conservation easement.*
> 2) *Measures to minimize the impacts of different land uses on wetlands, such as the examples summarized in Table 8C-8, are applied. For wetlands that score less than 6 points for habitat, the buffer width can be reduced to that required for moderate land-use impacts by applying measures to minimize the impacts of the proposed land uses (see examples in Table 8C-8).*

The essential component when considering a reduction in the buffer widths based upon land use is the no net loss requirement for impacts to habitat functions and values. This section must be revised to refer more directly to the wetland guidance language in its entirety, and to specify that any "measures to minimize impacts" must be evaluated to ensure that they will fully achieve no net loss to habitat functions and values.

Forage Fish are indicators of Fish and Wildlife Habitat Conservation Area

The CAO fails to designate forage fish spawning areas as a FWHCA. This is counter to the BAS, does not adopt the Gap Analysis recommendations, and is conflict with WAC and RCW.

[5] Washington Department of Ecology (ECY). (2018). Appendix 8-C: Guidance on buffers and ratios for Western Washington wetlands in Washington State volume 2 – Protecting and managing wetlands. https://apps.ecology.wa.gov/publications/parts/0506008part3.pdf

The Gap Analysis (p. 22) acknowledged the role of sand lance and other common forage fish, stating "we recommend including other forage fish spawning areas to maintain consistency with the GMA and provide protection for these habitats." Further, WAC 365-190-130(2)(d) requires that in addition to herring and smelt spawning areas, other forage fish spawning areas must be considered for classification and designation. Because of the requirement in RCW 36.70A.172(1) where "counties shall give special consideration to conservation or protection measures necessary to preserve or enhance anadromous fisheries", and because of the role of forage fish in supporting the marine foodweb, which supports ESA-threatened anadromous fish as well as ESA-endangered Southern Resident Killer Whales, the language in SCC 14.24.500 must be revised to designate "forage fish spawning areas" as a critical area.

FWHCA Water Type Classifications Mis-Represent State Criteria

The FWHCA regulations provide an overview of the Type S, F, Ns, Np stream classification structure and refer to WAC 222-16-030. Unfortunately, the summary statements about each stream type used in the draft SCC fail to capture details that are essential to appropriate application of the stream types. The Tribe is seriously concerned the lack of clarity in the Draft CAO will lead to mis-application of rules and protections as written.

These stream classifications are ubiquitous across state[6][7], and even Federal[8] regulations. However, the language shown in draft SCC 14.24.510 does not represent the factual use of those classifications for Type S, F, Ns, Np streams. For Type S, the definition is for 20 cubic feet per second (cfs) of mean annual flow and not 'averaging'. Additionally, WAC 222-16-030 states that Type S waters include associated wetlands. This detail is important because many Type S waters contain abundant floodplain off-channel wetlands that provide critical habitat functions for salmon and other wildlife.

Much more concerning, however, is the description for the Type F stream. The WAC is referenced in SCC 14.24.510, but in practice, the Department of Natural Resources (DNR) implements the rule using the Forest Practices Board Manual, which directs that:

> **"Waters meeting the physical characteristics for Type F streams described in this rule are presumed to have fish use unless a protocol survey or ID Team has verified otherwise."**[9]

[6] https://app.leg.wa.gov/waC/default.aspx?cite=222-16-030
[7] https://app.leg.wa.gov/WAC/default.aspx/default.aspx?cite=220-660
[8] https://ecology.wa.gov/getattachment/56d82d6b-5a68-411e-97d5-5a432aec30c1/NFIP_Puget-Sound_Biological_Opinion_w_Errata_2008.pdf in Appendix 4
[9] https://www.dnr.wa.gov/forest-practices-water-typing#:~:text=Type%20%22F%22%20%3D%20Fish,may%20be%20perennial%20or%20seasonal.

The methods for determining fish use commonly understood across natural resources specialists and are delineated in the Forest Practices Board Manual 13[10], which essentially presumes fish presence if the stream meets the physical criteria unless proven otherwise. The description in the SCC for Type F waters is concerning, because the WAC reference does not include important DNR Board Manual Methodology and DNR Policies that are essential to the application of the WAC. Experience indicates that a lay audience is not very good at assessing fish use, and this must not be left to property owners, or even consultants who visit the site at a single moment in time. In particular, anadromous fish deserve special consideration by the County under RCW 36.70A.172(1), and so are defined by their migratory life history. One observation of a lack of fish presence absolutely does not indicate that a stream is Type N.

In addition, in the coming weeks (June 6, 2025) the Forest Practices Board is expected to vote to ratify a permanent water typing rule[11] containing changes to the water typing system that are relevant to Skagit County code. The Tribe recommends that the County delay approving changes to the CAO code until after June 6 to adequately incorporate the expected changes to WAC 222-16-030.

Several important changes to this rule are expected that are relevant to County FWHCA:

- A new section of WAC is expected to be added (222-16-0301) 'Verification of fish habitat and break between Type F and Type N water'. In this section, a new component of the water typing system is established that is highly relevant to county regulations. The new component is called the Anadromous Fish Floor (AFF), which is a portion of the landscape that is assumed to contain fish whether or not fish are present on any particular day. Low gradient streams, wetlands and sloughs may provide important habitat for salmon even if salmon are not present during the typical water typing survey window. The AFF provides regulatory certainty for landowners by defining where protocol water typing surveys and default physical criteria for fish habitat may be utilized. The Tribe urges the County to incorporate this important concept into the CAO to reduce the chances of erroneously missing fish habitat.
- The new water typing system, including delineation of the AFF and implementation of field-based water typing surveys, will rely on a new Board Manual (section 23) for technical guidance. The Tribe recommends that the County require use of Board Manual 23 for determining water types.
- The new rule codifies the inclusion of off-channel habitat as Type F water. Off-channel habitats form important rearing areas for threatened and other species and must be protected as critical components of Type F water. If the county chooses to

[10] https://www.dnr.wa.gov/publications/fp_board_manual_section13.pdf
[11] https://www.dnr.wa.gov/publications/bc_fpb_wts_rm_20250514.pdf

repeat water typing definitions from 222-30-30, important details such as off-channel habitat should not be neglected.

Additionally, it is our understanding that Skagit County Forest Advisory Board (FAB) Chair has submitted comments in support of these proposed water typing rule changes on behalf of Skagit County[12]. The Tribe suggests coordinating with FAB to ensure current references are incorporated into the CAO and that the County remains consistent in its recommendations and implementation of stream water practices.

In order to address these concerns, the Tribe suggests that the SCC simply follow WAC 222-16-030 and not summarize its language. If SCC does wish to summarize, then the Draft CAO language should be revised to include the important role of wetlands in Type F waters and emphasize the guidance which evaluates a stream's physical characteristics for the Type F designation.

BAS for Riparian Areas is Incomplete

The BAS document[13] provided as a companion to this CAO update refers frequently to the WDFW guidance Riparian Ecosystems, Volume 2: Management Recommendations, compiled by Terra Rentz, et al. This document uses this citation (Rentz et al. 2020) in at least 7 locations. The Gap Analysis puts forward recommendations made in this document. But the WDFW Vol. 2 document – nor the WDFW Volume 1 Riparian Ecosystems that is peer-reviewed best science on riparian habitat buffer widths - are not included in the References list of the BAS that begins on page 59. The Tribe requests that these important technical documents are incorporated into the Best Available Science for the Critical Areas update and included in the Reference list of the BAS.

Proposed Buffers on Streams Do Not Follow BAS

The draft language in SCC 14.24.530.(1)(c) describe the Standard Buffer Widths proposed by the County in this CAO update, but these widths do not represent the best available science on the topic. Seeing that many of the waterbodies that these codes would be applied to are essential spawning, migration, or rearing habitat for anadromous fish, the County must give special consideration to conservation or protection measures necessary for these habitats (RCW 36.70A.172(1)).

[12] https://www.dnr.wa.gov/publications/bc_fpb_wts_rm_20250514.pdf

[13]https://www.skagitcounty.net/PlanningAndPermit/Documents/compplan2025/Skagit%20County%20BAS%202.24.2025%20-%20FINAL.pdf

As the BAS review describes, WDFW guidance[14] describes a shift from stream buffers to riparian management zones (RMZ) and recommends the RMZ is regulated as a FWHCA to protect its fundamental value, rather than as a buffer for a river or stream. Buffers do not provide full riparian function or a close approximation of it. Rather, WDFW recommends that "RMZs be considered a delineable, regulatory critical area and the guidance be applied to all streams and rivers, regardless of size and type." The WDFW recommendations provide a web-based mapping tool[15] for determining the site potential tree height for a given locale. Importantly, the WDFW recommends that the RMZ width is measured from the outer edge of the channel migration zone (if present) or the ordinary high-water mark, whichever is most landward.

The Tribe objects to the approach to riparian zone delineation that the Draft CAO has proposed because it provides sub-standard conservation and protection for streams associated with anadromous salmon. The Tribe recommends that the County revise its CAO to fully incorporate the WDFW recommendations for RMZs.

Buffer Width Enhancement Should Address Sub-standard Buffer Conditions

In SCC 14.24.530(1)(c)(i), the Draft CAO states that a "Standard Riparian Buffer Width" presumes that the buffer is in good and functioning condition, and provides performance standards for determining eligibility for a standard buffer width. The Draft CAO also indicates that if the existing buffer does not presently meet the performance standards in that item, that enhancement and/or increased width must be required. This is an important opportunity to codify that buffer width increase, and should be incorporated into SCC 14.24.540 by adding SCC 14.24.540(1)(c) and describes that scenario presented in SCC 14.24.530(1)(c)(i).

Summary and Conclusion

The Swinomish Tribe has identified numerous objections and concerns primarily because of inconsistent, confusing language and the County's failure to meet its obligation to give special consideration to conservation or protection measures necessary to preserve or enhance anadromous fisheries. The Tribe strongly urges Skagit County to incorporate the suggested revisions in order to meet its legal and moral obligations to protect and enhance the vast critical areas within the Skagit County boundary.

Thank you for consideration of our comments.

Sincerely,



[14] Rentz, R., A. Windrope, K. Folkerts, and J. Azerrad. 2020. Riparian Ecosystems, Volume 2: Management Recommendations. Habitat Program, Washington Department of Fish and Wildlife, Olympia. 80 pp

[15] https://wdfw.maps.arcgis.com/apps/MapJournal/index.html?appid=35b39e40a2af447b9556ef1314a5622d

Heather Spore, Environmental Policy Manager
Swinomish Indian Tribal Community

Cc: Angela.SanFilippo@commerce.wa.gov

Comment #17

Robby Eckroth

From: Jan Edelstein <jmeten@comcast.net>
Sent: Thursday, May 8, 2025 2:41 PM
To: PDS comments
Cc: Robby Eckroth
Subject: CAO Update - Follow Up to Hearing - Public Comment - Edelstein
Attachments: May 8 2025 Followup - CAO Update -Stormwater Runoff to Critical Areas How would this work .pdf; Dr.HornerOpinionBigLakeDegraded.pdf

Hello Robby,

I was prompted to write this follow-up because of the questions from Planning Commissioners. Hopefully they will know that I have attempted to more completely answer those questions.

As you know, this is the second submission of the Horner opinion.

Thanks for handling this,
Jan Edelstein
208-720-0709

Skagit County Code 14.24 Critical Areas Update
Amendments Needed to Protect Critical Areas
as required by the Washington Growth Management Act

May 8, 2025

SUBMITTED BY:

Jan M. Edelstein
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RE: How would this work? Protecting Critical Areas that may be affected by land development projects – stormwater runoff, etc.

I write to provide more information in response to questions from Planning Commissioners following my public comments made at the May 6, 2025 hearing. In my written comments and oral presentation, I submit that the Code needs to be revised to require a Critical Areas site assessment for impacts to all critical areas, not just those critical areas within 200' or 300' feet of the project boundary.

1. 2025 Revision: The proposed revised text to the CAO makes clear the County's practice of limiting its review of proposed new developments' impact on critical areas to only those critical areas on-site or within 300' (wetlands) or 200' (all others) of the project's perimeter. See revised 14.24(4):
    a. Wetland indicators are present within 300 feet ….
    b. Any other critical area type described in SCC 14.24.020 is present within 200 feet of the proposed developments. If a site inspection does not indicate a critical area on or within 200 feet of the subject property, no additional critical area assessment will be required. [Emphasis added.]

2. What should happen:
    a. The Critical Areas Checklist should require the Applicant to identify the presence of any critical areas "which may be affected by the proposed activity." Distance of the critical area from the project boundary should not matter.

    b. Stormwater discharge is a typical component of land use development. The Applicant's stormwater typically identifies the volume of stormwater to be discharged from the site, the path of flow, and the receiving water. The Critical Areas Checklist should inquire specifically about the path of stormwater discharge from the site: does it pass through critical areas (perhaps wetlands), is the receiving water a critical area?

c. With this Critical Areas disclosure, the Administrator would require the Applicant to submit a critical areas site assessment "by a qualified professional." This qualified professional(s) would be expert in stormwater pollutant loading, the methods available to reduce that loading, and determining what loading remains to be discharged to the receiving water TOGETHER WITH an assessment of the current functions and values of the receiving water's aquatic habitat, and the impact of the addition of stormwater pollutants on it.

3. Example of Stormwater Impact Assessment:
To provide an example of the issues to be addressed, I attach the Opinion of Dr. Richard Horner which serves as a textbook on these issues. This Opinion goes far beyond a standard critical areas report because it was prepared for a different purpose.

Please also see PDF pages 28 – 60 for Dr. Horner's background and many research papers written.

4. It is inadequate to rely solely on SCC 14.32 Stormwater Management to protect critical areas beyond 200' from the project boundary.

a. SCC 14.32 relies on compliance with Ecology's Stormwater Management Manual.
b. SCC 14.32 does NOT require treatment be used.
c. SCC 14.32 does NOT require any testing for pollution of the stormwater to be discharged from the project, nor does it require any consideration of the impact of the pollutants in the discharged stormwater on the receiving body of water, or wetlands that it might pass through.
d. Ecology tells us that compliance with the Stormwater Manual does not make the stormwater 'clean' and that only informed land use decisions can protect receiving waters from loss of beneficial uses.[1]
    i. "Although the 'best management practices' advocated by the 2024 manual and other stormwater manuals can reduce the impacts from new development to water quality, these systems cannot remove enough pollutants to replicate the water quality of pre-development conditions", and

[1] 2024 Stormwater Management Manual for Western Washington, pg. 60.
https://apps.ecology.wa.gov/publications/documents/2410013.pdf

ii. "Despite using some or all of the practices identified in the manual, some degradation of receiving waters will continue, and some beneficial uses will continue to be impaired or lost due to new development. This is because land development, as practiced today, is incompatible with the achievement of sustainable ecosystems. Unless land use development methods are adopted that cause significantly less disruption of the hydrologic cycle, new development followed by degradation of 'swimmable, fishable' surface waters will continue."

5. Growth Management Hearings Board Precedent

The Growth Management Hearings Board, as affirmed by Court of Appeals of Washington, Division Three No. 29191-0-III in *Stevens County v. E. Wash. Growth Mgmt. Hearings Bd*.,[2] rejected a Stevens County ordinance that required only minimizing stormwater impacts. Specifically, the Board concluded:

> "Stevens County has failed to enact legislation which complies with the Growth Management Act's requirements to protect the functions and values of critical areas as set forth in RCW. 36.07A.020(10), .060(2), and .172."

In other words, only minimizing the effect of impervious surfaces and stormwater runoff on critical areas, does NOT protect critical areas.

6. Critical Area Site Assessment is essential to the Planning Approval Process

To fulfill its GMA obligations, the County should expand its requirements for Critical Area Site Assessments beyond the 300' and 200' buffers.

There are some project sites that, through a combination of slope, soils, density of proposed development and other factors, could adversely impact critical areas.

The goal of the Critical Area Site-Assessment requirement is to identify those critical areas which may be affected by the proposed activity, so those impacts can be carefully considered and addressed in the project approval process. A Critical Areas Site-Assessment by a qualified professional provides the starting point for review both by the Planning Staff and for the Public.

[2] 163 Wn. App. 680, 262 P. 3d. 507, 2011 Wash. App. Lexis 1485

Comment #18

Robby Eckroth

From: Michael Wolten <michael@sauk-suiattle.com>
Sent: Thursday, May 8, 2025 2:52 PM
To: PDS comments
Cc: Robby Eckroth
Attachments: commect letter.pdf

Mike Wolten
Policy Coordinator
Sauk-Suiattle Indian Tribe
360-913-2751

Sauk-Suiattle Natural Resources Department
5318 Chief Brown Lane
Darrington, Washington 98241-9420

(360) 436-0347

May 8, 2025

Skagit County Planning and Development Services
Attention: Robby Eckroth
sent via email, pdscomments@co.skagit.wa.us

Re: Skagit County's 2025 Comprehensive Plan

Greetings,

The Sauk-Suiattle Indian Tribe is sending this letter as its official comments for the draft update of the Critical Areas Ordinance (CAO) in Skagit County's 2025 Comprehensive Plan. Much of the Tribe's traditional homelands are within Skagit County's boundary – Sauk-Suiattle has a keen interest in protecting environmentally critical areas for the well-being of the natural resources that Tribal members rely on for sustenance and cultural values.

Incorrect Citation in Introductory Section

The Introduction of the CAO in Skagit County Code (SCC) 14.24.010 provides a definition of "critical areas" but then provides a code reference (Revised Code of Washington (RCW) 36.70A.030(6)) for 'Agricultural Land.' This citation should be corrected to RCW 36.70A.030(11).

Buffer enhancement activities allowed without standard review

Buffer enhancement activities are included in SCC 14.24.070(12-13) as activities allowed without standard review, but the added language to (12) actually make riparian buffer enhancement harder to implement with added unnecessary requirements, including a review and approval by the Planning Director. Buffer enhancement activities include activities such as noxious weed management and installation and maintenance of native plant species.

We object to SCC 14.24.070(12) as written, and request that SCC 14.24.070(12)(b) be removed from the code, and request that SCC 14.24.070(12)(a) be modified to remove the first sentence, which restricts enhancement activities to handheld equipment. Across Skagit County, the vast majority of riparian enhancement activities conducted by entities such as the Skagit Conservation District, the Skagit Land Trust, the U.S. Forest Service, Tribes, and others includes the use of a dingo-mounted auger and tractors for mowing between rows of installed trees until the trees are tall enough to shade competing grasses.

The dingo-mounted auger is essential for the mental and physical well-being of the staff and volunteers who complete this work, as handheld augers result in very high rates of injury and job dissatisfaction. Without this tool, the work becomes untenable. Tractor mowing planting areas is a mechanical management tool to control competing and/or non-native species and limits the use of sprayed herbicides that can achieve similar results. Tractor mowing is much preferred and without the ability to use this tool, the proposed code changes limit the ability to accomplish this work.

Skagit County's own Best Available Science (BAS) review[1] demonstrates the importance of buffers to wetlands, geologic hazard areas, and fish and wildlife habitat conservation areas. The BAS review recommends the County "Promote buffers of adequate width to support wildlife guilds in adjacent habitat" (Ficetola et al. 2008; Semlitsch and Bodie 2003; Crawford and Semlitsch 2007), and to encourage stewardship on a parcel by parcel and county-wide scale. Further, the Gap Analysis[2] provides a clear recommendation to the County for this section of code. The Gap Analysis suggests that the County "incentivize restoration and reduce potential permitting barriers." This special consideration for enhancement of fish and wildlife habitat conservation areas is directed by the state's Growth Management Act (GMA) in RCW 36.70A.172(1) where "counties shall give special consideration to conservation or protection measures necessary to preserve or enhance anadromous fisheries."

As currently drafted, we object to SCC 14.24.070(12). We request that SCC 14.24.070(12)(b) be removed altogether, and substitute language suggested in the Gap Analysis that allows buffer enhancement without review "as long as the project is consistent with the chapter and does not harm critical areas or their buffers." We request that SCC 14.24.070(12)(a) be modified to remove the first sentence, which restricts enhancement activities to handheld equipment. We do not support the threshold of a 500 square foot riparian enhancement area being the threshold for no review, since the Standard Buffer Widths table in SCC 14.24.530.(1)(c) includes buffer widths of 100-200 feet, resulting in riparian buffer enhancement activities being allowed with review on 2.5 to 5 feet of stream length, which is unreasonable and useless; this number should represent a reasonable and feasible reach length that is at least a standard rural reserve parcel width in length.

Functions and Values of Fish and Wildlife Habitat Conservation Areas (FWHCAs) in Agricultural Lands

The stated intent of the Ongoing Agriculture section (SCC 14.24.120) includes protection of FWHCAs adjacent to watercourses. First, this excludes a number of FWHCAs described in SCC 14.24.500.1(a)-(l) that receive consideration in the SCC critical areas code. The language in SCC 14.24.120 should be inclusive of all FWHCAs.

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[1]https://www.skagitcounty.net/PlanningAndPermit/Documents/compplan2025/Skagit%20County%20BAS%202.24.2025%20-%20FINAL.pdf

[2]https://www.skagitcounty.net/PlanningAndPermit/Documents/compplan2025/Skagit%20CAO%20Gap%20Analysis%202025.02%20-%20FINAL.pdf

Further, SCC 14.24.120(1)(a) provides a short list of values and functions that are relevant to this section on Ongoing Agriculture. It is unclear why the functions and values of interest in Agricultural Lands are limited to water quality, large woody debris, buffers characteristics and shade, and channel morphology, but in the FWHCAs other functions and values are included, such as bank integrity, runoff pollutant removal, wildlife habitat, microclimate, and nutrient input. It seems that these should be evaluated consistently. We suggest revising SCC 14.24.120(1)(a) to offer consistent functions and values as other FWHCAs.

Critical Areas Report Requirements Confuse Existing and New Impacts
The drafted language for SCC 14.24.080(5)(c)(iv) requires that a critical areas report must include "an assessment of the probable direct and indirect impacts to the critical area(s) and buffer(s) as well as the cumulative impacts to the critical area resulting from the existing and proposed development." However, this will create confusion and difficulty in assessing the impacts of a development under review since the requirement muddies the two (existing and new development) impacts together.

Under SEPA rules, threshold determinations and probable adverse impacts of a proposed action are considered. If impacts from the proposed action are comingled with the impacts of the existing developments, there is no way to quantitively tease out the impacts of the action, make a threshold determination, or establish appropriate mitigation for the proposed action. To address this concern, we recommend that SCC 14.24.080(5)(c)(iv) be reworded to read: "an assessment of the probable direct and indirect impacts to the critical area(s) and buffer(s) resulting from the proposed development; and, an assessment of the cumulative impacts to the critical area resulting from the existing and proposed development."

Critical Areas Report Language Consistence
SCC 14.24.080.5(b) requires that the critical area report 'must be completed as follows,' but then the subsequent bullets all refer to a "site assessment." We suggest replacing "site assessment" with "critical areas report" for clarity and consistency.

PCA Tract Ownership Unnecessarily Restricted
Development proposals proximal to critical areas may result in the designation of a Protected Critical Area (PCA), in some cases resulting in the PCA being placed in a separate tract (SCC 14.24.090(5)(b) and the code specifies ownership may be "transferred to the County, homeowners association, or land trust." A tract may be a fully separate parcel (RCW 84.04.130). This drafted language specificity undermines the rights of a property owner to select the best or most financially advantageous owner for their PCA tract. There are other options for PCA ownership that are not listed, such as a Tribal government, an electrical utility, an adjacent City, or an interested neighbor. It is unfair to limit the financial options and personal interests of the property owner of the PCA to just these specific ownership scenarios. The essential component of any ownership of a PCA must be to uphold the terms and conditions of the PCA agreement, and it is unnecessary for the County to weigh in on any other relationship. If the County feels strongly about providing example ownership arrangements within this code, we suggest adding the language "for example" or "such as."

Inconsistent Use of FWHCA and HCA throughout CAO
There is a mix of references to Fish and Wildlife Habitat Conservation Areas, Fish and Wildlife HCAs, FWHCAs, and simply HCAs. All are used interchangeably. We suggest revising for consistency, with particular concern about the use of 'HCA.' Please revise for consistency and clarity.

Procedures Must Evaluate Completeness and Accuracy
In SCC 14.24.100, there is no description of how Skagit County might review a completed Critical Areas Report or how the County might make its determination of approval. There should be a statement that the County will review "the critical areas assessment report for completeness and accuracy and shall consider the recommendations and conclusions of the critical areas assessment report to assist in making administrative decisions concerning approval, conditional approval, or denial of the subject project and to resolve issues concerning critical areas jurisdiction and appropriate mitigation and protective measures". Without this type of statement, Skagit County seems unable to ask for any changes or additions to a Critical Areas Report. This is in conflict with SCC 14.24.050 which directs that the County "will utilize data from natural resource agencies as a source of best available science when reviewing sites and critical areas reports." This direction should be brought forward into SCC 14.24.100 in order to actually allow the County to utilize the resources from natural resources agencies.

If this agency data exists, and is accepted as the Best Available Science, but was excluded from the Critical Areas Report, the County needs a means to ensure that data is brought to the proposal and assessment to ensure protection of critical areas and safety. For example, if an applicant proposes a development on an unstable slope, but the Critical Areas Report fails to utilize available information from DNR Landslide Mapping that demonstrates a potential risk, the County should be able to review and determine a need for further assessment.

Obsolete Reference to Rescinded Permit Programmatic
SCC 14.24.120(4)(d) refers to the Tidegate-Fish Initiative, which was an agreement signed by participating Drainage, Diking and Irrigation Districts, Western Washington Agriculture Association (WWAA), the Washington Department of Fish and Wildlife (WDFW), the National Marine Fisheries Service (NMFS), and the U.S. Fish and Wildlife Service (USFWS). The intent of the agreement was to provide delta-wide coverage for districts to comply with federal permitting through the US Army Corps of Engineers (USACE), comply with the Endangered Species Act (ESA) consultation requirements, and ensure estuary habitat restoration occurred in the Skagit and Samish deltas. In 2010 a supporting ESA Section 7 biological opinion was written and signed by NMFS. The programmatic permit coverage through the USACE was revoked in 2021. Districts are in negotiations to develop a new program for regulatory permit coverage, but none is in place at this time. Meanwhile, tidegates are being federally permitted on an individual basis. Please remove the reference to the "Tidegate Fish Initiative."

Issuance of a Reasonable Use Exception Must Result in No Net Loss of Critical Areas

An essential criteria of approval of a Reasonable Use Exception (RUE) is the proposal results in No Net Loss of Critical Areas ecological functions and values. Proposed language in SCC 14.24.140(6) describe the Decision Criteria, and the No Net Loss requirement should be made clear as a requirement of approval. The provided language includes statements like "limiting disturbance," "less impact" on critical areas, "minimize impacts to priority habitats and species." But when it comes to mitigating for all remaining impacts, this is only indirectly required in the Review Criteria. When and only if an RUE can demonstrate that it achieves no net loss through avoidance, minimization or mitigation (in that order as required by WAC 197-11-768) of any impacts to the critical area should the exemption be granted.

Further, SCC 14.24.140(6)(a) limits the consideration to "impacts on wetlands, fish and wildlife habitat conservation areas, or buffers," but the County must consider all critical areas and their buffers (wetlands, CARAs, FFAs, geologically hazardous areas, and FWHCAs).

The Gap Analysis is in agreement with this concern of ours, stating on page 14 "we recommend that the reasonable use exception require no net loss of ecological function." Since "No Net Loss" of ecological functions and values is an essential requirement of the CAO, we believe that this criteria should be explicit in the Review Criteria, and request its inclusion at SCC 14.24.140(6)(e).

Variance Requirements Relation to RUE Application

SCC 14.24.150(3) describe the elements of Hearing Examiner (HE) decision making for a Variance request. All elements (a)-(g) must have an HE finding, and as such, we suggest adding an "and" at the end of (f) to make it clear that (a)-(g) require the finding.

Protected Critical Areas and Density Area Calculations

For "Protected Critical Areas (PCA) Designations for New Land Divisions" under SCC 14.24.090(5)(a), the drafted code indicates that the "Areas within a PCA can be included in the total acreage for development purposes and may be used in lot area or density calculations."

And under SCC 14.24.190(1)(c) the County proposes a Density Credit for residential uses from the area of the property containing the critical area to areas without critical areas, provided that this "does not create a density greater than that allowed under SCC 14.18.310(2)." We are concerned that this added statement is overly focused on Conservation and Reserve Development (CaRD) lots but ignores densities on other types of lots.

SCC 14.18.310(2) describes the allowable densities for "Maximum Residential Densities with a CaRD" and provides some limited exceptions regarding septic and water requirements. However, it seems that this should also include the general residential densities across zoning types which are described in SCC 14.16.030. We suggest that this language is revised to read "Does not create a density greater than that allowed under SCC 14.18.310(2) or SCC 14.16.030".

Measures to Minimize Land Use Impacts Must Result in No Net Loss

High intensity land uses, appropriately, require the broadest buffer to protect the functions and values of wetlands. Examples of high intensity land uses are described in Table 8C-3 (Appendix 8-C of modified Ecology Publication 05-06-008[3]) include commercial, industrial, dense residential, and dairies. The drafted code language suggests in SCC 14.24.230(1)(d) that a high impact land use may apply moderate impact land use buffers if "measures to minimize impacts to wetlands from high impact land uses are implemented." But this is not what the BAS indicates. The BAS resource "Department of Ecology Publication No. 05-06-008, Wetlands in Washington State, Volume 2" – already cited in the proposed code – provides "Special Conditions for a Possible Reduction in Buffer Widths." The buffer reductions suggested in the draft language are not a 'gimme' and must result in no net loss. The BAS[4] suggesting the possibility of a buffer reduction based on land use states that:

> ***Condition 1: Reduction in Buffer Width Based on Reducing the Intensity of Impacts from Proposed Land Uses***
> *The buffer widths recommended for proposed land uses with high-intensity impacts to wetlands can be reduced to those recommended for moderate-intensity impacts under the following conditions:*
>
> 1) *For wetlands that score moderate or high for habitat (6 points or more for the habitat functions), the width of the buffer can be reduced if both of the following criteria are met:*
>   a. *A relatively undisturbed, vegetated corridor at least 100-feet wide is protected between the wetland and any other Priority Habitats as defined by the Washington State Department of Fish and Wildlife. The latest definitions of priority habitats and their locations are available on the WDFW web site at: http://wdfw.wa.gov/hab/phshabs.htm). The corridor must be protected for the entire distance between the wetland and the Priority Habitat by some type of legal protection such as a conservation easement.*
> 2) *Measures to minimize the impacts of different land uses on wetlands, such as the examples summarized in Table 8C-8, are applied. For wetlands that score less than 6 points for habitat, the buffer width can be reduced to that required for moderate land-use impacts by applying measures to minimize the impacts of the proposed land uses (see examples in Table 8C-8).*

The essential component when considering a reduction in the buffer widths based upon land use is the no net loss requirement for impacts to habitat functions and values. This

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[3] Washington Department of Ecology (ECY). (2018). Appendix 8-C: Guidance on buffers and ratios for Western Washington wetlands in Washington State volume 2 – Protecting and managing wetlands. https://apps.ecology.wa.gov/publications/parts/0506008part3.pdf

[4] Washington Department of Ecology (ECY). (2018). Appendix 8-C: Guidance on buffers and ratios for Western Washington wetlands in Washington State volume 2 – Protecting and managing wetlands. https://apps.ecology.wa.gov/publications/parts/0506008part3.pdf

section should be revised to refer more directly to the wetland guidance language in its entirety, and to specify that any "measures to minimize impacts" must be evaluated for no net loss to habitat functions and values.

Forage Fish are indicators of Fish and Wildlife Habitat Conservation Area
The CAO fails to designate forage fish spawning areas as a FWHCA. This is counter to the BAS, does not adopt the Gap Analysis recommendations, and is conflict with Washington Administrative Code (WAC) and RCW.

The Gap Analysis (p. 22) acknowledged the role of sand lance and other common forage fish, stating "we recommend including other forage fish spawning areas to maintain consistency with the GMA and provide protection for these habitats." Further, WAC 365-190-130(2)(d) requires that in addition to herring and smelt spawning areas, other forage fish spawning areas must be considered for classification and designation. Because of the requirement in RCW 36.70A.172(1) where "counties shall give special consideration to conservation or protection measures necessary to preserve or enhance anadromous fisheries", and because of the role of forage fish in supporting the marine foodweb, which supports ESA-threatened anadromous fish as well as ESA-endangered Southern Resident Killer Whales, we suggest the language in SCC 14.24.500 is revised to designate "forage fish spawning areas" as a critical area.

FWHCA Water Type Classifications Misrepresent State Criteria
The FWHCA regulations provide an overview of the Type S, F, Ns, Np stream classification structure and refer to WAC 222-16-030. Unfortunately, the summary statements about each stream type used in the draft SCC fail to capture details essential to appropriate application of the stream types, and we are seriously concerned it will lead to misapplication of rules and protections as written.

These stream classifications are ubiquitous across state[5,6], and even Federal[7] regulations. But the language shown in draft SCC 14.24.510 does not represent either the factual use of those classifications for Type S, F, Ns, Np streams. For Type S, the definition is for 20 cubic feet per second (cfs) of mean annual flow and not 'averaging'. Additionally, WAC 222-16-030 states that Type S waters include associated wetlands. This detail is important because many Type S waters contain abundant floodplain off-channel wetlands that provide critical habitat functions for salmon and other wildlife.

Much more concerning, however, is the description for the Type F stream. The WAC is referenced in SCC 14.24.510, but in practice, the Department of Natural Resources (DNR) implements the rule using the Forest Practices Board Manual, which directs that

[5] https://app.leg.wa.gov/waC/default.aspx?cite=222-16-030
[6] https://app.leg.wa.gov/WAC/default.aspx/default.aspx?cite=220-660
[7] https://ecology.wa.gov/getattachment/56d82d6b-5a68-411e-97d5-5a432aec30c1/NFIP_Puget-Sound_Biological_Opinion_w_Errata_2008.pdf in Appendix 4

"Waters meeting the physical characteristics for Type F streams described in this rule are presumed to have fish use unless a protocol survey or ID Team has verified otherwise."[8]

The methods for determining fish use commonly understood across natural resources specialists and are delineated in the Forest Practices Board Manual 13[9], which essentially presumes fish presence if the stream meets the physical criteria unless proven otherwise. The description in the SCC for Type F waters is concerning, because the WAC reference does not include important DNR Board Manual Methodology and DNR Policies that are essential to the application of the WAC. Experience indicates that a lay audience is not very good at assessing fish use, and this must not be left up to property owners, or even consultants who visit the site at a moment in time. In particular, anadromous fish, who deserve special consideration by the County under RCW 36.70A.172(1), are so defined by their migratory life history. One observation of a lack of fish presence absolutely does not indicate that a stream is Type N.

In addition, in the coming weeks (June 6, 2025) the Forest Practices Board is expected to vote to ratify a permanent water typing rule[10] containing changes to the water typing system that are relevant to Skagit County code. We recommend the County delays approving changes to the CAO code until after June 6 to adequately incorporate the expected changes to WAC 222-16-030.

Several important changes to this rule are expected that are relevant to County FWHCA:

- A new section of WAC is expected to be added (222-16-0301) 'Verification of fish habitat and break between Type F and Type N water'. In this section, a new component of the water typing system is established that is highly relevant to county regulations. The new component is called the Anadromous Fish Floor (AFF), which is a portion of the landscape that is assumed to contain fish whether or not fish are present on any particular day. Low gradient streams, wetlands and sloughs may provide important habitat for salmon even if salmon are not present during the typical water typing survey window. The AFF provides regulatory certainty for landowners by defining where protocol water typing surveys and default physical criteria for fish habitat may be utilized. We urge the County to incorporate this important concept into the CAO to reduce the chances of erroneously missing fish habitat.
- The new water typing system, including delineation of the AFF and implementation of field-based water typing surveys, will rely on a new Board

[8] https://www.dnr.wa.gov/forest-practices-water-typing#:~:text=Type%20%22F%22%20%3D%20Fish,may%20be%20perennial%20or%20seasonal.
[9] https://www.dnr.wa.gov/publications/fp_board_manual_section13.pdf
[10] https://www.dnr.wa.gov/publications/bc_fpb_wts_rm_20250514.pdf

Manual (section 23) for technical guidance. We recommend the County require use of Board Manual 23 for determining water types.

- The new rule codifies the inclusion of off-channel habitat as Type F water. Off-channel habitats form important rearing areas for threatened and other species and must be protected as critical components of Type F water. If the county chooses to repeat water typing definitions from 222-30-30, important details such as off-channel habitat should not be neglected.

Additionally, we understand that Skagit County Forest Advisory Board (FAB) Chair has submitted comments in support of these proposed water typing rule changes on behalf of Skagit County[11]. We suggest coordinating with FAB to ensure current references are incorporated into the CAO and that the County remains consistent in its recommendations and implementation of stream water practices.

In order to address these concerns, we suggest that the SCC simply follow WAC 222-16-030 and not summarize its language. If SCC does wish to summarize, we request that the draft language be revised to include the important role of wetlands in Type F waters and emphasize the guidance which evaluates a stream's physical characteristics for the Type F designation.

BAS for Riparian Areas is Incomplete

The BAS document[12] provided as a companion to this CAO update refers frequently to the WDFW guidance Riparian Ecosystems, Volume 2: Management Recommendations, compiled by Terra Rentz, et al. This document uses this citation (Rentz et al. 2020) in at least 7 locations. The Gap Analysis puts forward recommendations made in this document. But the document is not included in the References list of the BAS that begins on page 59. We request that this important guidance document is incorporated into the Best Available Science for the Critical Areas update and it is included in the Reference list of the BAS.

Proposed Buffers on Streams Do Not Follow BAS

The draft language in SCC 14.24.530.(1)(c) describe the Standard Buffer Widths proposed by the County in this CAO update, but these widths do not represent the Best Available Science on the topic. Seeing that many of the waterbodies that these codes would be applied to are essential spawning, migration, or rearing habitat for anadromous fish, the County must give special consideration to conservation or protection measures necessary for these habitats (RCW 36.70A.172(1)).

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[11] https://www.dnr.wa.gov/publications/bc_fpb_wts_rm_20250514.pdf

[12]https://www.skagitcounty.net/PlanningAndPermit/Documents/compplan2025/Skagit%20County%20BAS%202.24.2025%20-%20FINAL.pdf

As the BAS review describes, WDFW guidance[13] describes a shift from stream buffers to Riparian Management Zones (RMZ) and recommends the RMZ is regulated as a FWHCA to protect its fundamental value, rather than as a buffer for a river or stream. Buffers do not provide full riparian function or a close approximation of it. Rather, WDFW recommends that "RMZs be considered a delineable, regulatory critical area and the guidance be applied to all streams and rivers, regardless of size and type." The WDFW recommendations provide a web-based mapping tool[14] for determining the site potential tree height for a given locale. Importantly, the WDFW recommends that the RMZ width is measured from the outer edge of the channel migration zone (if present) or the ordinary high-water mark, whichever is most landward.

We are concerned that the approach to riparian zones that Skagit County has proposed provides substandard conservation and protection for streams associated with anadromous salmon, and we recommend that the County revise this code to incorporate the WDFW recommendations for RMZs.

Buffer Width Increasing Should Address Substandard Buffer Conditions

In SCC 14.24.530(1)(c)(i), the draft code makes clear that a "Standard Riparian Buffer Width" presumes that the buffer is in good condition, and that code provides performance standards for determining eligibility for a standard buffer width. The code also indicates if the existing buffer does not presently meet the performance standards in that item, that enhancement and/or increased width must be required. The opportunity to codify that buffer width increase should be incorporated into SCC 14.24.540 by adding SCC 14.24.540(1)(c) and describes that scenario presented in SCC 14.24.530(1)(c)(i).

Summary and Conclusion

Thank you for consideration of the various concerns and comments we have described in this letter. Many of the protections we are calling for are designed to benefit the Tribe's treaty right to harvest salmon. We request that Skagit County incorporate the suggested revisions to produce an improved ordinance for protecting Skagit County's vast critical areas.

Sincerely,

Michael Wolten
Natural Resources Policy Coordinator
Sauk-Suiattle Indian Tribe

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[13] Rentz, R., A. Windrope, K. Folkerts, and J. Azerrad. 2020. Riparian Ecosystems, Volume 2: Management Recommendations. Habitat Program, Washington Department of Fish and Wildlife, Olympia. 80 pp

[14] https://wdfw.maps.arcgis.com/apps/MapJournal/index.html?appid=35b39e40a2af447b9556ef1314a5622d

Robby Eckroth

From: Kim Matthews <kmatthews@westag.org>
Sent: Thursday, May 8, 2025 3:17 PM
To: PDS comments
Subject: Comments on Skagit County's 2025 Draft Comprehensive Plan Update – Critical Areas Ordinance
Attachments: WWAA Comments on CAO Updates_Final.pdf

May 8, 2025

Skagit County Planning & Development Services
1800 Continental Place
Mount Vernon, WA 98273

RE: Comments on Skagit County's 2025 Draft Comprehensive Plan Update – Critical Areas Ordinance

Dear Skagit County Planning & Development Services,

On behalf of the Western Washington Agricultural Association (WWAA), thank you for the opportunity to provide comments on the draft update to Skagit County's Critical Areas Ordinance (CAO).

Agriculture is a cornerstone of Skagit County's economy, heritage, and landscape. WWAA supports the protection of natural resources in tandem with preserving the viability of working farmland and the critical infrastructure—such as drainage, diking, and irrigation systems—that sustains it.

Below we provide general process feedback, express specific concerns, and include recommended code revisions.

General Process Concerns
We are concerned by the comprehensive reorganization of the ordinance paired with substantial redline edits. This combination has made the document difficult to navigate and interpret, hindering effective public and stakeholder engagement. We recommend that structural and formatting updates be completed prior to introducing material policy changes. Sequencing in this way would enhance transparency, public understanding, and the ability to provide meaningful feedback.

Relation to Drainage, Diking, and Irrigation Infrastructure
Many of our recommendations align with the formal comments submitted by the Skagit Drainage and Irrigation District Consortium, LLC. WWAA defers to the Consortium's technical expertise on these matters while strongly supporting their input. These systems are foundational to agricultural viability and merit focused consideration in the CAO update.

Clarity on the Definition and Regulation of Watercourses
The draft includes vague references to "watercourses," which could result in regulatory overreach—particularly where man-made agricultural drainage infrastructure is concerned. To avoid misapplication, it is essential that the ordinance clearly distinguish between:

- Natural or modified natural watercourses, and
- Artificial watercourses maintained by drainage and irrigation districts.

This is especially important because the County lacks regulatory authority over artificial watercourses that are actively maintained by special purpose districts formed under Title 85 RCW. As such, any critical areas provisions must remain consistent with WAC 365-190-030(6)(a), which defines fish and wildlife habitat conservation areas, and RCW 36.70A.030(11), which expressly excludes irrigation delivery systems, infrastructure, and drainage ditches located within and maintained by a drainage or irrigation improvement district from the definition of critical areas.

Adoption of WDFW's Buffer Guidance
In response to concerns raised by Planning Commissioners during the April 22, 2025 Planning Commission meeting and as outlined in Section 6.4 of the GAP Analysis, the Western Washington Agricultural Association (WWAA) recommends

against adopting the Washington Department of Fish and Wildlife's (WDFW) 2020 Riparian Management Zone (RMZ) guidance for Fish and Wildlife Habitat Conservation Areas and related recommendations presented by FACET Consultants in Section 6.4 of the GAP Analysis. Instead, WWAA recommends maintaining the current CAO buffer standards.

While WWAA supports using best science as tool to guide policy, the RMZ framework based on Site Potential Tree Height (SPTH), and the related buffer increases recommended made by FACET Consulting, imposes uniform, one-size-fits-all buffer requirements. This approach does not reflect the practical realities of agricultural landscapes and poses a direct threat to the viability of farms that rely on man-made drainage systems. In Skagit County, many of these watercourses - maintained under RCW Title 85 - are at risk of being misclassified as natural streams, despite serving as essential infrastructure for crop production and flood management.
While Best Available Science is a required compass to be applied to CAO revision, it should be recognized that WDFW's own literature is contradictory and does not just recommend setting a one-size-fits-all standard. In fact, WDFW's Volume 2 Management Recommendations clearly state using site-specific strategies for policy:

> **"The most efficient way to protect riparian functions is to adopt protections that recognize [site] differences, rather than uniform-width RMZs… which may result in over-protection in some places and under-protection in others. (p. 11)"**

The site-specific Volume 2 recommendation is based on conclusions formed throughout Science Synthesis (Volume 1) that clearly articulates the uncertainty of outcomes associated with SPTH-based buffers. The agency notes:

- "Despite the large quantity of research… no widely accepted recommendations have emerged on minimum buffer widths needed to protect water quality. (p. 142)"
- "Riparian vegetation height and density may be more closely associated with shade than width… (p. 89)"
- "Models cannot predict exactly how much shade reduction will result in a specific temperature increase. (p.89)"
- **"The SPTH-based approach does not guarantee improved salmon returns. (p. 274)"**

Further, WDFW staff have clarified that Volume 2 represents policy preferences and acknowledged that land use decisions must also weigh human needs, such as food production and farm viability.

WWAA has quantified the real-world consequences of SPTH adoption. One member farm in south Mount Vernon would lose 40% of a single field - an 86-acre area currently producing 4.3 million pounds of potatoes, 103,000 pounds of spinach seed, and 175,000 pounds of grass seed annually. The long-term impacts to local agriculture and food security would be significant. We urge the County to reject the application of WDFW's STPH Framework.

Conclusion
We thank you for the opportunity to comment and urge the County to revise the ordinance in a manner that respects both environmental protection and agricultural sustainability. We remain committed to being a collaborative partner throughout this process.
Sincerely,

Kim Matthews
WWAA Executive Director

Board of Directors
Dan Gundersen | Aaron Taylor | Jennifer Smith | Brandon Hansen | Tyler Breum | Jacob Slosberg | Torey Wilson | Troy Hansen | Mikala Staples Hughes | Owen Peth |

Attachments: WWAA Chapter 14.24 Critical Areas Ordinance: Recommended Revisions

Chapter 14.24 Critical Areas Ordinance: Recommended Revisions

Page 8– SCC 14.24.070(7) – Activities Allowed Without Standard Review
Recommendation:

This exemption applies to the lawful operation and maintenance of public and private diking, drainage, and irrigation systems which protect life and property along the Skagit and Samish Rivers and tidal estuaries in Skagit County. This exemption does not apply to public or private activities that expand the levee, dike, or drain beyond its design characteristics as of June 1, 1999, the time of adoption of this Subsection; nor activities that expand or create new facilities.

Page 8– SCC 14.24.070(10) – Activities Allowed Without Standard Review
Recommendation:

Activities in or adjacent to watercourses which were constructed and are actively maintained for irrigation and drainage by diking, drainage, and irrigation improvement districts formed pursuant to Title RCW 85, provided, that any activity must comply with relevant state and federal regulations…

Page 21— SCC 14.24.120(1) Ongoing Agriculture
Recommendation:

Purpose and Intent. The purpose of this Section is to address two mandates under the Growth Management Act (GMA):

(a) to protect the existing functions and values of fish and wildlife habitat conservation areas (FWHCAs) in and adjacent to natural and modified natural watercourses as defined in SCC 14.04.020; and
(b) to conserve and protect agricultural lands of long-term commercial significance, specifically those in ongoing agricultural activity as defined in SCC 14.04.020 that are located adjacent to these watercourses.

Page 18– SCC 14.24.120(1)(a)(iii) Ongoing Agriculture
Recommendation:

The riparian vegetation characteristics and width, including but not limited to the amount of shade provided by the riparian vegetation at the time VSP was adopted.

Page 20– SCC 14.24.120(4) Ongoing Agriculture
Recommendation:

Required Protection Measures for Ongoing Agriculture in Fish and Wildlife Habitat Conservation Areas ("FWHCA"). Unless the emergency provisions of SCC 14.24.070(1) apply, the following watercourse protection measures are required:

Page 21– SCC 14.24.120(4)(c)(iv) Ongoing Agriculture
Recommendation:

V-ditching must not be constructed to drain into a natural watercourse that also contains salmonids, unless the topography of the field is such that this is the only alternative to drain the field by gravity. BMPs should be used to minimize sediment conveyed to the watercourse. For the purpose of determining whether a natural watercourse contains salmonids, the County will use:

(a) The Washington Department of Wildlife ("WDFW") SalmonScape Database for natural watercourses, and
(b) Maps prepared by WDFW for the purposes of the Drainage Fish Initiative.

Page 66– SCC 14.24.530 Fish and wildlife habitat conservation area protection standards
Recommendation:

Restore the original riparian buffers that were previously codified.

Kim Matthews
Executive Director
Cell: 541-810-4452

Western Washington Agricultural Association

May 8, 2025

Skagit County Planning & Development Services
1800 Continental Place
Mount Vernon, WA 98273

RE: Comments on Skagit County's 2025 Draft Comprehensive Plan Update – Critical Areas Ordinance

Dear Skagit County Planning & Development Services,

On behalf of the Western Washington Agricultural Association (WWAA), thank you for the opportunity to provide comments on the draft update to Skagit County's Critical Areas Ordinance (CAO).

Agriculture is a cornerstone of Skagit County's economy, heritage, and landscape. WWAA supports the protection of natural resources in tandem with preserving the viability of working farmland and the critical infrastructure—such as drainage, diking, and irrigation systems—that sustains it.

Below we provide general process feedback, express specific concerns, and include recommended code revisions.

General Process Concerns
We are concerned by the comprehensive reorganization of the ordinance paired with substantial redline edits. This combination has made the document difficult to navigate and interpret, hindering effective public and stakeholder engagement. We recommend that structural and formatting updates be completed prior to introducing material policy changes. Sequencing in this way would enhance transparency, public understanding, and the ability to provide meaningful feedback.

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This is especially important because the County lacks regulatory authority over artificial watercourses that are actively maintained by special purpose districts formed under Title 85 RCW. As such, any critical areas provisions must remain consistent with WAC 365-190-030(6)(a), which defines fish and wildlife habitat conservation areas, and RCW 36.70A.030(11), which expressly excludes irrigation delivery systems, infrastructure, and drainage ditches located within and maintained by a drainage or irrigation improvement district from the definition of critical areas.

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> **"The most efficient way to protect riparian functions is to adopt protections that recognize [site] differences, rather than uniform-width RMZs… which may result in over-protection in some places and under-protection in others. (p. 11)"**

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Conclusion

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Sincerely,



Kim Matthews
WWAA Executive Director

Board of Directors
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Recommendation:

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Page 66– SCC 14.24.530 Fish and wildlife habitat conservation area protection standards

Recommendation:

Restore the original riparian buffers that were previously codified.

Comment #20

Robby Eckroth

From: Allen Bush <bushman@mail.com>
Sent: Thursday, May 8, 2025 3:25 PM
To: PDS comments
Subject: 2025 Development Regulations and Critical Areas Ordinance Update

Guemes Island Planning Advisory Committee (GIPAC)

Date: May 8, 2025

To:
Skagit County Planning and Development Services
1800 Continental Place
Mount Vernon, WA 98273

Subject: 2025 Development Regulations and Critical Areas Ordinance Update

Dear Skagit County Planning and Development Services,

On behalf of GIPAC, I am writing to express our support with the some of the findings and recommendations presented in the recent gap analysis concerning updates to the County's critical areas regulations. Our committee would like to highlight a few key points that we believe would ensure responsible stewardship of our community's natural resources while supporting balanced land use planning.

Variance Standards (SCC 14.24.140)
We support the recommendation to strengthen the standard for variances by defining "significant adverse impacts" in a manner consistent with Best Available Science (BAS). Specifically, we agree that the standard should require "no net loss of ecological function," aligning with state environmental goals and scientific principles.

Buffer Reductions and Reasonable Use Exceptions (SCC 14.24.150)
We agree that buffer reductions should not be allowed below minimum recommendations outlined by BAS except under clearly justified reasonable use exceptions. The proposed update to streamline the reasonable use exception process—modeled after Snohomish County Code—is a constructive step toward more transparent, consistent, and scientifically grounded decision-making. Importantly, even under reasonable use exceptions, the standard of no net loss should be maintained, with mitigation being necessary when impacts are unavoidable.

Critical Areas Definitions (SCC 14.04)
We concur with the recommendation to update definitions for wetlands, Fish and Wildlife Habitat Conservation Areas (FWHCAs), geologically hazardous areas, critical aquifer recharge areas (CARAs), and frequently flooded areas to be consistent with WAC 365-190. Clear and standardized definitions are foundational to fair and effective regulation.

Seawater Intrusion Areas (SCC 14.24.380)
We support the recommendation to review and update development standards in areas at risk for seawater intrusion. Using updated risk criteria, ensures that development decisions are based on current science. We particularly support aligning risk measurement and well placement requirements with medium- and high-risk designations (100–200 mg/l and above), and recommend coordination with the health department in such cases.

Conclusion
The recommended updates and clarifications pointed out in the gap analysis are both scientifically sound and practical. Adopting these changes would significantly strengthen the County's critical areas ordinance, promote resilience in our ecosystems, and enhance transparency and fairness in land use decisions.

We appreciate the opportunity to provide feedback and look forward to supporting the implementation of these improvements.

Sincerely,

Allen Bush, Vice Chair
Guemes Island Planning Advisory Committee (GIPAC)

Comment #21

Robby Eckroth

From:	Ellen Bynum <skye@cnw.com>
Sent:	Thursday, May 8, 2025 3:25 PM
To:	PDS comments
Cc:	Randy & Aileen Good, FOSC.; Andrea Xaver; Lori Scott; FOSC Office
Subject:	Skagit County 2025 Comprehensive Plan Periodic GMA update and comments on CAO, CP and DRs
Attachments:	FoSC to PC 050625 comments 2025 CP, CAO and DRs Periodic Update.pdf

Attached please find Friends of Skagit County's comments regarding the proposed updates of the Critical Areas Ordinance, the Development Regulations and some additional related comments on the proposed 2025 Comprehensive Plan draft update.

Should you have questions or need additional information, please contact me at 360-488-3244.

Thanks very much,
Ellen Bynum

Ellen Bynum, Executive Director
Friends of Skagit County
PO Box 2632 (mailing)
Mount Vernon, WA 98273-2632
360-419-0988; friends@fidalgo.net
www.friendsofskagitcounty.org
“A valley needs FRIENDS”
Since 1994 - Common Goals - Common Ground - Common Good
DONATE NOW at Network for Good
nfggive.org

May , 2025

TO: Skagit County Planning Commission
FROM: Ellen Bynum, Executive Director, Friends of Skagit County (FoSC), PO Box 2632, Mount Vernon, WA 98273-2632. 360-488-3244.
RE: Comments concerning proposed changes to the draft Skagit County Comprehensive Plan 2025 Periodic GMA Update; Critical Areas Ordinance; and Skagit County Development Regulations

Thank you for the opportunity to comment on the Critical Areas Ordinance (CAO) update, the proposed updated development regulations (codes). We are providing additional comments regarding the 2025 Periodic update of the Skagit County Comprehensive Plan in addition to our March 13, 2025 comments.

The volume of material in the proposed drafts of the Comprehensive Plan, policies and development regulations was extremely difficult to review in the allotted comment time. We request that in future for plan, policy and regulations updates Planning and Development Services produce and release document drafts at least two weeks before setting the beginning of public comment periods.

CAO
Friends of Skagit County supports the suggested changes that Jan Edlestein (Protect Big Lake) proposes to the Critical Areas Ordinance update. Using Best Available Science is meaningless if it stops at the parcel/lot line or is limited by an arbitrary number of linear feet from proposed projects. The water doesn't stop at the lot line and neither do any pollution it may carry on to Skagit's lakes, creeks, streams or shores.

Since 1990, Friends has worked to develop planning documents that balance conservation of the land with the rural economy. Our focus on resource lands has continued as identify, designating and protecting these lands is the cornerstone of the Growth Management Act. We recognize the importance of previous planning decisions regarding Agricultural - Natural Resource Lands (Ag-NRL), natural vs. man-made drainage systems, creating buffers that are customized, not one size fits all, and the fact that these decisions were expensive to obtain and have not been without sacrifices on the part of Ag-NRL owners.

Over the years we have done less work on urban land issues because Skagit County and the cities/towns managed to achieve compliance with the GMA. Good decisions about resource lands and the economy were the drivers of the GMA when it passed and subsequent choices in Skagit's planning decisions have mainly managed to continue to support Skagit's rural economy. We urge the Planning Commission to continue to request additional information and ask any questions to be able to advise on choices that sustain the land, residents and the rural economy.

Related Comprehensive Plan update needed.
In reviewing drafts of the 2025 CP update we noted that the plan only mentions Big Lake Rural Village once. Please reinstate goals, policies and development regulations which originally had the Big Lake special provisions that require no pollution or degradation to Big Lake if the Overlook properties are developed. Staff or consultants removed Goal 12A-4.1 and 4.2 (now edited Goal 13A-4) in February, 2025 in the proposed changes to the 2025 Periodic update to the draft Skagit County Comprehensive Plan v.2.0 and subsequent versions of the draft CP updates.

Any updating of these omitted sections must reference the Ordinances and development regulations that reflect the settlement agreement that Friends of Skagit County has with Skagit County. Please include references to the Ordinances and settlement contracts so readers can understand the details of these requirements in the goals, policies and development regulations. Without 12A-4.2(a) - (f) the public has no history or understanding that rural villages and other parts of Skagit County have benefitted from developing subarea plans that guide development in the respective communities.

We include comments below on the removal of development regulations 14.16.310 Rural Village Residential (RVR) (7) Special Provisions—Big Lake Rural Village Overlook Golf Course Property, referenced in page 59 (noted below) of the draft development regulations update.

The Comprehensive Plan Periodic GMA update started in 2005 and concluded in 2007 when Skagit County adopted Ordinance #O20070009, 628 pages. It contains the final settlement of the Friends of Skagit County with Skagit County on the issues of the Overlook properties and Big Lake Rural Village development. The agreement amends the Comp Plan and the land division and other sections. See page 16 of 628.

“Policy Direction Concerning Undeveloped Parcels in East Big Lake.
48. Proposed policy 3C-1.8. in conjunction with revisions proposed to SCC 14.16.310(7) are consistent with, and necessary, to fulfill the terms of a settlement agreement pertaining to Hearings Board Case No. 00-2-0046(c). The current Plan policy (policy 4A-7.14) places restrictions on development of "larger undeveloped parcels on the east side of the lake" associated with Overlook Golf Course...".

The policy included "...no higher density than 1 per 5 acres unless … “ certain conditions were met, including use of the Conservation and Reserve Development (CaRD). All new "...development would be required to use public utilities (including sewer) and effectively protected Big Lake water quality. This revised policy direction and code will ensure the protection of Big Lake water quality while permitting appropriate rural development.".

Please include this and related Big Lake information in the 2025 development regulations and 2025 comprehensive plan updates.

DEVELOPMENT REGULATIONS

General comments. (unranked).
There are likely to be omissions, other than the Big Lake Rural Village Special Provisions from the adopted 2016 Skagit County Comprehensive Plan in the draft 2025 Skagit County Comprehensive Plan, policies and development regulations. We urge a thorough staff and consultants review of the two plans for sections which have not been carried forward to the new proposed draft plan. Please restore omitted sections that provide background, context, historical information or legal decisions some of which are critical to implementing the 2025 updates. Please provide updated decisions and information to fully inform the public.

The proposed draft 2025 CP update must provide the public with information that allows them to make informed comments to the Planning Commission and the Board of County Commissioners and to help make accurate decisions on options to file appeals to the Growth Management Hearings Board or Superior Court if necessary.

Please move the legend(s) for tables closer to the table to which it applies and insert more than once if needed so the reader has easy reference to the legend(s). Example: 14.10.050 Use tables; 14.13.020 Allowed Uses.

Where Ordinances are referenced, rather than removing, please create a reference table by SCC and number so readers have ready access to when and how the code was changed. Example: 14.07.070 (3) was originally (c) under Procedure for Verifying Abandonment and had this additional language. (Ord. O20240005 § 1 (Exh. A); Ord. O20070009 (part); Ord. 17938 Attch. F (part), 2000). Another example: 14.10.090 Uses not specifically identified original (3) (d) (Ord. O20240005 § 1 (Exh. A); Ord. O20090010 Attch. 1 (part); Ord. 17938 Attch. F (part), 2000), part of which is now (2)(e) and other sections.

Have we adequately addressed fee simple ownership on the Swinomish Reservation, inside state parks, national parks, national forests and/or other places where there may be different jurisdictions applicable to fee lands?

Specific comments.
Page 5 - Chapter 14.04 Definitions.
Please either reinstate a definition of the Agricultural Advisory Board or add information on the role of the AAB in advising planning decisions of the Planning Commission and Board of County Commissioners in the Chapter on Natural Resource Lands (also the Forest Advisory Board) or in the Ag-NRL section or in the

Implementation Chapter. The CP mentions the Non-Motorized Transportation Advisory Group, now called the Active Transportation Advisory Group and other advisory boards. The AAB and FAB should be considered on equal footing with the other mentioned advisory committees.

Page 7 - Terms and definitions deleted because they were unnecessary.
Reinstate Master Planned Resort.
There is one in Skagit County, formerly called Clark's Cabins, now Glacier Peak Resort & Winery, P45500, 58468 Clark Cabin Rd., Marblemount. Zoning Designation: Skagit County - Master Planned Resort. Staff report on a similar application, Thousand Trails, Bow, WA, that was denied docketing is in R20080573.

See page 12 of BOCC discussion of Staff recommendations 2023 Docket petitions, April 11, 2023, which state:
Partial quote - " .....The C23-4 is the Master Planned Resort Designation. This petition would amend code language to refer to Master Planned Resort as a zoning designation and not a special use, to remain consistent with the Comprehensive Plan and the Growth Management Act. Master Planned Resorts are “self-contained and fully integrated planned unit developments in a setting of significant natural amenities, with a primary focus on destination resort facilities consisting of short-term visitor accommodations associated with a range of developed on-site indoor or outdoor recreation facilities.

So examples of these in Washington state would include Crystal Mountain Resort, Skamania Lodge, the Sun Mountain Resort. And in Skagit County we have Clark’s Cabins in Marblemount. That is a Master Planned Resort. So currently in our special use permits code section there is language which would refer to an MPR as a special use, which would be subject to the special use permit regulations, but this is a zoning designation, not a special use. So this change would just simply fix an inconsistency in our code....".

Page 42 Non-Conforming Uses
14.16.880 Nonconforming uses and structures.
(1) (b) originally used the word "shall" in "....nonconformities shall not be used as grounds...". Changing this to "may" implies permission. Please restore "shall" or use "must" in this instance.

Generally we concur with the removal of "shall" elsewhere in the proposed changes when it clarifies but does not change the meaning of an action or use.

14.07.05 - good integration of the examples into the new chapter.

Page 43
14.08.060 Petitions—Approval criteria for map amendments and rezones (3).
Please determine if the criteria and standards listed will also adequately address the de facto conversions. From example, production opportunity losses per acre for a future time frame, say 50 - 100 years, if acres are removed from the county's total prime soils. The de-designation request language was originally due to expansion of UGAs and/or urban annexations for development purposes, but it is important that we address other changes in use that in effect remove production opportunities on converted or "lost" prime agricultural soils.

Please consider adding a definition for "comprehensive countywide analysis" to support this section.

Page 47
14.16.030 Districts, maps and boundaries, omitted table.
Please consider keeping the omitted table in an appendix at the end of the document for reference.

Page 59
14.16.310 Rural Village Residential (RVR) (7) Special Provisions—Big Lake Rural Village Overlook Golf Course Property.
The 2016 development regulations state:

"Prior to the adoption of a Big Lake Rural Village Community Plan, property that is commonly referred to as the Overlook Golf Course and as depicted on the Big Lake Rural Village Comprehensive Plan and Zoning map, may be developed (for purposes of vesting "developed" means the "filing of a complete development application and payment of all required fees for the proposed development") at the following densities:

(a) At 1 unit per 5 acres, or at a lower density, when the following condition is met:

(i) The development shall use public water.

(b) At a density of between 1 unit per 5 acres and 1 unit per 1 acre when all of the following conditions are met:

(i) The development shall be served by a public sewer system.

(ii) The development shall use public water.

(iii) The development shall only be permitted as a long CaRD subdivision and shall be subject to the provisions of the County's CaRD regulations (SCC 14.18.300 through 14.18.330 as now adopted or hereafter amended) that are in effect at the time of submittal of any complete CaRD subdivision application.

(iv) **The owner shall design all stormwater facilities and temporary erosion/ sedimentation control systems to ensure no pollution or degradation to Big Lake.** At a minimum, all developments shall comply with Chapter 14.32 SCC (as now adopted or hereafter amended). **(Emphasis added.)**

(v) The development standards described in Subsections (7)(b)(i) through (iv) of this Section shall no longer apply if the property becomes part of the Mount Vernon urban growth area. If that occurs, development shall be governed by the regulations then in effect. If the Overlook Golf Course property is not developed prior to the adoption of the Big Lake Rural Village Community Plan, then the subject property will have the potential to develop at whatever the density is allowed by the community plan. Consideration at that time shall be given to whether all or part of the property should be inside or outside of the Rural Village and whether the development standards in Subsections (7)(b)(i) through (iv) of this Section should or should not be applied to the Overlook Golf Course property by the community plan. (Ord. O20240005 § 1 (Exh. A); Ord. O20230007 § 1 (Att. 1); Ord. O20220003 § 1 (Att. 2); Ord. O20200005 § 1 (Att. 2); Ord. O20170006 § 1 (Att. 1); Ord. O20160004 § 6 (Att. 6); Ord. O20110007 Attch. 1 (part); Ord. O20090010 Attch. 1 (part); Ord. O20080012 (part); Ord. O20080004 (part); Ord. O20070009 (part); Ord. O20050003 (part); Ord. O20030012: Ord. 20020130 (part): Ord. 17938 Attch. F (part), 2000)."

Page 73 - Table 14.13.020-1 Allowed Uses in the Natural Resource Zones
Residential uses - last phrase in brackets please change to complete sentence - example: Land may be converted for accessory uses in zones SF or RRc.

Page 75 14.13.100 Agricultural—Natural Resource Lands (Ag-NRL)
Thanks for reorganizing these by what type of permissions are needed to do these activities.

Page 76 - (4) Siting Criteria.
(b) Siting of all structures in the Agricultural—Natural Resource Lands district must minimize potential impacts on agricultural activities. Please add "and agricultural accessory" after "agricultural".

Page 116 - Part 1 Residential Uses, 14.18.__ Residential Accessory Use (h) states "...agriculture which is secondary to use of the property as residence, including no employees;...". This is true except in Ag-NRL zones where residential uses are secondary to agricultural uses. Please clarify.

If the change discussed above was implemented, where is that reflected in the current or proposed changes to the Comp Plan, policies and code?

Page 177 - 182 Chapter 14.52 Special Use Permits for Mining
Please add the suggested language in red:
(b) "... A pre-mining map drawn to scale at a scale of not less than 1:500 with an appropriate scale bar showing the permit area...".

(c) "... A reclamation sequence map drawn to scale at a scale of not less than 1:500 with an appropriate scale bar...".

(d) A final reclamation map drawn to scale at a scale of not less than 1:500 with an appropriate scale bar...".

(2) "A report by a qualified geologist or hydrogeologist, ~~or licensed engineer~~ characterizing the area's ground water including, but not limited to, the following information:

(a) Please restore this sentence as the terms are standards and instructive to reports that rely on BAS.

(c) "A map at a scale of not less than 1:500 containing the limits of the mine...".

(9) A Final Reclamation Plan consistent with WAC……..prepared by a qualified Mining Engineer and approved by the Washington State Department of Natural Resources.

(10) A statement from the WA State Department of Natural Resources that the proponent is full compliance with any previous Mining Reclamation Plans.

14.52.040 Review Criteria
(2) (f) The decisionmaker will not approve a special use permit for a proposed mining plan modification or new mining plan if the proponent is not in compliance with existing reclamation plans per 14.52.030 (2), (10) above.

END OF COMMENTS.

Comment #22

Robby Eckroth

From: Nora Kammer <nkammer@skagitcoop.org>
Sent: Thursday, May 8, 2025 3:25 PM
To: PDS comments
Cc: Robby Eckroth; michael@sauk-suiattle.com; Amy Trainer
Subject: Skagit County's 2025 Comprehensive Plan - Critical Area Ordinance Comments
Attachments: SRSC Letter Skagit CAO Comments 20250508.pdf

Dear Mr. Eckroth,

Background and setting for our objections and concerns

The Skagit River System Cooperative (SRSC) is a tribal consortium between the Swinomish Indian Tribal Community and the Sauk Suiattle Indian Tribe that provides technical and scientific fisheries research, restoration and environmental services for the Tribes throughout the Skagit River watershed. On behalf of these two sovereign nations, SRSC works to actively improve fisheries recovery and restoration throughout Skagit County.

SRSC submits the following specific comments on the draft Critical Areas Ordinance.

Incorrect Citation to "Critical Areas" definition in Introductory Section
The Introduction of the CAO in SCC 14.24.010 provides a definition of "critical areas" but then provides a code reference (RCW 36.70A.030(6)) for 'Agricultural Land'. This citation should be corrected to RCW 36.70A.030(11).

Buffer enhancement activities allowed without standard review
Buffer enhancement activities are included in SCC 14.24.070(12-13) as activities allowed without standard review. However, the added language to subsection (12) actually makes riparian buffer enhancement activities more difficult to implement due to unnecessary requirements such as a review and approval by the Planning Director. Buffer enhancement activities include activities such as noxious weed management and installation and maintenance of native plant species. These activities should be streamlined for implementation rather than adding cumbersome procedural hurdles. As a result, **the Tribe objects** to SCC 14.24.070(12) as written, and request that SCC 14.24.070(12)(b) be removed from the code.

In addition, we request that SCC 14.24.070(12)(a) be modified to remove the first sentence, which restricts buffer enhancement activities to handheld equipment. Across Skagit County, the vast majority of riparian enhancement activities conducted by entities such as the Skagit Conservation District, the Skagit Land Trust, the USFS, the Tribes, and others includes the use of a dingo-mounted auger and tractors for mowing between rows of installed trees until the trees are tall enough to shade competing grasses. The dingo-mounted auger is essential for the mental and physical well-being of the staff and volunteers who complete this work, as handheld augers result in high rates of injury and job dissatisfaction. Without this tool, the work becomes untenable. Tractor mowing planting areas is a mechanical management tool to control competing and/or non-native species and limits the use of sprayed herbicides that can achieve similar results. Tractor mowing is much preferred and without the ability to use this tool, the proposed code changes limit the ability to accomplish this work.

Skagit County's own BAS review[1] demonstrates the importance of healthy, functioning buffers to key critical areas, including wetlands, geologic hazard areas, and fish and wildlife habitat conservation areas. The BAS review recommends that the County "Promote buffers of adequate width to support wildlife guilds in adjacent habitat" (Ficetola et al. 2008; Semlitsch and Bodie 2003; Crawford and Semlitsch 2007), and to encourage stewardship on a parcel-by-parcel and county-wide scale.

Further, the Gap Analysis[2] provides a clear recommendation to the County for this section of code. The Gap Analysis suggests that the County "incentivize restoration and reduce potential permitting barriers". This special consideration for enhancement of fish and wildlife habitat conservation areas is directed by the Growth Management Act directly in RCW 36.70A.172(1), which states that: "counties shall give special consideration to conservation or protection measures necessary to preserve or enhance anadromous fisheries".

The Tribe objects to SCC 14.24.070(12) as currently drafted. We request that SCC 14.24.070(12)(b) be removed altogether, and substitute language suggested in the Gap Analysis that allows buffer enhancement without review "as long as the project is consistent with the chapter and does not harm critical areas or their buffers." We request that SCC 14.24.070(12)(a) be modified to remove the first sentence, which restricts enhancement activities to handheld equipment. We do not support the threshold of a 500 square foot riparian enhancement area being the threshold for no review as recommended in the Gap Analysis, since there is no basis for this limitation and the Standard Buffer Widths table in SCC 14.24.530.(1)(c), which includes buffer widths of 100-200 feet. Limiting a "no review" threshold to enhancement areas of 500 square feet or less would result in riparian buffer enhancement activities being only allowed on 2.5 to 5 feet of stream length without Director review, which is unreasonable and useless. This places an unnecessary review burden on projects intended to achieve meaningful riparian function. Any minimum threshold for projects that would not require Director review should be consistent with the chapter and ensure the project does not harm critical areas or their buffers.

Inconsistent Functions and Values of FWHCAs in Agricultural Lands Must be Corrected

The stated intent of the Ongoing Agriculture section (SCC 14.24.120) includes protection of Fish and Wildlife Habitat Conservation Areas ("FWHCAs") adjacent to watercourses. First, this excludes a number of FWHCAs described in SCC 14.24.500.1(a)-(l) that receive consideration in the current Skagit County critical areas code. The language in SCC 14.24.120 must be revised to be inclusive of all FWHCAs.

Further, SCC 14.24.120(1)(a) provides an incomplete list of the values and functions that are relevant to the Ongoing Agriculture section. It is unclear why the functions and values of interest in Agricultural Lands is limited to water quality, large woody debris, buffers characteristics and shade, and channel morphology, but in the FWHCAs other functions and values are included, such as bank integrity, runoff pollutant removal, wildlife habitat, microclimate, and nutrient input. These must be evaluated consistently. As a result, SCC 14.24.120(1)(a) must be revised to align and be consistent with the functions and values of other FWHCAs.

Critical Areas Report Requirements Confuse Existing and New Impacts

The drafted language for SCC 14.24.080(5)(c)(iv) requires that a critical areas report must include "an assessment of the probable direct and indirect impacts to the critical area(s) and buffer(s) as well as the cumulative impacts to the critical area resulting from the existing and proposed development." This inappropriately lumps existing impacts together with new impacts, which will create confusion and difficulty in assessing the impacts of a development under review. The existing impacts must be detailed and assessed separate from the proposed development and anticipated impacts that would not occur but for its approval and implementation.

Under SEPA rules, threshold determinations and probable adverse impacts of a proposed action are considered. If impacts from the proposed action are comingled with the impacts of the existing developments, there is no way to qualitatively or quantitively understand the scope and magnitude of the impacts of each action, make a threshold determination, or to establish appropriate mitigation for the proposed action. To address this concern, we recommend that SCC 14.24.080(5)(c)(iv) be reworded to read: "an assessment of the probable direct and indirect impacts to the critical area(s) and buffer(s) resulting from the proposed development; and, an assessment of the cumulative impacts to the critical area resulting from the existing and proposed development".

Critical Areas Report Language Consistence

SCC 14.24.080.5(b) requires that the critical area report 'must be completed as follows', but then the subsequent bullets all refer to a "site assessment". We suggest replacing "site assessment" with "critical areas report" for clarity and consistency.

PCA Tract Ownership Unnecessarily Restricted
Development proposals proximal to critical areas may result in the designation of a Protected Critical Area (PCA), in some cases resulting in the PCA being placed in a separate ownership tract (SCC 14.24.090(5)(b). The code specifies that ownership may then be "transferred to the County, homeowners' association, or land trust." A tract may be a fully separate parcel (RCW 84.04.130). This drafted language specificity undermines the rights of a property owner to select the best or most financially advantageous owner for their PCA tract. There are other options for PCA ownership that are not listed, such as a Tribal government, an electrical utility, an adjacent City, or an interested neighbor. It is unfair and without any basis to limit the financial options and personal interests of the property owner of the PCA to just these specific ownership scenarios. The essential component of any ownership of a PCA must be to uphold the terms and conditions of the PCA agreement, and it is unnecessary for the County to weigh in on any other relationship. If the County feels strongly about providing example ownership arrangements within this code, we suggest adding the language "for example" or "such as."

Inconsistent Use of FWHCA and HCA throughout CAO
There is a mix of references to Fish and Wildlife Habitat Conservation Areas, Fish and Wildlife HCAs, FWHCAs, and simply HCAs. All are used interchangeably. For accuracy and consistency, these are not all interchangeable. The Tribe has particular concern about referring simply to a 'HCA'. This section should be revised for consistency and accuracy.

Incomplete Critical Areas Report Evaluation Procedures, Failure to Require Completeness and Accuracy
In SCC 14.24.100, there is no description of how or on what criteria Skagit County might review a completed Critical Areas Report or how and on what basis the County might make its determination of approval or disapproval. These are fundamental components that are simply missing. There is also no assurance that an interested party can submit best science and technical information into the record where a critical areas report is incomplete. There should be a statement that the County will review **"the critical areas assessment report for completeness and accuracy using best available science and shall consider the recommendations and conclusions of the critical areas assessment report, and other credible technical information submitted to the record by an interested party, to assist the County in making administrative decisions concerning approval, conditional approval, or denial of the subject project and to resolve issues concerning critical areas jurisdiction and appropriate mitigation and protective measures."** Without this type of statement, there is no regulatory certainty for project proponents about how a critical areas report will be evaluated, and seemingly limits Skagit County or an interested party from asking for any changes or additions to a Critical Areas Report. This conflicts with SCC 14.24.050 which directs that the County "will utilize data from natural resource agencies as a source of best available science when reviewing sites and critical areas reports." This direction, as well as ensuring that the best science and technical information can submitted to the record should be brought forward into SCC 14.24.100 in order to actually allow the County to utilize the best science and technical information submitted to the record from natural resources agencies and interested parties.[3] Only then can critical areas be assured complete and accurate protection.

Obsolete Reference to Rescinded Permit Programmatic
SCC 14.24.120(4)(d) refers to the Tidegate-Fish Initiative, which was an agreement signed by participating Drainage, Diking and Irrigation Districts, Western Washington Agriculture Association (WWAA), the Washington Department of Fish and Wildlife (WDFW), the National Marine Fisheries Service (NMFS), and the US Fish and Wildlife Service (USFWS). The intent of the agreement was to provide delta-wide coverage for districts to comply with federal permitting through the US Army Corps of Engineers (USACE), comply ESA consultation requirements, and ensure estuary habitat restoration occurred in the Skagit and Samish deltas at a pace to help achieve Skagit Chinook Recovery Plan habitat goals. In 2010 a supporting ESA Section 7 biological opinion was written and signed by NMFS. The programmatic permit coverage through the USACE was revoked in 2021. Districts are in negotiations to develop a new program for regulatory permit coverage, but none is in place at this time. Meanwhile, tidegates are being federally permitted on an individual basis. Please remove the reference to the "Tidegate Fish Initiative".

Issuance of a Reasonable Use Exception Must Result in No Net Loss of Critical Areas
An essential criteria for approval of a Reasonable Use Exception (RUE) is that the proposed development results in No Net Loss of Critical Areas ecological functions and values. Proposed language in SCC 14.24.140(6) describes the Decision Criteria, and the No Net Loss requirement must be clearly stated as a requirement of RUE approval. The provided language includes statements like "limiting disturbance", "less impact" on critical areas, "minimize impacts to priority habitats and species". But when it comes to mitigating for all remaining impacts, this is only indirectly required in the Review Criteria. **Unless and until an RUE proposal can fully demonstrate that it will achieve no net loss through avoidance, minimization or mitigation (in that order as required by WAC 197-11-768) of any impacts to the critical area then the RUE cannot be granted.**

Further, SCC 14.24.140(6)(a) limits the consideration to "impacts on wetlands, fish and wildlife habitat conservation areas, or buffers", but the County must consider all critical areas and their buffers (wetlands, CARAs, FFAs, geologically hazardous areas, and FWHCAs) for RUE proposals to achieve the no net loss standard. The Gap Analysis is in agreement with this concern, stating on page 14 that, "we recommend that the reasonable use exception require no net loss of ecological function." Since "No Net Loss" of ecological functions and values is an essential requirement of the CAO, we believe that this criteria should be explicit in the Review Criteria, and request its inclusion at SCC 14.24.140(6)(e).

Variance Requirements Relation to RUE Application
SCC 14.24.150(3) describes the elements of Hearing Examiner (HE) decision making for a Variance request. All elements (a)-(g) must have an HE finding, and as such, the word "and" needs to be added at the end of (f) to make it clear that (a)-(g) each require the finding.

Protected Critical Areas and Density Area Calculations
For "Protected Critical Areas (PCA) Designations for New Land Divisions" under SCC 14.24.090(5)(a), the drafted code indicates that the "Areas within a PCA can be included in the total acreage for development purposes and may be used in lot area or density calculations."

And under SCC 14.24.190(1)(c) the County proposes a Density Credit for residential uses from the area of the property containing the critical area to areas without critical areas, provided that this "does not create a density greater than that allowed under SCC 14.18.310(2)". We are concerned that this added statement is overly focused on Conservation and Reserve Development (CaRD) lots but ignores densities on other types of lots.

SCC 14.18.310(2) describes the allowable densities for "Maximum Residential Densities with a CaRD" and provides some limited exceptions regarding septic and water requirements. However, this should also include the general residential densities across zoning types which are described in SCC 14.16.030. Any increase in density must ensure that it has a legally allowable and adequate source of water. This language should be revised to read "Does not create a density greater than that allowed under SCC 14.18.310(2) or SCC 14.16.030".

Measures to Minimize Land Use Impacts Must Result in No Net Loss
High intensity land uses may need a broad buffer to protect the functions and values of wetlands. Examples of high intensity land uses are described in Table 8C-3 (Appendix 8-C of modified Ecology Publication 05-06-008[4]) include commercial, industrial, dense residential, and dairies. The drafted code language suggests in SCC 14.24.230(1)(d) that a high impact land use may apply moderate impact land use buffers if "measures to minimize impacts to wetlands from high impact land uses are implemented." But **this is not what the Best Available Science indicates**.

The BAS resource "Department of Ecology Publication No. 05-06-008, Wetlands in Washington State, Volume 2" – already cited in the proposed code – provides "Special Conditions for a Possible Reduction in Buffer Widths". The buffer reductions suggested in the draft language **must result in no net loss**. The BAS[5] suggesting the possibility for a buffer reduction based on land use states that:

Condition 1: Reduction in Buffer Width Based on Reducing the Intensity of Impacts from Proposed Land Uses
The buffer widths recommended for proposed land uses with high-intensity impacts to wetlands can be reduced to those recommended for moderate-intensity impacts under the following conditions:

1) *For wetlands that score moderate or high for habitat (6 points or more for the habitat functions), the width of the buffer can be reduced if both of the following criteria are met:*
    a. *A relatively undisturbed, vegetated corridor at least 100-feet wide is protected between the wetland and any other Priority Habitats as defined by the Washington State Department of Fish and Wildlife. The latest definitions of priority habitats and their locations are available on the WDFW web site at: http://wdfw.wa.gov/hab/phshabs.htm). The corridor must be protected for the entire distance between the wetland and the Priority Habitat by some type of legal protection such as a conservation easement.*
2) *Measures to minimize the impacts of different land uses on wetlands, such as the examples summarized in Table 8C-8, are applied. For wetlands that score less than 6 points for habitat, the buffer width can be reduced to that required for moderate land-use impacts by applying measures to minimize the impacts of the proposed land uses (see examples in Table 8C-8).*

The essential component when considering a reduction in the buffer widths based upon land use is the no net loss requirement for impacts to habitat functions and values. This section must be revised to refer more directly to the wetland guidance language in its entirety, and to specify that any "measures to minimize impacts" must be evaluated to ensure that they will fully achieve no net loss to habitat functions and values.

Forage Fish are indicators of Fish and Wildlife Habitat Conservation Area
The CAO fails to designate forage fish spawning areas as a FWHCA. This is counter to the BAS, does not adopt the Gap Analysis recommendations, and is conflict with WAC and RCW.

The Gap Analysis (p. 22) acknowledged the role of sand lance and other common forage fish, stating "we recommend including other forage fish spawning areas to maintain consistency with the GMA and provide protection for these habitats." Further, WAC 365-190-130(2)(d) requires that in addition to herring and smelt spawning areas, other forage fish spawning areas must be considered for classification and designation. Because of the requirement in RCW 36.70A.172(1) where "counties shall give special consideration to conservation or protection measures necessary to preserve or enhance anadromous fisheries", and because of the role of forage fish in supporting the marine foodweb, which supports ESA-threatened anadromous fish as well as ESA-endangered Southern Resident Killer Whales, the language in SCC 14.24.500 must be revised to designate "forage fish spawning areas" as a critical area.

FWHCA Water Type Classifications Mis-Represent State Criteria
The FWHCA regulations provide an overview of the Type S, F, Ns, Np stream classification structure and refer to WAC 222-16-030. Unfortunately, the summary statements about each stream type used in the draft SCC fail to capture details that are essential to appropriate application of the stream types. The Tribe is seriously concerned the lack of clarity in the Draft CAO will lead to mis-application of rules and protections as written.

These stream classifications are ubiquitous across state[6][7], and even Federal[8] regulations. However, the language shown in draft SCC 14.24.510 does not represent the factual use of those classifications for Type S, F, Ns, Np streams. For Type S, the definition is for 20 cubic feet per second (cfs) of mean annual flow and not 'averaging'. Additionally, WAC 222-16-030 states that Type S waters include associated wetlands. This detail is important because many Type S waters contain abundant floodplain off-channel wetlands that provide critical habitat functions for salmon and other wildlife.

Much more concerning, however, is the description for the Type F stream. The WAC is referenced in SCC 14.24.510, but in practice, the Department of Natural Resources (DNR) implements the rule using the Forest Practices Board Manual, which directs that:

"Waters meeting the physical characteristics for Type F streams described in this rule are presumed to have fish use unless a protocol survey or ID Team has verified otherwise."[9]

The methods for determining fish use commonly understood across natural resources specialists and are delineated in the Forest Practices Board Manual 13[10], which essentially presumes fish presence if the stream meets the physical criteria unless proven otherwise. The description in the SCC for Type F waters is concerning, because the WAC reference does not include important DNR Board Manual Methodology and DNR Policies that are essential to the application of the WAC. Experience indicates that a lay audience is not very good at assessing fish use, and this must not be left to property owners, or even consultants who visit the site at a single moment in time. In particular, anadromous fish deserve special consideration by the County under RCW 36.70A.172(1), and so are defined by their migratory life history. One observation of a lack of fish presence absolutely does not indicate that a stream is Type N.

In addition, in the coming weeks (June 6, 2025) the Forest Practices Board is expected to vote to ratify a permanent water typing rule[11] containing changes to the water typing system that are relevant to Skagit County code. The Tribe recommends that the County delay approving changes to the CAO code until after June 6 to adequately incorporate the expected changes to WAC 222-16-030.

Several important changes to this rule are expected that are relevant to County FWHCA:

- A new section of WAC is expected to be added (222-16-0301) 'Verification of fish habitat and break between Type F and Type N water'. In this section, a new component of the water typing system is established that is highly relevant to county regulations. The new component is called the Anadromous Fish Floor (AFF), which is a portion of the landscape that is assumed to contain fish whether or not fish are present on any particular day. Low gradient streams, wetlands and sloughs may provide important habitat for salmon even if salmon are not present during the typical water typing survey window. The AFF provides regulatory certainty for landowners by defining where protocol water typing surveys and default physical criteria for fish habitat may be utilized. The Tribe urges the County to incorporate this important concept into the CAO to reduce the chances of erroneously missing fish habitat.
- The new water typing system, including delineation of the AFF and implementation of field-based water typing surveys, will rely on a new Board Manual (section 23) for technical guidance. The Tribe recommends that the County require use of Board Manual 23 for determining water types.
- The new rule codifies the inclusion of off-channel habitat as Type F water. Off-channel habitats form important rearing areas for threatened and other species and must be protected as critical components of Type F water. If the county chooses to repeat water typing definitions from 222-30-30, important details such as off-channel habitat should not be neglected.

Additionally, it is our understanding that Skagit County Forest Advisory Board (FAB) Chair has submitted comments in support of these proposed water typing rule changes on behalf of Skagit County[12]. The Tribe suggests coordinating with FAB to ensure current references are incorporated into the CAO and that the County remains consistent in its recommendations and implementation of stream water practices.

In order to address these concerns, the Tribe suggests that the SCC simply follow WAC 222-16-030 and not summarize its language. If SCC does wish to summarize, then the Draft CAO language should be revised to include the important role of wetlands in Type F waters and emphasize the guidance which evaluates a stream's physical characteristics for the Type F designation.

BAS for Riparian Areas is Incomplete

The BAS document[13] provided as a companion to this CAO update refers frequently to the WDFW guidance Riparian Ecosystems, Volume 2: Management Recommendations, compiled by Terra Rentz, et al. This document

uses this citation (Rentz et al. 2020) in at least 7 locations. The Gap Analysis puts forward recommendations made in this document. But the WDFW Vol. 2 document – nor the WDFW Volume 1 Riparian Ecosystems that is peer-reviewed best science on riparian habitat buffer widths - are not included in the References list of the BAS that begins on page 59. The Tribe requests that these important technical documents are incorporated into the Best Available Science for the Critical Areas update and included in the Reference list of the BAS.

Proposed Buffers on Streams Do Not Follow BAS

The draft language in SCC 14.24.530.(1)(c) describe the Standard Buffer Widths proposed by the County in this CAO update, but these widths do not represent the best available science on the topic. Seeing that many of the waterbodies that these codes would be applied to are essential spawning, migration, or rearing habitat for anadromous fish, the County must give special consideration to conservation or protection measures necessary for these habitats (RCW 36.70A.172(1)).

As the BAS review describes, WDFW guidance[14] describes a shift from stream buffers to riparian management zones (RMZ) and recommends the RMZ is regulated as a FWHCA to protect its fundamental value, rather than as a buffer for a river or stream. Buffers do not provide full riparian function or a close approximation of it. Rather, WDFW recommends that "RMZs be considered a delineable, regulatory critical area and the guidance be applied to all streams and rivers, regardless of size and type." The WDFW recommendations provide a web-based mapping tool[15] for determining the site potential tree height for a given locale. Importantly, the WDFW recommends that the RMZ width is measured from the outer edge of the channel migration zone (if present) or the ordinary high-water mark, whichever is most landward.

The Tribe objects to the approach to riparian zone delineation that the Draft CAO has proposed because it provides sub-standard conservation and protection for streams associated with anadromous salmon. The Tribe recommends that the County revise its CAO to fully incorporate the WDFW recommendations for RMZs.

Buffer Width Enhancement Should Address Sub-standard Buffer Conditions

In SCC 14.24.530(1)(c)(i), the Draft CAO states that a "Standard Riparian Buffer Width" presumes that the buffer is in good and functioning condition, and provides performance standards for determining eligibility for a standard buffer width. The Draft CAO also indicates that if the existing buffer does not presently meet the performance standards in that item, that enhancement and/or increased width must be required. This is an important opportunity to codify that buffer width increase, and should be incorporated into SCC 14.24.540 by adding SCC 14.24.540(1)(c) and describes that scenario presented in SCC 14.24.530(1)(c)(i).

Summary and Conclusion

SRSC has identified numerous concerns primarily because of the obligation for the County to give special consideration to conservation or protection measures necessary to preserve or enhance anadromous fisheries, as described in the comments herein. We request that Skagit County incorporate the suggested revisions in order to produce an improved ordinance for protecting Skagit County's vast critical areas.

Thank you for consideration of our comments.

Sincerely,

Nora Kammer
Habitat Protection Program Director
Skagit River System Cooperative
MAILING: PO Box 368, La Conner, WA 98257
PHYSICAL: 11426 Moorage Way, La Conner, WA 98257
Phone: 360.391.8472
Fax: 360.466.4047

SRSC's offices are open Monday through Thursday.

[1]https://www.skagitcounty.net/PlanningAndPermit/Documents/compplan2025/Skagit%20County%20BAS%202.24.2025%20-%20FINAL.pdf
[2]https://www.skagitcounty.net/PlanningAndPermit/Documents/compplan2025/Skagit%20CAO%20Gap%20Analysis%202025.02%20-%20FINAL.pdf
[3] If this agency data exists, and is accepted as the best available science, but was excluded from the Critical Areas Report, the County needs a means to ensure that data is brought to the proposal and assessment to ensure protection of critical areas and safety. For example, if an applicant proposes a development on an unstable slope, but the Critical Areas Report fails to utilize available information from DNR Landslide Mapping that demonstrates a potential risk, the County or an interested party should be able to review and determine a need for further assessment.
[4] Washington Department of Ecology (ECY). (2018). Appendix 8-C: Guidance on buffers and ratios for Western Washington wetlands in Washington State volume 2 – Protecting and managing wetlands. https://apps.ecology.wa.gov/publications/parts/0506008part3.pdf
[5] Washington Department of Ecology (ECY). (2018). Appendix 8-C: Guidance on buffers and ratios for Western Washington wetlands in Washington State volume 2 – Protecting and managing wetlands. https://apps.ecology.wa.gov/publications/parts/0506008part3.pdf
[6] https://app.leg.wa.gov/waC/default.aspx?cite=222-16-030
[7] https://app.leg.wa.gov/WAC/default.aspx/default.aspx?cite=220-660
[8] https://ecology.wa.gov/getattachment/56d82d6b-5a68-411e-97d5-5a432aec30c1/NFIP_Puget-Sound_Biological_Opinion_w_Errata_2008.pdf in Appendix 4
[9] https://www.dnr.wa.gov/forest-practices-water-typing#:~:text=Type%20%22F%22%20%3D%20Fish,may%20be%20perennial%20or%20seasonal.
[10] https://www.dnr.wa.gov/publications/fp_board_manual_section13.pdf
[11] https://www.dnr.wa.gov/publications/bc_fpb_wts_rm_20250514.pdf
[12] https://www.dnr.wa.gov/publications/bc_fpb_wts_rm_20250514.pdf
[13]https://www.skagitcounty.net/PlanningAndPermit/Documents/compplan2025/Skagit%20County%20BAS%202.24.2025%20-%20FINAL.pdf
[14] Rentz, R., A. Windrope, K. Folkerts, and J. Azerrad. 2020. Riparian Ecosystems, Volume 2: Management Recommendations. Habitat Program, Washington Department of Fish and Wildlife, Olympia. 80 pp
[15] https://wdfw.maps.arcgis.com/apps/MapJournal/index.html?appid=35b39e40a2af447b9556ef1314a5622d

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May 8, 2025

Robby Eckroth, Senior Planner
Skagit County Planning and Development Services
1800 Continental Place
Mount Vernon, Washington 98273

Sent electronically via email to:

RE: Skagit County Critical Areas Ordinance Open for Public Comment

Dear Mr. Eckroth,

Background and setting for our objections and concerns

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Buffer enhancement activities are included in SCC 14.24.070(12-13) as activities allowed without standard review. However, the added language to subsection (12) actually makes riparian buffer enhancement activities more difficult to implement due to unnecessary requirements such as a review and approval by the Planning Director. Buffer enhancement activities include activities such as noxious weed management and installation and maintenance of native plant species. These activities should be streamlined for implementation rather than adding cumbersome procedural hurdles. As a result, **the Tribe objects** to SCC 14.24.070(12) as written, and request that SCC 14.24.070(12)(b) be removed from the code.

In addition, we request that SCC 14.24.070(12)(a) be modified to remove the first sentence, which restricts buffer enhancement activities to handheld equipment. Across Skagit County, the

vast majority of riparian enhancement activities conducted by entities such as the Skagit Conservation District, the Skagit Land Trust, the USFS, the Tribes, and others includes the use of a dingo-mounted auger and tractors for mowing between rows of installed trees until the trees are tall enough to shade competing grasses. The dingo-mounted auger is essential for the mental and physical well-being of the staff and volunteers who complete this work, as handheld augers result in high rates of injury and job dissatisfaction. Without this tool, the work becomes untenable. Tractor mowing planting areas is a mechanical management tool to control competing and/or non-native species and limits the use of sprayed herbicides that can achieve similar results. Tractor mowing is much preferred and without the ability to use this tool, the proposed code changes limit the ability to accomplish this work.

Skagit County's own BAS review[1] demonstrates the importance of healthy, functioning buffers to key critical areas, including wetlands, geologic hazard areas, and fish and wildlife habitat conservation areas. The BAS review recommends that the County "Promote buffers of adequate width to support wildlife guilds in adjacent habitat" (Ficetola et al. 2008; Semlitsch and Bodie 2003; Crawford and Semlitsch 2007), and to encourage stewardship on a parcel-by-parcel and county-wide scale.

Further, the Gap Analysis[2] provides a clear recommendation to the County for this section of code. The Gap Analysis suggests that the County "incentivize restoration and reduce potential permitting barriers". This special consideration for enhancement of fish and wildlife habitat conservation areas is directed by the Growth Management Act directly in RCW 36.70A.172(1), which states that: "counties shall give special consideration to conservation or protection measures necessary to preserve or enhance anadromous fisheries".

The Tribe objects to SCC 14.24.070(12) as currently drafted. We request that SCC 14.24.070(12)(b) be removed altogether, and substitute language suggested in the Gap Analysis that allows buffer enhancement without review "as long as the project is consistent with the chapter and does not harm critical areas or their buffers." We request that SCC 14.24.070(12)(a) be modified to remove the first sentence, which restricts enhancement activities to handheld equipment. We do not support the threshold of a 500 square foot riparian enhancement area being the threshold for no review as recommended in the Gap Analysis, since there is no basis for this limitation and the Standard Buffer Widths table in SCC 14.24.530.(1)(c), which includes buffer widths of 100-200 feet. Limiting a "no review" threshold to enhancement areas of 500 square feet or less would result in riparian buffer enhancement activities being only allowed on 2.5 to 5 feet of stream length without Director review, which is unreasonable and useless. This places an unnecessary review burden on projects intended to achieve meaningful riparian function. Any minimum threshold for projects that would not require Director review should be consistent with the chapter and ensure the project does not harm critical areas or their buffers.

[1]https://www.skagitcounty.net/PlanningAndPermit/Documents/compplan2025/Skagit%20County%20BAS%202.24.2025%20-%20FINAL.pdf

[2]https://www.skagitcounty.net/PlanningAndPermit/Documents/compplan2025/Skagit%20CAO%20Gap%20Analysis%202025.02%20-%20FINAL.pdf

Inconsistent Functions and Values of FWHCAs in Agricultural Lands Must be Corrected
The stated intent of the Ongoing Agriculture section (SCC 14.24.120) includes protection of Fish and Wildlife Habitat Conservation Areas ("FWHCAs") adjacent to watercourses. First, this excludes a number of FWHCAs described in SCC 14.24.500.1(a)-(l) that receive consideration in the current Skagit County critical areas code. The language in SCC 14.24.120 must be revised to be inclusive of all FWHCAs.

Further, SCC 14.24.120(1)(a) provides an incomplete list of the values and functions that are relevant to the Ongoing Agriculture section. It is unclear why the functions and values of interest in Agricultural Lands is limited to water quality, large woody debris, buffers characteristics and shade, and channel morphology, but in the FWHCAs other functions and values are included, such as bank integrity, runoff pollutant removal, wildlife habitat, microclimate, and nutrient input. These must be evaluated consistently. As a result, SCC 14.24.120(1)(a) must be revised to align and be consistent with the functions and values of other FWHCAs.

Critical Areas Report Requirements Confuse Existing and New Impacts
The drafted language for SCC 14.24.080(5)(c)(iv) requires that a critical areas report must include "an assessment of the probable direct and indirect impacts to the critical area(s) and buffer(s) as well as the cumulative impacts to the critical area resulting from the existing and proposed development." This inappropriately lumps existing impacts together with new impacts, which will create confusion and difficulty in assessing the impacts of a development under review. The existing impacts must be detailed and assessed separate from the proposed development and anticipated impacts that would not occur but for its approval and implementation.

Under SEPA rules, threshold determinations and probable adverse impacts of a proposed action are considered. If impacts from the proposed action are comingled with the impacts of the existing developments, there is no way to qualitatively or quantitively understand the scope and magnitude of the impacts of each action, make a threshold determination, or to establish appropriate mitigation for the proposed action. To address this concern, we recommend that SCC 14.24.080(5)(c)(iv) be reworded to read: "an assessment of the probable direct and indirect impacts to the critical area(s) and buffer(s) resulting from the proposed development; and, an assessment of the cumulative impacts to the critical area resulting from the existing and proposed development".

Critical Areas Report Language Consistence
SCC 14.24.080.5(b) requires that the critical area report 'must be completed as follows', but then the subsequent bullets all refer to a "site assessment". We suggest replacing "site assessment" with "critical areas report" for clarity and consistency.

PCA Tract Ownership Unnecessarily Restricted
Development proposals proximal to critical areas may result in the designation of a Protected Critical Area (PCA), in some cases resulting in the PCA being placed in a separate ownership tract (SCC 14.24.090(5)(b). The code specifies that ownership may then be "transferred to the County, homeowners' association, or land trust." A tract may be a fully separate parcel (RCW 84.04.130). This drafted language specificity undermines the rights of a property owner to select

the best or most financially advantageous owner for their PCA tract. There are other options for PCA ownership that are not listed, such as a Tribal government, an electrical utility, an adjacent City, or an interested neighbor. It is unfair and without any basis to limit the financial options and personal interests of the property owner of the PCA to just these specific ownership scenarios. The essential component of any ownership of a PCA must be to uphold the terms and conditions of the PCA agreement, and it is unnecessary for the County to weigh in on any other relationship. If the County feels strongly about providing example ownership arrangements within this code, we suggest adding the language "for example" or "such as."

Inconsistent Use of FWHCA and HCA throughout CAO

There is a mix of references to Fish and Wildlife Habitat Conservation Areas, Fish and Wildlife HCAs, FWHCAs, and simply HCAs. All are used interchangeably. For accuracy and consistency, these are not all interchangeable. The Tribe has particular concern about referring simply to a 'HCA'. This section should be revised for consistency and accuracy.

Incomplete Critical Areas Report Evaluation Procedures, Failure to Require Completeness and Accuracy

In SCC 14.24.100, there is no description of how or on what criteria Skagit County might review a completed Critical Areas Report or how and on what basis the County might make its determination of approval or disapproval. These are fundamental components that are simply missing. There is also no assurance that an interested party can submit best science and technical information into the record where a critical areas report is incomplete. There should be a statement that the County will review "**the critical areas assessment report for completeness and accuracy using best available science and shall consider the recommendations and conclusions of the critical areas assessment report, and other credible technical information submitted to the record by an interested party, to assist the County in making administrative decisions concerning approval, conditional approval, or denial of the subject project and to resolve issues concerning critical areas jurisdiction and appropriate mitigation and protective measures."** Without this type of statement, there is no regulatory certainty for project proponents about how a critical areas report will be evaluated, and seemingly limits Skagit County or an interested party from asking for any changes or additions to a Critical Areas Report. This conflicts with SCC 14.24.050 which directs that the County "will utilize data from natural resource agencies as a source of best available science when reviewing sites and critical areas reports." This direction, as well as ensuring that the best science and technical information can submitted to the record should be brought forward into SCC 14.24.100 in order to actually allow the County to utilize the best science and technical information submitted to the record from natural resources agencies and interested parties.[3] Only then can critical areas be assured complete and accurate protection.

[3] If this agency data exists, and is accepted as the best available science, but was excluded from the Critical Areas Report, the County needs a means to ensure that data is brought to the proposal and assessment to ensure protection of critical areas and safety. For example, if an applicant proposes a development on an unstable slope, but the Critical Areas Report fails to utilize available information from DNR Landslide Mapping that demonstrates a potential risk, the County or an interested party should be able to review and determine a need for further assessment.

Obsolete Reference to Rescinded Permit Programmatic
SCC 14.24.120(4)(d) refers to the Tidegate-Fish Initiative, which was an agreement signed by participating Drainage, Diking and Irrigation Districts, Western Washington Agriculture Association (WWAA), the Washington Department of Fish and Wildlife (WDFW), the National Marine Fisheries Service (NMFS), and the US Fish and Wildlife Service (USFWS). The intent of the agreement was to provide delta-wide coverage for districts to comply with federal permitting through the US Army Corps of Engineers (USACE), comply ESA consultation requirements, and ensure estuary habitat restoration occurred in the Skagit and Samish deltas at a pace to help achieve Skagit Chinook Recovery Plan habitat goals. In 2010 a supporting ESA Section 7 biological opinion was written and signed by NMFS. The programmatic permit coverage through the USACE was revoked in 2021. Districts are in negotiations to develop a new program for regulatory permit coverage, but none is in place at this time. Meanwhile, tidegates are being federally permitted on an individual basis. Please remove the reference to the "Tidegate Fish Initiative".

Issuance of a Reasonable Use Exception Must Result in No Net Loss of Critical Areas
An essential criteria for approval of a Reasonable Use Exception (RUE) is that the proposed development results in No Net Loss of Critical Areas ecological functions and values. Proposed language in SCC 14.24.140(6) describes the Decision Criteria, and the No Net Loss requirement must be clearly stated as a requirement of RUE approval. The provided language includes statements like "limiting disturbance", "less impact" on critical areas, "minimize impacts to priority habitats and species". But when it comes to mitigating for all remaining impacts, this is only indirectly required in the Review Criteria. **Unless and until an RUE proposal can fully demonstrate that it will achieve no net loss through avoidance, minimization or mitigation (in that order as required by WAC 197-11-768) of any impacts to the critical area then the RUE cannot be granted.**

Further, SCC 14.24.140(6)(a) limits the consideration to "impacts on wetlands, fish and wildlife habitat conservation areas, or buffers", but the County must consider <u>all</u> critical areas and their buffers (wetlands, CARAs, FFAs, geologically hazardous areas, and FWHCAs) for RUE proposals to achieve the no net loss standard.
<u>The Gap Analysis is in agreement with this concern, stating on page 14 that, "we recommend that the reasonable use exception require no net loss of ecological function." Since "No Net Loss" of ecological functions and values is an essential requirement of the CAO, we believe that this criteria should be explicit in the Review Criteria, and request its inclusion at SCC 14.24.140(6)(e).</u>

Variance Requirements Relation to RUE Application
SCC 14.24.150(3) describes the elements of Hearing Examiner (HE) decision making for a Variance request. All elements (a)-(g) must have an HE finding, and as such, the word "and" needs to be added at the end of (f) to make it clear that (a)-(g) each require the finding.

Protected Critical Areas and Density Area Calculations
For "Protected Critical Areas (PCA) Designations for New Land Divisions" under SCC 14.24.090(5)(a), the drafted code indicates that the "Areas within a PCA can be included in the total acreage for development purposes and may be used in lot area or density calculations."

And under SCC 14.24.190(1)(c) the County proposes a Density Credit for residential uses from the area of the property containing the critical area to areas without critical areas, provided that this "does not create a density greater than that allowed under SCC 14.18.310(2)". We are concerned that this added statement is overly focused on Conservation and Reserve Development (CaRD) lots but ignores densities on other types of lots.

SCC 14.18.310(2) describes the allowable densities for "Maximum Residential Densities with a CaRD" and provides some limited exceptions regarding septic and water requirements. However, this should also include the general residential densities across zoning types which are described in SCC 14.16.030. Any increase in density must ensure that it has a legally allowable and adequate source of water. This language should be revised to read "Does not create a density greater than that allowed under SCC 14.18.310(2) or SCC 14.16.030".

Measures to Minimize Land Use Impacts Must Result in No Net Loss

High intensity land uses may need a broad buffer to protect the functions and values of wetlands. Examples of high intensity land uses are described in Table 8C-3 (Appendix 8-C of modified Ecology Publication 05-06-008[4]) include commercial, industrial, dense residential, and dairies. The drafted code language suggests in SCC 14.24.230(1)(d) that a high impact land use may apply moderate impact land use buffers if "measures to minimize impacts to wetlands from high impact land uses are implemented." But **this is not what the Best Available Science indicates**.

The BAS resource "Department of Ecology Publication No. 05-06-008, Wetlands in Washington State, Volume 2" – already cited in the proposed code – provides "Special Conditions for a Possible Reduction in Buffer Widths". The buffer reductions suggested in the draft language **must result in no net loss**. The BAS[5] suggesting the possibility for a buffer reduction based on land use states that:

Condition 1: Reduction in Buffer Width Based on Reducing the Intensity of Impacts from Proposed Land Uses

The buffer widths recommended for proposed land uses with high-intensity impacts to wetlands can be reduced to those recommended for moderate-intensity impacts under the following conditions:

1) *For wetlands that score moderate or high for habitat (6 points or more for the habitat functions), the width of the buffer can be reduced if both of the following criteria are met:*
    a. *A relatively undisturbed, vegetated corridor at least 100-feet wide is protected between the wetland and any other Priority Habitats as defined by the Washington State Department of Fish and Wildlife. The latest*

[4] Washington Department of Ecology (ECY). (2018). Appendix 8-C: Guidance on buffers and ratios for Western Washington wetlands in Washington State volume 2 – Protecting and managing wetlands. https://apps.ecology.wa.gov/publications/parts/0506008part3.pdf

[5] Washington Department of Ecology (ECY). (2018). Appendix 8-C: Guidance on buffers and ratios for Western Washington wetlands in Washington State volume 2 – Protecting and managing wetlands. https://apps.ecology.wa.gov/publications/parts/0506008part3.pdf

definitions of priority habitats and their locations are available on the WDFW web site at: http://wdfw.wa.gov/hab/phshabs.htm). The corridor must be protected for the entire distance between the wetland and the Priority Habitat by some type of legal protection such as a conservation easement.

2) *Measures to minimize the impacts of different land uses on wetlands, such as the examples summarized in Table 8C-8, are applied. For wetlands that score less than 6 points for habitat, the buffer width can be reduced to that required for moderate land-use impacts by applying measures to minimize the impacts of the proposed land uses (see examples in Table 8C-8).*

The essential component when considering a reduction in the buffer widths based upon land use is the no net loss requirement for impacts to habitat functions and values. This section must be revised to refer more directly to the wetland guidance language in its entirety, and to specify that any "measures to minimize impacts" must be evaluated to ensure that they will fully achieve no net loss to habitat functions and values.

Forage Fish are indicators of Fish and Wildlife Habitat Conservation Area
The CAO fails to designate forage fish spawning areas as a FWHCA. This is counter to the BAS, does not adopt the Gap Analysis recommendations, and is conflict with WAC and RCW.

The Gap Analysis (p. 22) acknowledged the role of sand lance and other common forage fish, stating "we recommend including other forage fish spawning areas to maintain consistency with the GMA and provide protection for these habitats." Further, WAC 365-190-130(2)(d) requires that in addition to herring and smelt spawning areas, other forage fish spawning areas must be considered for classification and designation. Because of the requirement in RCW 36.70A.172(1) where "counties shall give special consideration to conservation or protection measures necessary to preserve or enhance anadromous fisheries", and because of the role of forage fish in supporting the marine foodweb, which supports ESA-threatened anadromous fish as well as ESA-endangered Southern Resident Killer Whales, the language in SCC 14.24.500 must be revised to designate "forage fish spawning areas" as a critical area.

FWHCA Water Type Classifications Mis-Represent State Criteria
The FWHCA regulations provide an overview of the Type S, F, Ns, Np stream classification structure and refer to WAC 222-16-030. Unfortunately, the summary statements about each stream type used in the draft SCC fail to capture details that are essential to appropriate application of the stream types. The Tribe is seriously concerned the lack of clarity in the Draft CAO will lead to mis-application of rules and protections as written.

These stream classifications are ubiquitous across state[6][7], and even Federal[8] regulations. However, the language shown in draft SCC 14.24.510 does not represent the factual use of those classifications for Type S, F, Ns, Np streams. For Type S, the definition is for 20 cubic feet per

[6] https://app.leg.wa.gov/waC/default.aspx?cite=222-16-030
[7] https://app.leg.wa.gov/WAC/default.aspx/default.aspx?cite=220-660
[8] https://ecology.wa.gov/getattachment/56d82d6b-5a68-411e-97d5-5a432aec30c1/NFIP_Puget-Sound_Biological_Opinion_w_Errata_2008.pdf in Appendix 4

second (cfs) of mean annual flow and not 'averaging'. Additionally, WAC 222-16-030 states that Type S waters include associated wetlands. This detail is important because many Type S waters contain abundant floodplain off-channel wetlands that provide critical habitat functions for salmon and other wildlife.

Much more concerning, however, is the description for the Type F stream. The WAC is referenced in SCC 14.24.510, but in practice, the Department of Natural Resources (DNR) implements the rule using the Forest Practices Board Manual, which directs that:

"Waters meeting the physical characteristics for Type F streams described in this rule are presumed to have fish use unless a protocol survey or ID Team has verified otherwise."[9]

The methods for determining fish use commonly understood across natural resources specialists and are delineated in the Forest Practices Board Manual 13[10], which essentially presumes fish presence if the stream meets the physical criteria unless proven otherwise. The description in the SCC for Type F waters is concerning, because the WAC reference does not include important DNR Board Manual Methodology and DNR Policies that are essential to the application of the WAC. Experience indicates that a lay audience is not very good at assessing fish use, and this must not be left to property owners, or even consultants who visit the site at a single moment in time. In particular, anadromous fish deserve special consideration by the County under RCW 36.70A.172(1), and so are defined by their migratory life history. <u>One observation of a lack of fish presence absolutely does not indicate that a stream is Type N.</u>

In addition, in the coming weeks (June 6, 2025) the Forest Practices Board is expected to vote to ratify a permanent water typing rule[11] containing changes to the water typing system that are relevant to Skagit County code. <u>The Tribe recommends that the County delay approving changes to the CAO code until after June 6 to adequately incorporate the expected changes to WAC 222-16-030.</u>

Several important changes to this rule are expected that are relevant to County FWHCA:

- A new section of WAC is expected to be added (222-16-0301) 'Verification of fish habitat and break between Type F and Type N water'. In this section, a new component of the water typing system is established that is highly relevant to county regulations. The new component is called the Anadromous Fish Floor (AFF), which is a portion of the landscape that is assumed to contain fish whether or not fish are present on any particular day. Low gradient streams, wetlands and sloughs may provide important habitat for salmon even if salmon are not present during the typical water typing survey window. The AFF provides regulatory certainty for landowners by defining where protocol water typing surveys and default physical criteria for fish habitat may be utilized. <u>The Tribe urges the County to incorporate</u>

[9] https://www.dnr.wa.gov/forest-practices-water-typing#:~:text=Type%20%22F%22%20%3D%20Fish,may%20be%20perennial%20or%20seasonal.
[10] https://www.dnr.wa.gov/publications/fp_board_manual_section13.pdf
[11] https://www.dnr.wa.gov/publications/bc_fpb_wts_rm_20250514.pdf

this important concept into the CAO to reduce the chances of erroneously missing fish habitat.

- The new water typing system, including delineation of the AFF and implementation of field-based water typing surveys, will rely on a new Board Manual (section 23) for technical guidance. The Tribe recommends that the County require use of Board Manual 23 for determining water types.
- The new rule codifies the inclusion of off-channel habitat as Type F water. Off-channel habitats form important rearing areas for threatened and other species and must be protected as critical components of Type F water. If the county chooses to repeat water typing definitions from 222-30-30, important details such as off-channel habitat should not be neglected.

Additionally, it is our understanding that Skagit County Forest Advisory Board (FAB) Chair has submitted comments in support of these proposed water typing rule changes on behalf of Skagit County[12]. The Tribe suggests coordinating with FAB to ensure current references are incorporated into the CAO and that the County remains consistent in its recommendations and implementation of stream water practices.

In order to address these concerns, the Tribe suggests that the SCC simply follow WAC 222-16-030 and not summarize its language. If SCC does wish to summarize, then the Draft CAO language should be revised to include the important role of wetlands in Type F waters and emphasize the guidance which evaluates a stream's physical characteristics for the Type F designation.

BAS for Riparian Areas is Incomplete

The BAS document[13] provided as a companion to this CAO update refers frequently to the WDFW guidance Riparian Ecosystems, Volume 2: Management Recommendations, compiled by Terra Rentz, et al. This document uses this citation (Rentz et al. 2020) in at least 7 locations. The Gap Analysis puts forward recommendations made in this document. But the WDFW Vol. 2 document – nor the WDFW Volume 1 Riparian Ecosystems that is peer-reviewed best science on riparian habitat buffer widths - are not included in the References list of the BAS that begins on page 59. The Tribe requests that these important technical documents are incorporated into the Best Available Science for the Critical Areas update and included in the Reference list of the BAS.

Proposed Buffers on Streams Do Not Follow BAS

The draft language in SCC 14.24.530.(1)(c) describe the Standard Buffer Widths proposed by the County in this CAO update, but these widths do not represent the best available science on the topic. Seeing that many of the waterbodies that these codes would be applied to are essential spawning, migration, or rearing habitat for anadromous fish, the County must give special consideration to conservation or protection measures necessary for these habitats (RCW 36.70A.172(1)).

[12] https://www.dnr.wa.gov/publications/bc_fpb_wts_rm_20250514.pdf

[13]https://www.skagitcounty.net/PlanningAndPermit/Documents/compplan2025/Skagit%20County%20BAS%202.24.2025%20-%20FINAL.pdf

As the BAS review describes, WDFW guidance[14] describes a shift from stream buffers to riparian management zones (RMZ) and recommends the RMZ is regulated as a FWHCA to protect its fundamental value, rather than as a buffer for a river or stream. Buffers do not provide full riparian function or a close approximation of it. Rather, WDFW recommends that "RMZs be considered a delineable, regulatory critical area and the guidance be applied to all streams and rivers, regardless of size and type." The WDFW recommendations provide a web-based mapping tool[15] for determining the site potential tree height for a given locale. Importantly, the WDFW recommends that the RMZ width is measured from the outer edge of the channel migration zone (if present) or the ordinary high-water mark, whichever is most landward.

The Tribe objects to the approach to riparian zone delineation that the Draft CAO has proposed because it provides sub-standard conservation and protection for streams associated with anadromous salmon. The Tribe recommends that the County revise its CAO to fully incorporate the WDFW recommendations for RMZs.

Buffer Width Enhancement Should Address Sub-standard Buffer Conditions
In SCC 14.24.530(1)(c)(i), the Draft CAO states that a "Standard Riparian Buffer Width" presumes that the buffer is in good and functioning condition, and provides performance standards for determining eligibility for a standard buffer width. The Draft CAO also indicates that if the existing buffer does not presently meet the performance standards in that item, that enhancement and/or increased width must be required. This is an important opportunity to codify that buffer width increase, and should be incorporated into SCC 14.24.540 by adding SCC 14.24.540(1)(c) and describes that scenario presented in SCC 14.24.530(1)(c)(i).

Summary and Conclusion
SRSC has identified numerous concerns primarily because of the obligation for the County to give special consideration to conservation or protection measures necessary to preserve or enhance anadromous fisheries, as described in the comments herein. We request that Skagit County incorporate the suggested revisions in order to produce an improved ordinance for protecting Skagit County's vast critical areas.

Thank you for consideration of our comments.

Sincerely,



Nora Kammer, Habitat Protection Program Director

[14] Rentz, R., A. Windrope, K. Folkerts, and J. Azerrad. 2020. Riparian Ecosystems, Volume 2: Management Recommendations. Habitat Program, Washington Department of Fish and Wildlife, Olympia. 80 pp
[15] https://wdfw.maps.arcgis.com/apps/MapJournal/index.html?appid=35b39e40a2af447b9556ef1314a5622d

Comment #23

Skagit Audubon Society
P.O. Box 1101
Mount Vernon, WA 98273

RECEIVED
MAY 08 2025
SKAGIT COUNTY PDS

May 8, 2025

Planning and Development Services
Comments on "2025 Development Regulations and Critical Areas Ordinance Update"
1800 Continental Place
Mount Vernon WA 98273

Dear Skagit County Commissioners, Planning Commission, and Planning & Development Services Staff:

We appreciate the opportunity to comment on the draft update of Skagit County's Critical Areas Ordinance (CAO). The following comments are on behalf of the 494 members of Skagit Audubon Society, the National Audubon chapter focused on Skagit County. Skagit Audubon's members share the organization's mission of protecting birds and other wildlife and preserving or restoring wildlife habitat. All Skagit Audubon members appreciate that our county's natural and managed landscapes support numerous bird species and, in many cases, significant numbers of these species. This abundance attracts people to visit or live in Skagit County. Our organization is dedicated to preserving and enhancing what is best about our home in this regard. We appreciate Skagit County's rural lands, its undeveloped habitat areas, and its bays and rivers that support diverse and abundant bird populations.

Please accept our gratitude for the work of the Planning & Development Services staff and of the county's contractors, Kimley-Horn and Associates, Facet, and Ryan Walters Law, in updating the draft revised CAO and Development Regulations and compiling the associated reports.

WE offer the following comments on a few aspects of the Critical Areas Ordinance. All page references are to the red-lined version. The words of the CAO are in bold.

1. 14.24.020 Title and purpose.
We are happy to see that the statement of purpose has been revised to reflect the state regulation that critical areas be protected under a standard of no net loss of ecological functions.[1] However, this change to the CAO must not replace a first priority of protecting existing critical areas as they are. Mitigation, which is not always successful, is not an equal substitute for protection. Also, there are instances where we believe it appropriate to set a higher standard of net ecological gain, but a declarative standard of no net loss, understood in the context described above, is a positive step.

2. (5) PCA Designations for New Land Divisions.
(e) PCA Maintenance. "The PCA is to be left undisturbed in its natural state."[2]
We appreciate the emphasis here and elsewhere in the CAO on leaving Protected Critical Areas (PCA) in their natural state. However, we suggest adding, "Owners are encouraged to

[1] P. 4, Critical Areas Ordinance (CAO) 14.24 Code Updates 2025, redline
[2] Ibid., p.5

remove non-native vegetation, particularly invasive species in addition to those whose removal is required by regulation, such as Class A weeds listed by the Skagit County Noxious Weed Board."[3]

3. **14.24.130 Hazard tree removal**
(2) (b) "If standing dead trees and snags can reasonably and safely be left in place they should be prioritized over the retention of logs in order to accommodate the preservation of wildlife habitat;"[4]
Given the large importance of dead trees and snags to cavity nesting birds and other wildlife, we are strongly in support of this new language.

4. **14.24.230 Wetland protection standards**
(1) (c) "Vegetated buffer standards: All wetland buffer widths presume the buffer is densely vegetated with a native plant community appropriate for the ecoregion, consisting of an average of 80% native cover comprised of trees, shrubs and groundcover plants. If the existing buffer is sparsely vegetated or vegetated with invasive species, the buffer must either be enhanced through an approved mitigation plan or increased per SCC 14.24.240(1)(c) to ensure the buffer provides adequate functions." [5]
We generally support this wetland protection standard, but the meaning of "an average of 80% native cover" is unclear. Please consider changing this to read, "a minimum of 80% native plant cover over the entire buffer area."

5 . **14.24.230 Wetland protection standards;**
(7) (b) "Wetlands less than 1,000 square feet may be exempted from buffer provisions contained in this Chapter."[6]
Please clarify this statement. Does it mean that wetlands less than 1,000 feet square do not require any buffer? Do wetlands of this size have any protection at all? Even a small wetland with a buffer as narrow as 25 feet vegetated with natural species adds significant habitat diversity. Those knowledgeable in avian habitat use can attest to this fact. The Critical Areas Ordinance should mandate protection and vegetated buffers for these small wetlands.
Please see the relevant statement in the Gap Analysis under "Exemptions for small wetlands."[7]

6. **14.24.500 Fish and wildlife habitat conservation area designations.**
(1) (d) Kelp and eelgrass beds, herring and smelt spawning areas; ...[8]
Forage fish such as herring and smelt are essential in the diets of many marine mammals and sea birds, including the federal and state listed marbled murrelet. Sand lance, which spawn on beaches as do smelt, are in the same category with smelt and herring in this regard and should be added to (1)(d). This point is also made in the Gap Analysis:

> "6.1 Fish and wildlife habitat conservation area designations (SCC 14.24.500) Forage Fish Spawning Habitat The SCC identifies herring and smelt spawning

[3] Skagit County Code 5.56; RCW 17.10
[4] Op. cit., CAO, p. 24
[5] Ibid., p.32
[6] Ibid., p.34
[7] *Gap Analysis, Skagit County Critical Areas Ordinance Update*, (Facet), Feb. 25, 2025, p. 12
[8] Op. cit., CAO, p.63

areas as FWHCAs but does not include "other forage fish spawning areas" as specific in WAC 365-190-130. Sand lance is another common forage fish species that is mapped and regulated by WDFW. We recommended including other forage fish spawning areas to maintain consistency with the GMA and provide protection for these habitats."[9]

(4) (a) Great blue heron nest sites; ...[10]
Foraging areas are also essential to great blue heron populations. Please update this listing to read, " Great blue heron nest sites and foraging areas."

(4) (e) Townsend big-eared bat communal roosts;[11]
Note that the correct name for this species uses the possessive: "Townsend's big-eared bat."

(4) (g) Trumpeter swan concentrations; ...[12]
A smaller number of tundra swans also winter in Skagit County and are also protected under the Migratory Bird Treaty Act. Please update this listing to read, "Trumpeter and tundra swan concentrations; ..."

7. The list of conservation area designations under "**14.24.500 Fish and wildlife habitat conservation area designations**" needs to be updated to more accurately reflect the areas of importance in Skagit County. Note this entry in the *Best Available Science Review's* suggested measures to manage climate change impacts to fish and wildlife habitat conservation areas:

> "Update and maintain regulations for habitats and species of local importance. This may include adding mapping resources to help identify the locations of potential habitats and species requiring protection and management."[13]

The following suggested additions are based on Washington Department of Fish and Wildlife's *Priority Habitat and Species List.*[14]

- White Pelican, concentration and breeding areas.
  For more than the past five years, large numbers of white pelicans have congregated in summer on Padilla Bay, particularly on the dredge material islands off the northern mouth of the Swinomish Channel. Some pairs have nested on these islands.[15]

- Harlequin Duck, "Regular Concentrations in Salt Water"
  This species is regularly present in small numbers near Rosario Beach in Deception Pass State Park and along other rocky shorelines in Skagit County.[16]

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[9] Op. cit., Gap Analysis, p.22
[10] Op. cit., CAO redlined version, p.64
[11] Ibid., CAO redlined version, p.64
[12] Ibid., p.64
[13] *Best Available Science Review - Skagit County Critical Areas Ordinance Update*, FACET, February 24, 2025, p.58
[14] *Priority Habitat and Species List,* Washington Department of Fish and Wildlife, 2008 (updated June 2023)
[15] Ibid., p.131
[16] Ibid., p.149

- Western High Arctic Brant, concentration areas[17]
  Nearly the entire population of this species winters on Padilla and other Skagit County bays. Sand spits near their foraging areas are an essential feature of this brant's required habitat. In Skagit County, some examples include the sandspit at Camp Kirby on Samish Island and Crandall Spit on the west side of March Point peninsula.

- Bufflehead, concentration areas[18]
  Skagit Audubon's monthly winter surveys in cooperation with the Samish Indian Nation's Department of Natural Resources have documented Secret Harbor (Cypress Island) as a significant concentration area for bufflehead. Secret Harbor is in the Department of Natural Resource's (DNR) Cypress Island Aquatic Reserve. Similarly, Skagit Audubon's monthly winter surveys for the Fidalgo Bay Aquatic Reserve's Citizens Advisory Committee have found that reserve also accommodates a large concentration of bufflehead ducks.

8. **14.24.520 Fish and wildlife habitat conservation area site assessment requirements (3) Bald Eagle habitats ...**[19]

We appreciate the updated information about protecting bald eagle habitats and the inclusion of roost sites as well as nest locations. The wording calls for a cooperative management plan to be developed in coordination with the U.S. Fish & Wildlife Service and the Washington Department of Fish & Wildlife, "whenever activities that alter habitat are proposed near a verified nest territory or communal roost." More specificity is needed about what would constitute "near." If there are specific requirements set by either the federal or state agency, those should be included in the CAO. If not, it would still provide greater certainty for project applicants if there were a specified distance. One thousand feet would seem reasonable, but a distance should be chosen in consultation with a qualified bald eagle biologist.

9. **Beavers**

We note that the CAO has no reference to beavers or the areas of their activity where development could be at risk. There are places in Skagit County with a long history of beaver activity where development permitting should take into account the potential for problems. It would seem appropriate for the parts of the CAO dealing with wetlands to address the potential situations in areas where beavers are active. The ordinance should at the least discourage development in places affected by beaver activity or most likely to be affected in the future. It is well-documented that removing beavers is not an effective long-term action.

10. **Strategies to manage climate change impacts to FWHCAs**

We note that the *Best Available Science Review - Skagit County Critical Areas Ordinance Update* presents a list of strategies to manage climate change impacts in Fish & Wildlife

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[17] Ibid., p.154
[18] Ibid., p.156
[19] Op. cit., CAO redlined version, p.65

Habitat Conservation Areas (FWHCAs).[20] We urge that Skagit County incorporate any of these strategies relevant to our area.

11. **Habitat corridors**

Corridors connecting habitat areas are important to those areas fully functioning to support wildlife. The four occurrences of the word "connectivity" in the CAO are all in the context of buffers, particularly wetland buffers. The sole mention of habitat corridors in the CAO is in the section about buffer averaging:

> **14.24.540 "Fish and wildlife habitat conservation area performance-based buffer alternatives and mitigation standards:**
> **"Buffer Width Increasing. The Director may require the standard buffer width to be increased or to establish habitat corridors, when such buffers are necessary for 1 of the following: (a)To protect priority fish or wildlife using the HCA (Habitat Conservation Area)."[21]**

Please incorporate direction for establishing and maintaining habitat corridors at appropriate places in the CAO in addition to those addressing wetlands. We support, for example, this suggestion in the *Best Available Science Review*'s list of strategies to manage climate change impact:

> "Encourage and incentivize enhancement and restoration of native forest patches throughout the County, particularly where connectivity to one or more FWHCAs is identified."[22] (FWHCA = Fish and Wildlife Habitat Conservation Area)

We appreciate your attention to our comments. Please direct questions about any of these to conservation@skagitaudubon.org (Skagit Audubon Society, PO Box 1101, Mount Vernon, WA 98273).

Sincerely,

Timothy Manns
Conservation Chair
For the Skagit Audubon Board

[20] Op. cit., Best Available Science Review, p.58
[21] Op. cit., CAO redlined version, p.68
[22] Op. cit., Best Available Science, p.58

Comment #24

Robby Eckroth

From: Andrea Xaver <dancer@fidalgo.net>
Sent: Thursday, May 8, 2025 3:58 PM
To: PDS comments
Subject: Skagit County 2025 Comprehensive Plan Periodic GMA update and comments on CAO, CP and DRs

I support the comments submitted today (5-8-25) by Friends of Skagit County.
One of the reasons is that the Big Lake area, and the lake within it which also has some wetlands and farmland adjacent, is becoming more of a safety and environmental concern.

Thank you.

Andrea Xaver
19814 State Route 9, Mount Vernon, WA 98274
360-202-9533

Comment #25

Robby Eckroth

From: Sophia Steele <ssteele@wspa.org>
Sent: Thursday, May 8, 2025 11:20 AM
To: PDS comments
Cc: Jessica Spiegel
Subject: 2025 Development Regulations and Critical Areas Ordinance Update
Attachments: 5.8.25 WSPA Comments to Skagit re CAO.pdf

Dear Skagit County Planning and Development Services,

The Western States Petroleum Association (WSPA) appreciates the opportunity to provide comments on the Skagit County Draft Critical Areas Ordinance (CAO) dated April 15, 2025. We recognize and support the County's efforts to update this important ordinance to protect critical environmental resources in Skagit County.

WSPA is a non-profit trade association representing companies that create the energy we need today for the future of transportation. This includes renewable diesel, other biofuels, innovative solar and sustainable energy projects, electric charging infrastructure, and carbon capture and sequestration. WSPA member companies also continue to produce traditional petroleum products, which remain a vital energy source for Washington.

WSPA members own and operate major facilities in Skagit County that are critical to the regional and state economy. These facilities are heavily regulated by federal, state, and regional environmental, health, and safety standards, and are committed to operating in a safe, responsible, and sustainable manner.

We offer the following technical comments on the Draft CAO:

Aboveground Tanks
In our review of the *Redline Draft Skagit County Critical Area Ordinance Update* and the *Critical Areas Ordinance Best Available Science Review*, we did not see a definition for "Hazardous Substance" or "Aboveground Tanks". We recommend the term aligning with state law for clarity, hazardous substance and aboveground tanks have the meaning provided in WAC 173-303-040.

The proposed updates to CARA protections (Sections 14.24.320, 14.24.330, and 14.24.340) introduce significant new requirements for facilities handling hazardous substances. The industry complies with API standards for new tank construction.[1] Some of these standards include the following:

- **API-650 (Welded Tanks for Oil Storage).** Developed for the design/construction of above ground atmospheric storage tanks[2]. These standards are intended to improve operational excellence, ensure compliance/safe practices, and mitigate risks.
- **API-2610 (Design, Construction, Operation, Maintenance, and Inspection of Terminal and Tank Facilities).** Covers the design, construction, operation, inspection, and maintenance of petroleum terminal and tank facilities associated with marketing, refining, pipeline, and other similar activities. Section 9 provides requirements for dike/berm height, capacity, and permeability

In addition to the API standards, facilities with total aboveground oil storage of >1,320 gallons must prepare and implement an Spill Prevention, Control, and Countermeasure (SPCC) Plan. In an effort to avoid duplicative regulations, we would recommend the County consider the following amendments in CARA 14.24.320.
(4)(B) Aboveground Tanks. All new aboveground storage facilities used or to be used for the aboveground storage of hazardous substances or hazardous waste must be designed and constructed with a double walled tank and or a secondary containment system separate from the tank that will hold 110 percent of the tank's capacity. The

secondary containment system or dike system must be designed and constructed to contain material stored in the tank(s). Facilities that are subject to Oil Pollution Prevention regulation 40 CFR Part 112 (Spill Prevention, Control, and Countermeasure) are exempt from this standard.

Wetland Buffer

The updated wetland buffer standards (Sections 14.24.210, 14.24.230, and 14.24.240) expand required buffers for industrial development. We encourage the County to allow buffer averaging and reduction where impacts to wetland functions are minimized and recognize existing industrial land uses when applying new buffer standards.

Geotechnical Analysis and Hazard Mitigation

New requirements (Sections 14.24.410 and 14.24.430) for detailed geotechnical analysis and hazard mitigation will increase project design and permit complexity. WSPA requests that the County review whether there is a material increase in hazardous risk that would justify changes. Otherwise, WSPA recommends the county streamline review for modifications or upgrades that do not materially increase hazard risks.

We would encourage the county to work with WSPA and our members in Skagit County to ensure that these updates do not create unintended consequences. We recommend that the county provide clear guidance and criteria for when conditional use permits are required, allow flexibility for modernization and upgrade projects that improve environmental performance, and incorporate reasonable timelines for compliance and transition for existing facilities.

On behalf of WSPA and its member companies, we appreciate the County's work in updating the CAO and the opportunity to comment on the draft. We respectfully request that the County balance protection of critical environmental resources with support for existing industrial operations that are essential to the local and regional economy.

We would be happy to meet with Planning staff to discuss our comments in more detail or provide additional technical information as needed.

If you have any questions regarding our comments, please contact me directly at (360) 352-4516 or via email at ssteele@wspa.org.

Thank you,

Sophia Steele
Sr. Manager, Northwest Region
WSPA

O 360.352.4516

[1] **American Petroleum Institute (API) Standards.** The American Petroleum Institute (API) is a key trade association for the oil and natural gas industry, with a history dating back to 1919. API's long-standing role and its continuous involvement in industry challenges have made it a respected authority. The standards API develops are created through collaboration with industry experts, ensuring they reflect the latest technology and best practices. These standards are globally recognized and often integrated into regulations, making compliance with them a legal requirement in many areas. API's commitment to updating its standards ensures they remain relevant and effective, solidifying its trust among industry stakeholders.

[2] *"Above ground tank"* means that the tank is above the surface of the earth and *"atmospheric tank"* means that the tank is not pressurized but at atmospheric pressure. For example: gas (methane through butane) holding tanks are pressurized to keep the gas liquified for storage. But gasoline, diesel and heavier than pentane containing tanks are normally under no pressurization.

WSPA

Sophia Steele
Senior Manager, Northwest Region

May 8, 2025

Sent via email to: pdscomments@co.skagit.wa.us

Skagit County Planning and Development Services
1800 Continental Place
Mount Vernon, WA 98273

Re: WSPA Comments on Draft Skagit County Critical Areas Ordinance (CAO) Update

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If you have any questions regarding our comments, please contact me directly at (360) 352-4516 or via email at ssteele@wspa.org.

Sincerely,



CC: Jessica Spiegel, Vice President NW Region

Comment #26

Robby Eckroth

From: Lora Claus <lorac@skagitonians.org>
Sent: Thursday, May 8, 2025 4:58 PM
To: PDS comments
Cc: Kim Rubenstein; Tim Knue
Subject: 2025 Development Regulations and Critical Areas Ordinance Update
Attachments: 2025 0508 SPF_Comp Plan Comments.pdf

May 8, 2025

Skagit County Planning & Development Services
1800 Continental Place
Mount Vernon, WA 98273

RE: Comments to Draft Skagit County 2025 Comprehensive Plan Update, Critical Areas Ordinance (CAO) and Development Regulations

Dear Planning Department:

Thank you for the opportunity to comment on behalf of Skagitonians to Preserve Farmland. We appreciate the hard work of the planning department in incorporating these and prior comments into the Comprehensive Plan for the good of Skagit County and its citizens. Our suggested changes are in support of the long-term economic viability of agriculture in Skagit County. Skagit County's citizens made clear that farmland preservation is the top priority, as found by the survey conducted in 2024 as part of this process.

Critical Areas Ordinance
General Comments:

1. The distinction between natural managed watercourses and artificial watercourses is of primary importance. The county's authority does not extend to artificial watercourses maintained by special purposes districts formed under Title RCW 85. WAC RCW 36.70A.030 (11) excepts from the definition of critical areas irrigation delivery systems, infrastructure, and drainage ditches with the boundaries of, and that are maintained by, a drainage and irrigation improvement district. Skagit County agriculture relies on this critical infrastructure. Skagitonians to Preserve Farmland recommends adoption of the comments submitted by the Skagit Drainage and Irrigation District Consortium to support this infrastructure and its maintenance.

2. In regards to buffers cited through the CAO, buffers impacting Ag-NRL land should be considered carefully and not as a one-size fits all proposition. The Voluntary Stewardship Program is the appropriate approach to avoid additional mandates on farmers that remove land from production and increase economic hardship.

Development Regulations
Comment re: page 44, 14.08.060 Petitions item 3)
This item references the de-designation of natural resource lands. Consistent with our prior comments regarding many sections of the comprehensive plan, it is vital that "**Skagit County** conducts a comprehensive countywide analysis." Otherwise, there exists an opening for a well-funded individual or group, likely lacking neutrality, to pay for a private countywide analysis to achieve a pre-determined outcome.

Thank you for the opportunity to comment on the 2025 Comprehensive Plan Update. We look forward to reviewing the next draft of the plan and working with the County to ensure the long-term viability of Skagit agriculture.

Sincerely,



Lora H. Claus
Executive Director
Skagitonians to Preserve Farmland
414A Snoqualmie Street
Mount Vernon, WA 98273

#Pavement is Forever

May 8, 2025

Skagit County Planning & Development Services
1800 Continental Place
Mount Vernon, WA 98273

RE: Comments to Draft Skagit County 2025 Comprehensive Plan Update, Critical Areas Ordinance (CAO) and Development Regulations

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Sincerely,



Lora H. Claus
Executive Director
Skagitonians to Preserve Farmland
414A Snoqualmie Street
Mount Vernon, WA 98273

Comment #27

State of Washington
Department of Fish and Wildlife, Region 4
Region 4 information: 16018 Mill Creek Blvd, Mill Creek, WA 98012 | phone: (425)-775-1311

May 8, 2025

Robby Eckroth, Senior Planner
1800 Continental Pl
Mount Vernon, WA 98273

RE: Submittal 2025-S-8322, WDFW comments for Skagit County's Critical Areas Ordinance 14.24 Code Update

Dear Mr. Eckroth,

On behalf of the Washington Department of Fish and Wildlife (WDFW), thank you for the opportunity to comment on Skagit County's Critical Area Ordinance (CAO) 14.24 update as part of the current periodic update. Within the State of Washington's land use decision-making framework, WDFW is a technical advisor for the habitat needs of fish and wildlife and routinely provides input into the implications of land use decisions. We provide these comments and recommendations in keeping with our legislative mandate to preserve, protect, and perpetuate fish and wildlife and their habitats for the benefit of future generations – a mission we can only accomplish in partnership with local jurisdictions.

Table 1. Recommended changes to proposed ordinance language.

Page or Section Number	Ordinance Language (with WDFW suggestions in red)	WDFW Comment
14.24.020 Title and purpose Page 4	...ensuring no net loss of ecological functions and values	Protection of Critical Areas means providing for no net loss of ecosystem functions **and values** (WAC 365-196-830(4)).
14.24.020 Title and purpose (5) Fish and Wildlife Habitat Conservation Areas Page 5	...In addition to their intrinsic and functional value, certain habitats and species of fish and wildlife represent important historic, cultural, recreational and economic resources. It is the purpose of this Chapter to protect fish and wildlife populations and their associated habitats and provide special consideration to conservation or protection	Fish and Wildlife Habitat Conservation Areas (FWHCAs) provide not only intrinsic value but also essential functional benefits, such as wetlands that absorb excess floodwaters and riparian zones that filter pollutants before they reach our waterways.

	measures necessary to preserve or enhance anadromous species.	
14.24.070 Activities allowed without standard review Page 7	...All activities that do not require standard critical areas review will be carried out in ways that shall not cause ~~the least~~ impact to critical areas and their buffers. If any incidental damage is caused to a critical area or buffer in connection with such activity, the critical area and its buffer must be restored to achieve no net loss of ecological functions and values ~~the extent feasible~~...	It is required that no net loss of ecological functions and values be maintained for all impacts, even if exempt, to critical areas (WAC 365-190-080 and WAC 365-196-830).
14.24.070 Activities allowed without standard review Page 7	(1)...The responsible party must restore the critical area and buffer after the emergency to achieve no net loss of ecological functions and values ~~the extent feasible~~...	See comment above.
14.24.070 Activities allowed without standard review Page 7	(3) ...provided any maintenance or repair activities must use best management practices (BMPs) ~~with the least amount of potential~~ and result in no impact to the critical areas and any incidental impact to a critical area or its buffer must be restored after the maintenance to meet no net loss standards ~~the extent feasible~~.	See comment above.
14.24.070 Activities allowed without standard review Page 7	(4) ...provided any maintenance or repair activities must use reasonable methods that result in no ~~with the least amount of potential~~ impacts to the critical areas and any incidental impact to a critical area or its buffer must be restored after the maintenance to meet no net loss standards ~~the extent feasible~~...	See comment above.
14.24.070 Activities allowed without standard review Page 9	(12) Fish, wildlife, wetland and/or riparian buffer enhancement activities not required as mitigation such as native plant and mulch installation and/or reasonable removal of non-native vegetation provided all of the following apply:	Some meaningful enhancement efforts, such as removing extensive invasive root systems, mowing, or planting trees at scale, are not practical using only handheld tools. Restoration practitioners may be discouraged from pursuing enhancement projects if their work can not be completed by hand.

	(a) Enhancement work will be restricted to handheld equipment unless otherwise approved by the Director. Handheld equipment includes shovels, tillers, clippers, loppers, weed wrenches, and brush cutters and any handheld gas or electric equipment; (b) A planting restoration plan must be submitted to the Director for review and approval prior to any disturbance to the buffer....	Importantly, this section already requires Director review and approval of a planting restoration plan, even when the activity is permit-exempt. This review process provides a safeguard to ensure any proposed use of non-handheld tools is appropriate and environmentally sound. Furthermore, the section explicitly states that projects must be consistent with the chapter and not harm critical areas or their buffers, adding another layer of protection. We encourage the County to allow restoration permit exemptions based on the project itself because of the diverse nature of project types.
14.24.070 Activities allowed without standard review Page 9	13) Fish, wildlife, wetland and/or riparian buffer enhancement activities not required as mitigation approved by the U.S. Department of Fish and Wildlife, U.S. Army Corps of Engineers, the Washington State Department of Fish and Wildlife or the Washington State Department of Ecology.	Clarification is requested regarding whether the County requires a formal letter or documentation from state agencies, or if a state-issued permit is considered sufficient for demonstrating compliance.
14.24.080 Standard critical areas review and site assessment procedures. Page 11	5.c.(vi) A detailed analysis demonstrating the proposal meets mitigation sequencing requirements pursuant to Subsection (5)(a) of this Section, demonstrating that the following were considered as options to satisfy avoidance of impacts, if applicable; (A) Alternative building locations on the property; (B) Adjustments to the project footprint and orientation; (C) Modification of setbacks, where feasible, as a first option before encroaching into critical areas or their buffers; (D) Multi-story design or alternate building design; and	We encourage the county to more clearly define the "avoidance" step in the mitigation sequence to ensure applicants prioritize avoiding impacts and can demonstrate that all feasible alternatives have been fully considered before proposing impacts to critical areas or their buffers. This clarity helps ensure that avoidance is meaningfully evaluated before moving to other steps within the mitigation sequence. Additionally, and in alignment with Facet Consulting's *Gap Analysis*, we recommend the county place the mitigation sequence within its own section. Examples of the adjacent edit: Bellevue's code, Section 20.25H.040, outlines standards for modifying non-critical area setbacks, while Section 20.25H.110 requires that the mitigation sequence be addressed within critical area reports.
14.24.090 Protected critical	(5)(a)...Areas within a PCA can be included in the total acreage for development purposes and may	Allowing Protected Critical Areas (PCAs) to be included in total lot area or density calculations appears counterintuitive, as these areas are set

areas (PCA) requirements Page 15	be used in lot area or density calculations...	aside specifically to remain undeveloped and to preserve ecological functions. Including PCAs in buildable land calculations may inflate perceived development potential.
14.24.120 Ongoing agriculture. Page 19	(2)(a) As defined in SCC 14.04.020, all ongoing agriculture (including operation and maintenance of agricultural drainage infrastructure) which is located within 200 feet from a watercourse, or any ongoing agriculture (including operations and maintenance of agricultural drainage infrastructure) that adversely impacts the existing functions and values of a watercourse, is subject to the requirements of this Section.	We appreciate the County's effort to develop detailed standards to protect riparian functions and values associated with watercourses in agricultural landscapes. However, we note a significant gap in the applicability of this section. While the language focuses almost exclusively on the protection of FWHCAs associated with streams and riparian buffers, it does not adequately address other forms of fish and wildlife habitat conservation areas, such as those identified under WDFW's Priority Habitats and Species (PHS) program. Other FWHCAs might include intact prairie habitats, wetlands not directly tied to watercourses, important upland habitats for species of local importance, or documented breeding and foraging areas for priority species. These areas may exist in proximity to ongoing agricultural activities and are susceptible to degradation through clearing, chemical application, or other disturbances not addressed by current buffer-based protections. We recommend the County expand the scope of this section to address agricultural BMPs for other FWHCAs beyond streams and riparian zones. Doing so will better align the code with best available science (BAS), support no net loss of ecological functions and values, and ensure comprehensive protection for the full range of habitat types
14.24.120 Ongoing agriculture Page 19	(3)(a) All ongoing agricultural activities must be conducted so as not to cause harm or degradation to the existing functions and values of FWHCAs ~~in and adjacent to watercourses~~ (the "no harm or degradation" standard).	See comment above.
14.24.130 Hazard tree removal Page 24	(2) Suggested addition (e) Total tree removal must only be considered if snag creation is infeasible.	Snags (standing dead or dying trees) serve as essential habitat features for countless species in Washington. They provide nesting, roosting, foraging, and shelter opportunities, supporting biodiversity and contributing to the health of ecosystems. By prioritizing snag creation over complete tree removal, jurisdictions can be sure to

		save crucial habitat features on the landscape. Many jurisdictions have included snag protection directly into municipal code (e.g. Seattle, 25.09.070). This suggestion is also in alignment with Facet's *Gap Analysis* of the county's CAO. See WDFW's website for more details.
14.24.140 Reasonable use exception Page 24	(1) Reasonable Use Standards. An applicant who is unable to comply with the specific standards of this chapter without forfeiting all economically viable use of the property may seek approval of a "reasonable use" exception for one single-family residential development under this section.	If it is not the intent to allow subdivisions under this section, we suggest that it should be clearly stated.
14.24.140 Reasonable use exception Page 25	5(a) RUE will only be applicable to sites that do not have an area of 4000 square feet or more available for development outside the standard buffer.	WDFW appreciates the inclusion of subsection (a) as a creative and thoughtful approach. Setting a 4,000-square-foot threshold outside of the critical area buffer for RUEs is a unique and effective way to ensure that the RUE pathway is reserved for truly constrained sites.
14.24.500 Fish and wildlife habitat conservation area designations. Page 63	(1)(f) Waters of the State as defined by RCW 90.48.020 and Typed Waters as defined by WAC 222-16-030	Steam typing can be a useful tool within jurisdictional code, but more restrictive regulations placed on, for instance, type F vs. Np streams, is not supported by WDFW's BAS. WDFW's BAS finds that all streams are important for ecosystem services and salmon recovery, regardless of whether or not they are fish-bearing. Headwater streams (Type Np and Ns) provide cold water, sediment regulation, and organic inputs that are critical to maintaining the physical, chemical, and biological integrity of downstream fish-bearing waters. Non-fish-bearing streams also contribute substantially to habitat quality for amphibians, invertebrates, birds, and mammals, which are all interconnected in the broader food web supporting salmonids. The loss or degradation of Np and Ns streams through reduced buffer widths or unregulated disturbance (such as greater flexibility for timber removal) leads to cascading effects on water quality, base flow contributions, and thermal loading, ultimately impairing conditions for salmon downstream. Furthermore, WDFW Volume 2 emphasizes that protection of these areas is necessary to meet no net loss of ecological functions and values, as even

		ephemeral or intermittent streams play an important role in hydrologic connectivity and nutrient transport, which are essential components of functional riparian corridors. In short, it is not the presence of fish that makes a stream valuable, it is the ecological services that all streams provide to the landscape and to the species that rely on them.
14.24.530 Fish and wildlife habitat conservation area protection standards Page 65	(1) Riparian ~~Buffers~~ Management Zone	We suggest the county adopt the term Riparian Management Zone (RMZ) to align more closely with WDFW's BAS. The following resources are available for further information: **Riparian Standards and Mapping Resources**- *WDFW's Riparian Ecosystems, Volume 1: Science Synthesis and Management Implications* *WDFW's Riparian Ecosystems, Volume 2: Management Recommendations* Site Potential Tree Height Mapping tool Site Potential Tree Height GIS polygon downloads Riparian Management Zone RMZ-CAO checklist designed to help translate volume 2 recommendations into CAO amendments See checklist Addendum for CAO examples **These final two resources provide a methodology for site-specific assessment of the RMZ, allowing landowners the opportunity to ground-truth the mapped RMZ width and make adjustments as necessary.** - **Guidelines for Determining Site Potential Tree Height from Field Measurements** - **Site-Potential Tree Height 200 (SPTH-200) Calculator**
14.24.530 Fish and wildlife habitat conservation area protection standards Page 65	(1)(a) Intent of Riparian Buffers. The intent of riparian buffers is to protect the following basic ~~riparian forest~~ functions ~~that influence in-stream and near-stream habitat quality~~: (viii) Wildlife Habitat Connectivity. Riparian areas serve as critical corridors that allow terrestrial wildlife to move between habitats. These corridors support	We suggest the adjacent deletions to align this section more closely with WDFW's BAS. Riparian areas that are not forested also provide important ecological functions and values. Additionally, we suggest the adjacent text insertion. WDFW's *Riparian Ecosystems, Volume 1,* and *Landscape Planning for Washington's Wildlife* both identify habitat connectivity as a critical riparian function, emphasizing that buffers should be managed not just for water quality but also for their landscape-scale value to wildlife. As habitats shift due to climate stressors, wildlife need

	biodiversity by facilitating species migration, dispersal, foraging, and access to water.	connected landscapes to move and adapt. Riparian corridors offer some of the most viable routes due to their water availability, vegetation, and relatively undeveloped state. Many species, such as amphibians, birds, mammals, and pollinators, depend on connected habitat to access food, mates, and seasonal habitat. When riparian corridors are degraded or fragmented, these species face population decline due to isolation and limited resources.
14.24.530 Fish and wildlife habitat conservation area protection standards Page 66	Standard Riparian Buffers Measurement. Riparian buffer areas are measured horizontally in a landward direction from the ordinary high water mark or from the edge of the channel migration zone, if present.	Channel migration zones (CMZs) are crucial for planning purposes because they indicate areas where rivers or streams may naturally shift over time. Failing to account for CMZs can lead to increased flood risks, property damage, and habitat loss. We encourage the city to incorporate this CMZ definition as well as delineate riparian management zones (RMZs) from the edge of the CMZ if present, as outlined in WDFW's *Riparian Ecosystems, Volume 2: Management Recommendations.*
14.24.530 Fish and wildlife habitat conservation area protection standards Page 66	Standard Riparian Buffer Widths. Riparian areas have the following standard buffer widths:	We appreciate the County's incorporation of WDFW's recommended 100-foot minimum riparian buffer (or RMZ), which reflects an important baseline protection. However, we strongly recommend adopting WDFW's Site Potential Tree Height at 200 years ($SPTH_{200}$) methodology, as it offers an approach that accounts for **site-specific** conditions rather than applying a static buffer width across diverse landscapes. **During the April 22, 2025, Skagit County Planning Commission briefing, commissioners raised valid concerns about using a uniform buffer standard when parcel conditions vary so widely. As one commissioner noted, some riparian areas in the county lack large trees and are unlikely to support them in the future. WDFW guidance directly addresses this scenario, recommending that the buffer (RMZ) be based on the area covered by existing bank vegetation or a minimum of 100 feet, whichever is greater, to ensure adequate pollution removal functions are maintained.** Further, we recognize that WDFW's $SPTH_{200}$ mapping tool may show variations in soil types and corresponding riparian area widths within a single parcel. **Like any landscape-scale model, these**

		maps are screening tools, not prescriptive boundaries. That's why WDFW has provided guidance for practitioners to collect site-specific field data, giving project proponents the opportunity to measure conditions directly on the ground and determine accurate, science-aligned riparian widths. In summary, $SPTH_{200}$ offers a flexible, science-informed alternative to static buffer standards by empowering landowners and jurisdictions to respond to the real conditions on the ground.
14.24.530 Fish and wildlife habitat conservation area protection standards Page 67	(3) It is equal to or greater than 50 percent of the current required standard buffer width for the ~~wetland~~ FWHCA classification; and	We recommend this edit to align this statement with the correct section (FWHCA, not wetland).
14.24.540 Fish and wildlife habitat conservation area performance-based buffer alternative and mitigation standards	(1) (b) Suggested addition (iv) To protect habitat corridor connections between open spaces and critical areas inside and outside the county.	In January 2009, Skagit County adopted the Skagit Countywide UGA Open Space Concept Plan, which identifies and prioritizes open space corridors and greenbelts within and between UGAs that include lands useful for recreation, wildlife habitat, trails, and connection of critical areas, and working farm and forestlands. If not done so already, all the identified and designated Open Space Corridors should be shown on their Future Land Use Map and the Official Zoning Map to direct development away from these areas. Additionally, **these areas should be integrated as a type of FWHCA** for wildlife movement corridors. Alternatively, the Public Open Space of Regional/Statewide Importance (OSRSI) is one of the county's zoning designations. There could be an opportunity to include additional lands in this zoning district for habitat connectivity purposes like floodplain acquisition areas on major rivers and regionally important wildlife crossing areas, such as the wildlife crossing overpass project east of Red Cabin Creek (milepost 76) on State Route 20 (SR 20).
14.24.540 Fish and wildlife habitat conservation area performance-	(2) Buffer Width Averaging.	To our knowledge, there is no scientific evidence supporting the idea that reducing a riparian buffer in one area while expanding it elsewhere achieves no net loss of ecological functions and values. WDFW's *Riparian Ecosystems, Volume 1: Science Synthesis and Management Implications* (2020)

based buffer alternatives and mitigation standards. Page 68		shows that riparian buffer widths are established based on the specific ecological functions they are intended to support which are directly tied to the width, continuity, and quality of vegetation within the buffer. We recommend excluding riparian buffers from this section.
14.24.540 Fish and wildlife habitat conservation area performance-based buffer alternative and mitigation standards	5.a. Roads, Bridges and Utilities and driveways…	We suggest the addition of climate resilience language in this section. In the WDFW Water Crossing Designing Guidelines, we encourage jurisdictions to consider reducing the risk of culvert failure by designing culverts and bridges to be climate resilient to prevent future fish barriers and accommodate higher stream flows that may occur. Please see WDFW's climate-change-resilient culvert webpage and Incorporating Climate Change into the Design of Water Crossing Structures: Final Project Report for resources on how to incorporate climate-resiliency into culvert designs.
14.24.540 Fish and wildlife habitat conservation area performance-based buffer alternatives and mitigation standards. Pages 70-71	(5)(g) Timber harvest within HCAs	Allowing timber harvest within riparian buffers, regardless of conditions or proposed performance standards, compromises the critical ecological functions and values these areas are intended to protect. Trees within riparian zones are integral components of a wider, interconnected system. They contribute large woody debris that shapes stream morphology and creates habitat complexity, provide canopy cover that regulates stream temperatures vital for salmonid survival, stabilize streambanks through extensive root systems, and play a key role in filtering pollutants and maintaining water quality. These functions are the result of long-term ecological development and cannot be easily replaced or recreated through short-term replanting or metrics-based mitigation. For these reasons, we strongly recommend eliminating this provision and reinforcing protections for intact riparian vegetation to maintain water quality, fish habitat, and the long-term resilience of riparian ecosystems.

Thank you for taking the time to consider our recommendations to better reflect the best available science for fish and wildlife habitat and ecosystems. We value the relationship we have with your jurisdiction and the opportunity to work collaboratively with you throughout this periodic update cycle. If you have any questions or need our technical assistance or

resources at any time during this process, please don't hesitate to contact Morgan Krueger, our regional land use lead.

Sincerely,



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Riparian Ecosystems, Volume 1: Science Synthesis and Management Implications



A Priority Habitats and Species Document of the Washington Department of Fish and Wildlife

Washington Department of FISH and WILDLIFE

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While we acknowledge and appreciate all review comments, WDFW bears sole responsibility for the content of this document.

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Leopard Frog Lithobates pipiens/*Scott Fitkin, WDFW*

Preface

This Priority Habitats and Species (PHS) document of the Washington Department of Fish and Wildlife (WDFW) is provided in support of the agency's mission to preserve, protect, and perpetuate the state's fish, wildlife, and ecosystems while providing sustainable fish and wildlife recreational and commercial opportunities. WDFW works cooperatively with land use decision makers and landowners to facilitate solutions that accommodate local needs and needs of fish and wildlife. One of WDFW's important roles in land use decision making is that of technical advisor: we provide information about the habitat needs of fish and wildlife and the likely implications of various land use decisions for fish and wildlife.

The nine chapters of Volume 1 are a partial update of a 1997 document entitled *Management Recommendations for Washington's Priority Habitats: Riparian.* This document, called *Riparian Ecosystems, Volume 1: Science Synthesis and Management Implications* is a partial update because it addresses only aquatic species. Riparian needs of terrestrial species will be updated in the future. Until that update is complete, readers can consult the 1997 document, available at **http://wdfw.wa.gov/publications/00029/**, for information about riparian ecosystems and terrestrial species.

Priority Habitats are places that warrant special consideration for protection when land use decisions are made. For more information, see *Washington Department of Fish and Wildlife. 2008. Priority Habitat and Species List,* available at **https://wdfw.wa.gov/species-habitats/at-risk/phs.**

The PHS program provides land use decision support to clients such as local governments, tribes, government agencies, non-governmental organizations, and landowners. PHS consists of a PHS List, PHS Maps available at **https://wdfw.wa.gov/species-habitats/at-risk/phs/maps**, PHS Management Recommendations, and technical assistance from our regional habitat biologists.

This PHS document compliments a family of PHS documents including *Landscape Planning for Washington's Wildlife: Managing for Biodiversity in Developing Areas* and *Land Use Planning for Salmon, Steelhead and Trout: A land use planner's guide to salmonid habitat protection and recovery,* available at **https://wdfw.wa.gov/species-habitats/at-risk/phs/recommendations**.

List of Acronyms

BAS	best available science
BFW	bankfull width
CMZ	channel migration zone
DBH	diameter at breast height
DNR	(Washington) Department of Natural Resources
EPA or (US)EPA	United States Environmental Protection Agency
FEMAT	Forest Ecosystem Management Assessment Team
HCP	habitat conservation plan
IMW	intensively monitored watersheds
LWD	large woody debris
NOAA	National Oceanographic and Atmospheric Administration
NRC	National Research Council
PHS	Priority Habitats and Species
PNW	Pacific Northwest
RCW	Revised Code of Washington
RMZ	riparian management zone
SMA	Shoreline Management Act
SPTH	site-potential tree height
$SPTH_{200}$	site-potential tree height at tree age equal to 200 years
TAG	Technical Advisory Group
USFS	United States Forest Service
USFWS	United States Fish and Wildlife Service
USGS	United States Geological Survey
WAC	Washington Administrative Code
WDFW	Washington Department of Fish and Wildlife
WNHP	Washington Natural Heritage Program
WSAS	Washington State Academy of Sciences



Bank of the Chehalis River/Kaysie Cox, WDFW

Chapter 1. Introduction

By: Timothy Quinn, Kirk L. Krueger, and George F. Wilhere

1.1. Document Description

Volume 1 is part one of a two-volume set. It contains reviews and syntheses of scientific literature for the purpose of informing the development of policies related to management of riparian areas and watersheds of Washington State. Volume 1 adds additional information to the science summarized in the PHS report titled *Management Recommendations for Washington's Priority Habitats: Riparian* (Knutson and Naef 1997).

Volume 1 was designed to answer the following three general questions:

- What is currently known about the key ecological functions of riparian areas?
- How do riparian areas and watersheds affect the freshwater habitats of fish and wildlife?
- How do human activities affect the capacity of riparian areas and watersheds to provide habitat for fish and wildlife in rivers and streams?

Volume 1 is intended to serve two goals. The first goal is to be a source of best available science (BAS) for understanding how riparian areas and surrounding



Chehalis River meander paths between 1938 and 2013/Ken Pierce, WDFW

watersheds affect ecological functions and aquatic habitats. The second goal is to provide a scientific foundation for management recommendations presented in Volume 2, which are consistent with Washington Department of Fish and Wildlife's (WDFW) mandate (RCW 77.04.012) to protect, preserve, and perpetuate Washington's fish and wildlife. Both goals also relate to WDFW's responsibility to support and provide technical assistance for conservation and protection measures necessary to preserve or enhance anadromous fisheries under the Growth Management Act (GMA; RCW 36.70A.172) and the Shoreline Management Act (SMA; WAC 173-26-221(5)(b)).

Volume 1 does not directly address instream flows as affected by water withdrawal for domestic and commercial uses, or instream water quality, both of which are regulated by the Washington Department of Ecology. However, because water quality is affected by land use, we discuss this issue in the context of riparian and watershed science. In addition, Volume 1 does not specifically address riverine wetlands, i.e., wetland associated with rivers and streams and commonly found in floodplains. Rather, riverine wetlands are usually considered part of riparian ecosystems, which are the focus of this document. Other specific wetland management guidance is available from Washington Department of Ecology (https://ecology.wa.gov/Water-Shorelines/Wetlands).

Volume 2 translates these science reviews and syntheses into land use guidance for local governments and other organizations to conserve watershed processes and riparian ecosystems in support of aquatic species and their habitats. The guidance presented in Volume 2 is not in and of itself "best available science." Rather, it represents the recommendations of WDFW as to how a local government could include the best available science in policies, plans, and regulations to protect riparian ecosystems and their associated aquatic habitats.

WDFW recognizes that natural resource management and land use policies must often balance competing ecological, economic, and social goals (Wilhere and Quinn 2018). In fact, one of WDFW's conservation principles is that management decisions should integrate ecological, economic, and social perspectives. This volume addresses only the ecology of riparian areas within the context of watershed conditions; it does not cover economic and social aspects. Determining an acceptable balance requires a political process involving stakeholders, local governments, tribes, and state agencies. Such a process would establish society's goals for freshwater habitats for salmon and other species of fish and wildlife, and lead to management for achieving those goals. This volume can help to inform that process.

1.1.1. Ecosystems

The ecosystem, a fundamental concept in natural resource management, can be defined as "a spatially explicit unit of the Earth that includes all of the organisms, along with all components of the abiotic environment" (Likens 1992). Throughout this document we use the term ecosystem composition to mean "the different parts (components) which something is made of" (Oxford Dictionary 2015). We define ecosystem structure as the "arrangement of and relations among the parts or elements of something complex" (Oxford Dictionary 2015). We define ecosystem function(ing) to include the first and second definitions of ecological function by Jax (2005): 1) the process, or the cause-effect-relationship underlying two or more interacting components, and 2) the sum of processes that sustain the system. Note that the definitions of functions we use here are broader and more inclusive than "functions" defined solely as ecosystem outputs that benefit humans, namely goods and services (Jax 2005; MEA 2005).

In this volume, we explicitly consider the composition, structure, and function of riparian ecosystems in the context of the surrounding watershed. This is especially important in light of the challenges of managing ecosystems sustainably and the risks associated with scientific uncertainty, i.e., the consequences of being wrong.

The composition, structure, and function of ecosystems describe the organization of biotic and abiotic elements and the processes occurring among elements. These concepts are closely related but not equally well studied nor understood. For example, describing an ecosystem's composition and structure is easier than describing its functions (Hunter et al. 1988; Noss 1992). Likewise, management objectives are often expressed in terms of composition and structure, not functions, because they are easier to characterize.

Composition and structure versus function have a chicken-and-egg relationship. That is, functions (processes) are in large part responsible for maintaining composition and structure, but some functions could not exist without an ecosystem's particular composition and structure. Myster (2001), for instance, argues that ecosystem structure can be defined as the minimal organization necessary for a function to operate. Others argue that managing for functions (Beechie and Bolton 1999) is likely to be more successful than managing for composition and structure because processes likely exert stronger influences on composition and structure than the other way around (Odum 1953), and processes are more directly affected by land use activities (Reid 1998). Furthermore, some land use laws or regulations stipulate no net loss of ecological functions, not no net loss of composition and structure (RCW 90.58, WAC 173-26-186, WAC 365-196-830), however, compliance is often determined through evaluating ecosystem composition and structure, not functions. Such conceptual ambiguity suggests that we consider the entire ecosystem, i.e., composition, structure, and functions, when studying riparian areas, and furthermore, that land managers understand how composition and structure manifest ecological functions. The following chapters synthesize our review of the relationships among composition, structure, and functions of riparian ecosystems in the Pacific Northwest.

1.1.2. Riparian Ecosystems

WDFW has adopted the following conceptual definition of riparian ecosystems:

Riparian areas are transitional between terrestrial and aquatic ecosystems and are distinguished by gradients in biophysical conditions, ecological processes, and biota. They are areas through which surface and subsurface hydrology connect waterbodies with their adjacent uplands. They include those portions of terrestrial ecosystems that significantly influence exchanges of energy and matter with aquatic ecosystems (i.e., a zone of influence).



Riparian ecosystem/Scott Fitkin, WDFW

Riparian ecosystems are sometimes referred to by different names: riparian areas, riparian zones, or riparian habitats. To compound confusion, the "riparian zone" is sometimes identified as a distinctive area within riparian ecosystems (Sedell et al. 1989; Naiman et al. 1992; Steiner et al. 1994). Some definitions include the adjacent waters whereas others do not. Unless stated otherwise, we consider riparian area, riparian habitat, riparian corridor, and riparian ecosystem to be synonyms. Furthermore, our definition of riparian ecosystem does not include adjacent waters (i.e., rivers or streams) and recognizes the riparian zone as a distinctive area within riparian ecosystems. The riparian zone contains wet or moist soils and plants adapted to growing conditions associated with periodically saturated soils.

Recent definitions reflect common conceptual understanding and identify similar composition, structure, and functions, including distinct plant communities and soil types; disturbance regimes unique to fluvial systems; gradients in soil, vegetation, and microclimate that manifest an ecotone between terrestrial and aquatic environments; and essential interactions between terrestrial and aquatic ecosystems. Riparian areas are the loci of terrestrial and aquatic interactions, however, the exact boundaries of riparian ecosystems can be difficult to delineate because: 1) ecosystems are not uniquely identified entities (Karr 1996); 2) the environmental heterogeneity of riparian areas is expressed in a variety of plant life history strategies and successional patterns; and 3) some ecosystem functions depend on environmental setting (Naiman et al. 1998).

Following Naiman et al. (1998), our definition of riparian ecosystem includes the active floodplain, including riverine wetlands, and the terraces or adjacent uplands that directly contribute organic matter or large wood to the active channel or active floodplain (Figure 1.1 and 1.2). Terraces and adjacent uplands that contribute organic matter or large wood are located in the "zone of influence." The active channel is defined by the lower limit of continuous riparian vegetation (Naiman et al. 1998), and it may be delineated by absence of both moss on rocks and rooted vegetation (USFS 2008). The upper most elevation of the active channel is sometimes equated with the ordinary high water mark. The active floodplain is located between the active channel and adjacent terrace or hillslopes (Fetherston et al. 1995; Harris 1987). Depending on the watershed, the flood return interval of the active floodplain varies between 1 and 10 years (Wolman and Leopold 1957; Ward and Stanford 1995; Lichvar et al. 2006; Williams et al. 2009; BLM 2015).

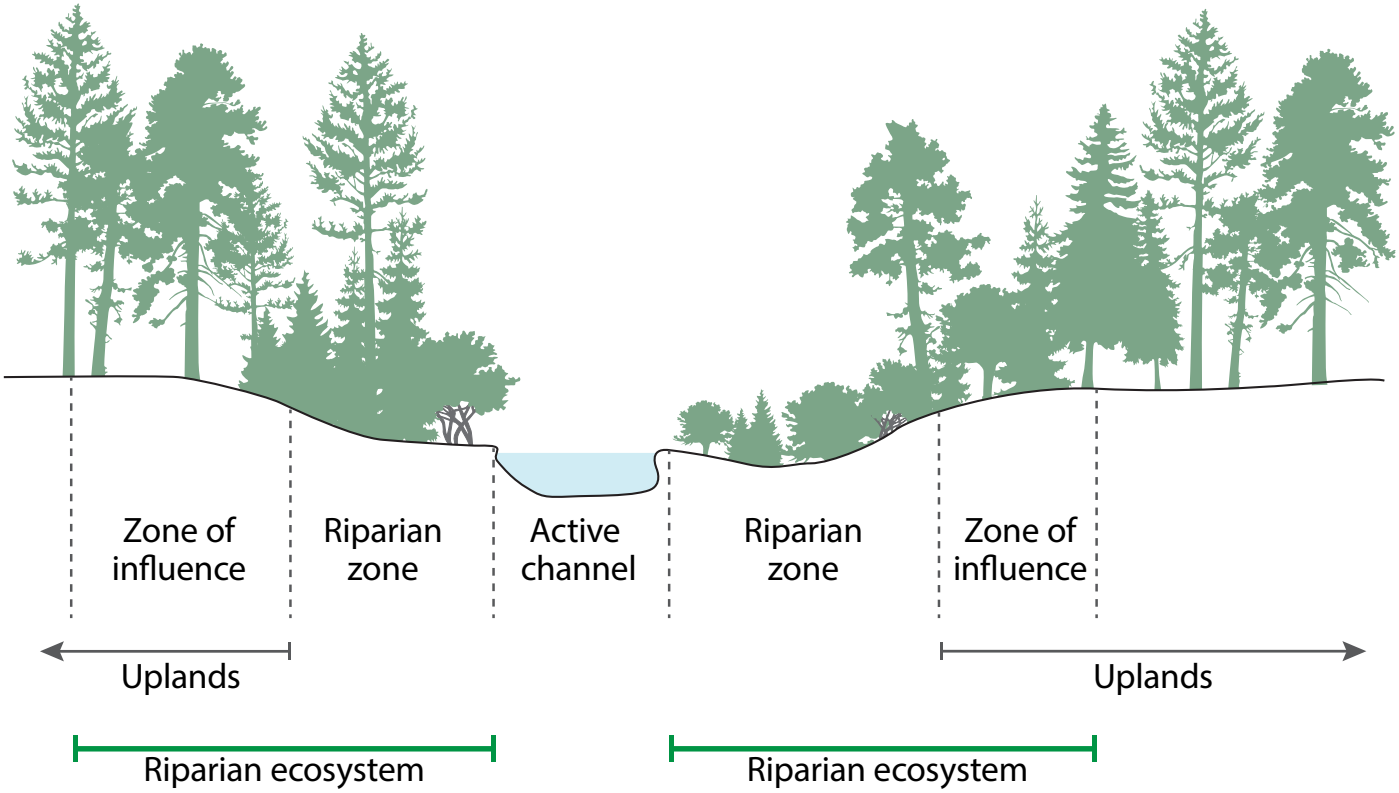
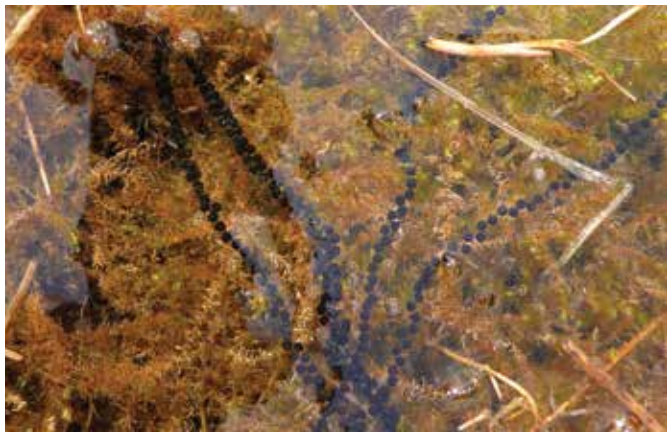


Figure 1.1. A generalized diagram of the riparian ecosystem. The NRC (2002) states that, "Riparian areas are transitional between terrestrial and aquatic ecosystems and are distinguished by gradients in biophysical conditions, ecological processes, and biota. They are areas through which surface and subsurface hydrology connect waterbodies with their adjacent uplands. They include those portions of terrestrial ecosystems that significantly influence exchanges of energy and matter with aquatic ecosystems (i.e., the zone of influence)." The portion of the ecosystem characterized by moist soils and plants adapted to periodically saturated soils is the riparian zone. The width of the riparian ecosystem is typically based on riparian functions (i.e., wood recruitment to the stream in forested regions and the pollution removal function in dryland regions).

Riparian ecosystems are priority habitats in part because wildlife occurs more often and in greater variety in riparian areas than in any other habitat type. "Natural riparian corridors are the most diverse, dynamic, and complex biophysical habitats on the terrestrial portion of the earth" (Naiman et al. 1993). Although riparian ecosystems constitute a small portion of the surface landscape, approximately 85% of Washington's wildlife species are known to use riparian areas associated with rivers and streams (Knutson and Naef 1997). Of these, 170 species including 134 mollusks, 11 amphibians, 3 reptiles, 10 birds, and 9 mammals may be riparian obligates, i.e., require riparian habitat to survive (T. Quinn, unpublished). In addition, habitat for many upland and aquatic species is directly enhanced by the presence of adjacent riparian areas. A principal reason for high fish and wildlife diversity is that riparian ecosystems are exceptionally productive. Riparian



Western Toad Anaxyrus boreas *egg strings/Scott Fitkin, WDFW*

ecosystems are characterized by the availability of water, milder microclimate, and relatively fertile soils. These factors enhance the productivity of plant communities and support a complex food web that includes a rich variety and abundance of fish, invertebrates, amphibians, plants, bacteria, fungi, reptiles, birds, and mammals (Cummins 1974; Johnson and Carothers 1982). It is not surprising then, that $1.4 billion (57%) of $2.5 billion spent to recover salmon in Pacific Northwest since 2000 has been directed at enhancing, restoring, and maintaining salmon habitat (e.g., large wood supplementation, riparian planting, fine sediment remediation, land acquisition) previously provided in large part by functioning riparian areas (NOAA 2015).

In addition to their essential role as fish and wildlife habitats, riparian areas provide other significant benefits to humans (Naiman and Bilby 1998; NRC 2002). Briefly, riparian areas help provide a variety of ecosystem goods and services: provisioning services such as food and water; regulating services such as decreasing flood flows; supporting services such as nutrient cycling, sediment and pollutant filtering, and carbon sequestration; and cultural services such as recreational, spiritual, and other nonmaterial benefits (MEA 2005). These services provide real but often unquantified economic benefits to individuals and society; benefits that largely go unnoticed until they are lacking. According to the NRC (2002), protection and restoration of riparian areas should be a national goal because they have a major influence on achieving important national standards of the Clean Water Act, the Endangered Species Act, and flood damage control programs.

This document includes consideration of river-associated wetlands but does not consider other types of wetlands, which are covered by the Washington

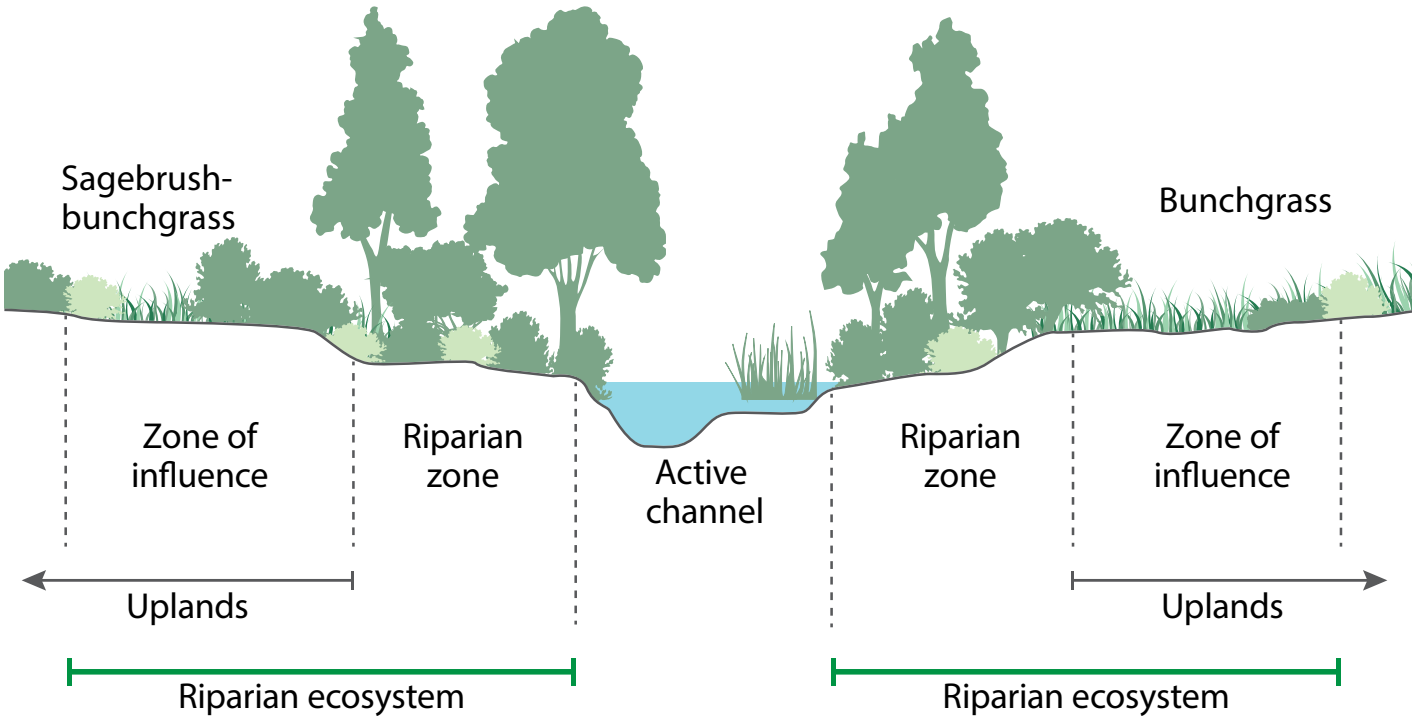


Figure 1.2. Dryland Riparian Ecosystem. The riparian ecosystem consists of two zones: riparian and zone of influence. The riparian zone extends from the edge of the active channel towards the uplands. This zone includes areas where terrestrial biota and soils are influenced, at least periodically, by surface or subsurface waters. Beyond this is the riparian "zone of influence." This includes areas where ecological processes significantly influence the stream (diagram modified from USFS 2004).

Department of Ecology, or areas bordering marine or estuarine (brackish) waters despite the potential applicability of this work to those environmental settings. A 2009 review of riparian functions of marine shorelines is available at https://wdfw.wa.gov/publications/00693.

1.2. Scope of Volume 1

1.2.1. Riparian Ecosystem Management

Riparian ecosystem management is often couched in terms of maintaining riparian functions thought to be important to fish and wildlife and their habitats (e.g., Bolton and Shellberg 2001, Everest and Reeves 2007). Some commonly identified riparian functions are described in FEMAT (1993) and the Forests and Fish Report (DNR 1999). The riparian ecosystem functions we discuss in this document, including some associated compositional and structural elements, are organized by chapter:

- Chapter 2. *Stream Morphology*—the interplay of water, sediment, and vegetation on channel form and riparian areas
- Chapter 3. *Wood*—effects of wood on channel morphology and habitat, and the recruitment of wood from riparian areas
- Chapter 4. *Stream Temperature*—effects of hydrology and shading on the thermal regime of streams
- Chapter 5. *Pollutant Removal*—the interception or filtration of fine sediments, excessive nutrients, pathogens, pesticides, and other contaminants in overland and shallow subsurface flows
- Chapter 6. *Nutrients Dynamics in Riparian Ecosystems*—dynamics and fate of the primary macro-nutrients: nitrogen, phosphorus, and carbon
- Chapter 7. *Riparian Areas of the Columbia Plateau*
- Chapter 8. *Watersheds*—relationship of watershed-scale management to the goal of achieving beneficial effects for fish and wildlife

Riparian functions are affected and in turn affect aquatic and terrestrial systems at multiple spatial scales. We focus much attention on riparian functions at the site (e.g., stream reach or land parcel) scale for three reasons. First, riparian areas are disproportionately important, relative to area, for fish and wildlife and other ecosystem services (Naiman and Bilby 1998; NRC 2002). Second, local governments and individual landowners, important users of WDFW's PHS guidance, typically manage at the parcel scale. Most land use activity, outside of public lands, occurs at the site-scale on ownership parcels that are relatively small compared to the watershed in which they occur. Third, effective and efficient conservation of fish and wildlife habitats requires management at multiple scales and thus good site-scale riparian management is an essential complement to good watershed management (Chapter 8), although approaches at different scales can vary dramatically.

1.2.2. Watershed Management

Even when all riparian functions are protected, rivers, streams, and riparian ecosystems are not immune to the effects of upland management. To varying degrees, riparian and stream structure, composition, and function reflect land uses and conditions throughout watersheds.

Regardless of its size, no ecosystem is entirely closed. Upslope activities can considerably alter the magnitude and timing of stream flows; the mobilization, routing, and storage of sediment, wood, and fine organic matter; and the quality of water, thereby influencing riparian ecosystem functions (NRC 2002; Figure 1.3). Thus, the management of riparian ecosystems at the site or reach scale should be considered just one important part, not

the sole requirement, of holistic watershed management for the protection of fish and wildlife and other values. We include Chapter 8, which focuses on watershed-scale issues that are important to the management of aquatic systems as a whole, with the intent of increasing the effectiveness of collective riparian conservation efforts. This chapter provides a conceptual framework that identifies the key watershed processes and their primary influences by, on, and through riparian areas and adjacent watercourses.

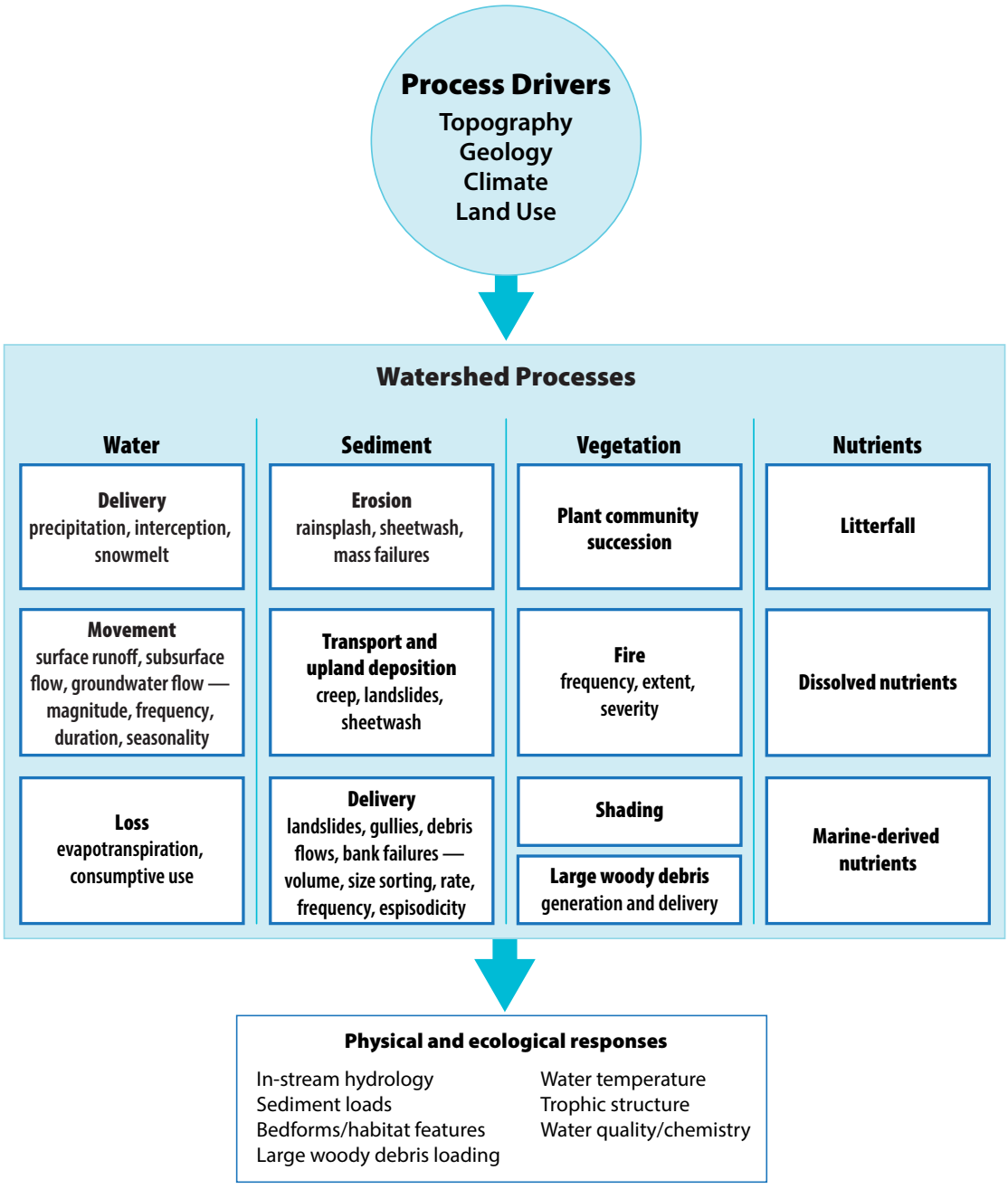


Figure 1.3. Conceptual framework for the hierarchical relationship of invariant, large-scale "process drivers," the suite of watershed processes that are determined by these drivers, and the instream physical and biological responses to those processes. Multiple additional interactions between elements and levels are not shown on this diagram to emphasize the primary influences; but in any given setting, one or more of these secondary interactions may temporarily achieve equivalent importance. This framework embraces the definition of watershed processes from Stanley et al. (2011): "[t]he dynamic physical and chemical interactions that form and maintain the landscape and ecosystems."



Devil's Club Oplopanax horridus *is common in wet soils of western Washington riparian areas/Ned Pittman, WDFW*

1.2.3. Science Synthesis

Chapter 9, *Science Synthesis to Management Implications,* of this volume summarizes important scientific finding from chapters 1-8 and provides a brief discussion of scientific themes that can inform thoughtful approaches to protecting aquatic systems.

1.2.4. Scope: Protection and Restoration

Protection and restoration of riparian ecosystems and watersheds are both essential for Washington's fish and wildlife, and especially for endangered and threatened salmonids. However, planning, management practices, regulations, and legal context for protection are different from those for restoration, and thoroughly covering both topics was beyond our scope. Thus, restoration is not explicitly incorporated in the scope of this document. Nevertheless, much of the science presented in this document can inform restoration activities. For instance, while this document does not review scientific literature on instream large wood placement, a common restoration activity, it does summarize large wood recruitment and reference conditions for the amount and size of instream large wood. Thus, the body of science that informs protection also helps to inform restoration, at least in terms of establishing resource goals and objectives.

1.3. Document Development

We employed the following approach to developing this document. We first established a Technical Advisory Group (TAG) of scientists from the region. Second, with guidance from the TAG, we conducted a literature review designed to inform the general state of knowledge regarding ecosystem protection and another literature review more focused on recent developments in riparian ecology and management. Third, we contracted with regional topic experts to author and co-author chapters. WDFW staff provided conceptual and technical guidance as possible. Finally, we subjected the draft final documents to several rounds of peer review. Each of these steps is discussed below.

1.3.1. Technical Advisory Group

The TAG helped provide overall science guidance, that is, contribute expertise and scientific perspective, provide important references and other sources of information, and review draft products. The TAG was composed of 13 individuals who were selected by virtue of their scientific expertise as opposed to affiliation with particular organization or stakeholder group. However, given the broad potential applicability of this document, it is conceivable that TAG members belong to one or more stakeholder groups. All TAG members were expected to attend three all-day meetings over the course of the project. Members of the TAG volunteered their time, except one who was paid a small stipend because she was employed by a non-profit organization. The first meeting was designed to introduce TAG members to the nature of the PHS update, to discuss different approaches to conducting a literature review and synthesizing new scientific information, and to

secure their ongoing commitment to helping WDFW meet high scientific standards. The second and third TAG meetings were designed to solicit review and feedback from TAG members on draft products. As part of their review process, we invited all TAG members to edit draft chapters and provide additional citations for WDFW's considerations. Although the TAG played a key role in advising WDFW on the science of riparian management and conservation, WDFW bears sole responsibility for the contents of this document.

1.3.2. Literature Review

We organized summaries around ecological functions including stream channel morphology, wood, pollution removal, nutrients, water temperatures, and watershed processes. Note that many of the issues we address here are directly or indirectly related to fish and wildlife habitats and other ecosystem services. We did not, however, explicitly consider cultural services that are important values for many stakeholders (e.g., spiritual, cultural and aesthetic values of riparian areas).

We enlisted the assistance of scientists with specific areas of expertise as technical advisors, authors, and informal and formal reviewers to help ensure that our summaries of pertinent scientific information were sufficiently accurate and inclusive. We were most interested in characterizing the state of knowledge and important, recent findings about each topic. That is, we tried to assesses what we know, how well we know it, and what we do not know. The summary statements in each chapter are important to the development of management recommendations because they often identify important management challenges that are not well described in the published literature (e.g., the importance of habitat connectivity to fish population persistence). To this end, when appropriate, we encouraged authors to consider the broad body of scientific information and how it might be extrapolated to unstudied locales; in other words, to consider the body of literature with regard to our ability to make reliable predictions.

Where information existed and as time allowed, we also attempted to summarize how riparian composition, structure, and functions differ among natural plant communities. In most cases, we used the broadest division called Major Vegetational Areas, which is made up of two groups in Washington State, i.e., Forested Regions and Steppe Regions (Franklin and Dyrness 1988). Regions can be further subdivided into forested zones (e.g., *Tsuga heterophylla* Zone) and steppe communities (e.g., shrub-steppe with *Artemisia tridentata*) that contain similar climax plant communities influenced by similar disturbance regimes. When information was available, for example, in the case of large wood in forested regions, we report that information at the finer division within the vegetation classification.

In addition, and as time and resources allowed, we summarized some potential effects of common land use activities on stream and riparian areas as a precursor to providing useful land use advice. We considered four general categories of land use: 1) urban, which includes commercial, industrial, urban, suburban, and rural development, 2) agricultural, which includes cultivated crops and grazing uses, 3) forestry, which includes timber management and associated activities such as

Chapter 9 summarizes scientific findings from chapters 1 through 8 and includes a brief discussion of scientific themes that can inform thoughtful approaches to protecting aquatic systems.

road building and maintenance, and 4) other activities (e.g., mining), which were not discussed due to the paucity of available research results.

We started this work by assembling topical literature reviews including Bolton and Shellberg (2001), Pizzimenti (2002), Bezener and Bishop (2005), Mayer et al. (2005), and Naiman et al. (2005). We compiled relevant literature cited in these review articles, from other reference materials we encountered, and from recommendations of TAG members. We also did an extensive literature search on computerized databases. We mostly focused our literature search on peer reviewed articles published after 1993, published in English, and conducted in proximity to Washington State. This last criterion was designed to focus on studies thought most relevant to Washington State's ecological conditions.



The North Fork Skokomish River runs through mature conifer forests of the Olympic National Park/Tim Quinn, WDFW

We also documented the type of review the study received according to RCW 34.05.271 (Appendix 1). Studies with no record of review were not considered further. As we (authors) reviewed the published literature, we noted important study findings that we believed would be especially useful for writing the PHS document. For empirical studies, our notes typically included the primary research questions or objectives, key results, management implications, and study limitations or assumptions. For literature reviews and syntheses, our notes summarized main conclusions by subject area. The intent here was to capture a sufficient level of detail for each paper so that we could use our collective notes as sources for writing the synthesis.

We found a massive quantity of literature related to riparian and watershed science despite focusing on information published after 1993. Due to the sheer volume of information, we could not cover all the literature in depth, so we covered those topics that were most relevant for management of riparian areas in Washington State. This document provides a comprehensive review on the current state of the science regarding certain riparian functions. Further, as described above, we enlisted the services of experts with specific areas of expertise as technical advisors, authors, and informal and formal reviewers to help ensure that our summaries of pertinent scientific information were sufficiently accurate and inclusive.

1.3.3. Peer Review

The peer review for Volume 1 consisted of a series of iterative steps, wherein we tried to gain as much agreement about the science synthesis as possible among those involved in the writing and reviewing process. Our intent was to provide the best available science. As described above, the TAG reviewed and often edited incomplete chapter drafts during the literature review and synthesis stage of the project. These draft syntheses were then given to topic experts to complete.

In cases, where WDFW lacked sufficient topic expertise, we provided stipends up to $10,000 to outside authors (i.e., contractors) for completing a chapter. The steps involved in completion of drafts included adding one or more conceptual models describing the system and its functioning and a synthesis or summary of the important findings over the last approximately 20 years. These steps often entailed a series of editing and reediting by WDFW staff and contractors. Once completed by contractors and returned to WDFW, the drafts were reviewed a final time by TAG members. This last review by TAG members was to ensure that completion of the chapters was consistent with their earlier guidance and with their understanding of the literature. WDFW attempted to resolve all disagreement that occurred between contractors and TAG members and provided a written description of how those issues were resolved to both the contractor and the TAG. After final WDFW review, the document was submitted for review by the Washington State Academy of Sciences (WSAS).

We enlisted the WSAS to conduct the final, independent peer review of the PHS document. Modeled after the National Academy of Science, which is charged with providing independent, objective advice to the nation on matters related to science and technology, the WSAS provides expert scientific analysis to inform public policy making at the state level (WSAS 2015). The final peer review with the WSAS was also iterative. That is, WDFW in consultation with authors and TAG members, addressed WSAS comments, made appropriate changes to the document, and then discussed those comments with the WSAS in an attempt to resolve differences. This process proceeded until we reached agreement about scientific contents and conclusions.

1.4. Literature Cited[1]

Beechie, T., and S. Bolton. 1999. An approach to restoring salmonid habitat-forming processes in Pacific Northwest watersheds. Fisheries 24:6-15. (i)

Bezener, A.M., and C.A. Bishop. 2005. Literature review of riparian habitat requirements for aquatic and terrestrial wildlife and its application to habitat restoration projects: a case example in the South Okanagan and Similkameen Valleys, British Columbia. Technical Report Series No. 379. Canadian Wildlife Service, Pacific and Yukon Region, British Columbia. (viii)

BLM (Bureau of Land Management). 2015. Riparian area management: proper functioning condition assessment for lotic areas. Technical Reference 1737-15. National Operations Center, Denver, Colorado. (viii)

Bolton, S.M., and J. Shellberg. 2001. Ecological issues in floodplains and riparian corridors. Center for Streamside Studies, University of Washington, Seattle. (viii)

Cummins, K.W. 1974. Structure and function of streams ecosystems. BioScience 24:631-641. (i)

DNR (Washington Department of Natural Resources). 1999. Forests and Fish Report. Forest Practices Division, Olympia. (viii)

Everest, F.H., and G.H. Reeves. 2007. Riparian and aquatic habitats of the Pacific Northwest and southeast Alaska: ecology, management history, and potential management strategies. PNW-GTR-692. U.S. Forest Service, Pacific Northwest Research Station, Portland, Oregon. (viii)

FEMAT (Forest Ecosystem Management Assessment Team). 1993. Forest ecosystem management: an ecological, economic and social assessment. U.S. Department of Agriculture and U.S. Department of the Interior, Portland, Oregon. (viii)

[1] References are classified according to RCW 34.05.271 (see Appendix 1) denoted by a lower case roman numeral (i – viii) in parentheses at the end of the citation.

Fetherston, K.L., R.J. Naiman, and R.E. Bilby. 1995. Large woody debris, physical process, and riparian forest succession in montane river networks of the Pacific Northwest. Geomorphology 13:133-144. (i)

Franklin, J.F., and C.T. Dyrness. 1988. Natural vegetation of Oregon and Washington. Oregon State University Press, Corvallis. (i)

Harris, R.R. 1987. Occurrence of vegetation on geomorphic surfaces in the active floodplain of a California alluvial stream. American Midland Naturalist 118:393-405. (i)

Hunter, M.L. Jr., G.L. Jacobson Jr., and T. Web III. 1988. Paleoecology and the coarse filter approach to maintaining biological diversity. Conservation Biology 2:375-385. (i)

Jax, K. 2005. Function and "functioning" in ecology: what does it mean? Oikos 111:641-648. (i)

Johnson, R.R., and S.W. Carothers. 1982. Riparian habitat and recreation: interrelationships and impacts in the southwest and Rocky Mountains region. Eisenhower Consortium Bulletin 12. Rocky Mountain Forest and Range Experiment Station, Fort Collins, Colorado. (viii)

Karr, J.R. 1996. Ecological integrity and ecological health are not the same. Pages 97-109 *in* P.C. Schulze, R. Frosch, and P. Risser, editors. Engineering within ecological constraints. National Academy of Engineering, Washington, D.C. (viii)

Knutson, K.L., and V.L. Naef. 1997. Management recommendations for Washington's priority habitats: Riparian. Washington Department of Fish and Wildlife, Olympia. (iv)

Lichvar, R.W., D.C. Finnegan, M.P. Ericsson, and W. Ochs. 2006. Distribution of ordinary high water mark (OHWM) indicators and their reliability in identifying the limits of "waters of the United States" in arid southwestern channels. ERDC/CRREL TR-06-5. U.S. Army Corps of Engineers, Washington, D.C. (viii)

Likens, G. 1992. An ecosystem approach: its use and abuse. Ecology Institute, Oldendorf/Luhe Germany. (i)

Mayer, P.M., S.K. Reynolds, M.D. McMutchen, and T.J. Canfield. 2005. Riparian buffer width, vegetative cover, and nitrogen removal effectiveness: a review of current science and regulations. EPA/600/R-05/118. USEPA, Office of Research and Development, Washington, D.C. (viii)

MEA (Millennium Ecosystem Assessment). 2005. Ecosystems and human well-being: synthesis. Island Press, Washington, D.C. (i)

Myster, R.W. 2001. What is ecosystem structure? Caribbean Journal of Science 37(1-2):132-134. (i)

Naiman, R.J., T.J. Beechie, L.E. Benda, D.R. Berg, P.A. Bisson, L.H. MacDonald, M.D. O'Conner, P.L. Olsen, and E.A. Steel. 1992. Fundamental elements of ecologically healthy watersheds in the Pacific Northwest Coastal Ecoregion. Pages 127-188 *in* R.J. Naiman, editor. Watershed management: balancing sustainability and environmental change. Springer, New York. (i)

Naiman R.J., and R.E. Bilby, editors. 1998. River ecology and management: lessons from the Pacific Coastal Ecoregion. Springer Science & Business Media, New York. (i)

Naiman, R.J., H. Decamps, and M.E. McClain. 2005. Riparia: ecology, conservation, and management of streamside communities. Elsevier Academic Press, San Francisco. (i)

Naiman, R.J., H. Decamps, and M. Pollock. 1993. The role of riparian corridors in maintaining regional biodiversity. Ecological Applications 3:209-212. (i)

Naiman, R.J., K.L. Fetherston, S.J. McKay, and J. Chen. 1998. Riparian forests. Pages 289-323 *in* R.J. Naiman and R.E. Bilby, editors. River ecology and management: lessons from the Pacific Coastal Ecoregion. Springer, New York. (i)

NOAA (National Oceanic and Atmospheric Administration). 2015. Pacific Coastal salmon recovery funds: project and performance metric database. Available: **https://www.webapps.nwfsc.noaa.gov/apex/f?p=309:13**. (January 2019). (viii)

Noss, R.F. 1992. The Wildlands Project: land conservation strategy. Wild Earth (Special Issue):10-25. (i)

NRC (National Research Council). 2002. Riparian areas: functions and strategies for management. National Academy Press, Washington, D.C. (i)

Odum, E.P. 1953. Fundamentals of ecology. W. B. Saunders, Philadelphia. (i)

Oxford Dictionary. 2015. Available: https://www.lexico.com/en/definition/structure. (January 2019). (viii)

Pizzimenti, J. 2002. Efficacy and economics of riparian buffers on agricultural lands, State of Washington. GEI Consultants, Inc., Englewood, Colorado. (viii)

Reid, L.M. 1998. Cumulative watershed effects and watershed analysis. Pages 476-501 *in* R.J Naiman and R. E. Bilby, editors. River ecology and management. Springer-Verlag, New York. (i)

Stanley, S., S. Grigsby, D.B. Booth, D. Hartley, R. Horner, T. Hruby, J. Thomas, P. Bissonnette, R. Fuerstenberg, J. Lee, P. Olson, and G. Wilhere. 2011. Puget Sound characterization. volume 1: the water resources assessments (water flow and water quality). Publication #11-06-016. Washington State Department of Ecology, Olympia. Available: https://fortress.wa.gov/ecy/publications/documents/1106016.pdf. (January 2019). (iv)

Steiner, F., S. Pieart, E. Cook, J. Rich, and V. Coltman. 1994. State wetlands and riparian area protection programs. Environmental Management 18:183–201. (i)

Sedell, J.R., F.H. Everest, and D.R. Gibbons. 1989. Streamside vegetation management for aquatic habitat. Pages 115-125 *in* Proceedings of the National Silviculture Workshop, U.S. Forest Service, Washington, D.C. (viii)

USFS (U.S. Forest Service). 2008. Stream simulation: an ecological approach to providing passage for aquatic organisms at road-stream crossings. National Technology and Development Program, San Dimas, California. (viii)

Ward, J.V., and J.A. Stanford. 1995. Ecological connectivity in alluvial river ecosystems and its disruption by flow regulation. Regulated Rivers: Research & Management 11:105-119. (i)

Williams, P.B., E. Andrews, J.J. Opperman, S. Bozkurt, and P.B. Moyle. 2009. Quantifying activated floodplains on a lowland regulated river: its application to floodplain restoration in the Sacramento Valley. San Francisco Estuary and Watershed Science 7(1). (i)

Wolman, M.G., and L.B. Leopold. 1957. River flood plains: some observations on their formation. Geological Survey Professional Paper 282-C. U.S. Government Printing Office, Washington, D.C. (i)

Wilhere, G.F., and T. Quinn. 2018. How wide is wide enough?: values, science, and law in riparian habitat conservation. Natural Resources Journal 58:279-318. (i)

WSAS (Washington State Academy of Science). 2015. Available: http://www.washacad.org/aboutus/. (January 2019). (v)

Chapter 2. Stream Morphology

By: Jane B. Atha, Mike Liquori, Kirk L. Krueger, George F. Wilhere, and Timothy Quinn

2.1. Introduction

The composition, structure, and functions of lotic systems are largely due to dynamic interactions of water, sediment, wood, and riparian vegetation. The nature of these interactions is affected by topography (e.g., channel slope), flow regime, sources and characteristics of sediment, the size, strength, and density of riparian vegetation (Naiman and Bilby 1998), and the actions of some animal species, most notably the American Beaver *Castor canadensis* and salmon. The influences of water and channel slope on sediment results in channel patterns (i.e., straight, meandering, braided) (Leopold and Wolman 1957) and geomorphic zones (i.e., source, transport, depositional) (Schumm 1977) that occur somewhat predictably from headwaters to river mouth. Furthermore, variation in fluvial processes (e.g., frequency and intensity of floods) and controls (e.g., lithology, large wood, riparian vegetation) result in a wide range of channel forms or reach types that are often described based on their bedform (e.g., slope, sinuosity, distribution of sediment sizes, etc.) (Montgomery and Buffington 1997). These channel forms can be useful descriptors of aquatic species' habitats. Tributary junctions (Kiffney et al. 2006), natural disturbances (Frissell et al. 1986), and artificial structures (Stanford and Ward 2001) can create discontinuities in these general patterns.

The composition and structure of riparian vegetation affects channel morphology, which in turn affects riparian vegetation (Hupp and Osterkamp 1996; Corenblit et al. 2007; Osterkamp and Hupp 2010; Gurnell 2014). Additionally, channel morphology and the processes that shape it can be impacted by human activities (e.g., levees, dams, Beaver trapping), usually resulting in loss of habitats, reduced habitat diversity, and diminished habitat functions for aquatic species. Management actions such as bank armoring, channelization, and riparian vegetation removal tend to reduce natural variability of geomorphic processes, often amounting to stream habitat degradation greater than the sum of its parts.



Yakima River/Justin Haug, WDFW

Knowledge of the fluvial processes that affect riparian and aquatic systems is important for making sound policy and management decisions. This chapter provides an overview of water and sediment in fluvial processes, their interactions with riparian vegetation, and potential alterations of fluvial processes by human activities. We first describe a general conceptual model for considering how physical processes affect channel morphology. Next, we describe stream flow and sediment processes in more detail. We then consider the watershed-scale context that directly influences fluvial processes. Lastly, we review impacts of human activities on stream functioning, introduce the "riverscape" concept for the management of fish habitats, and describe some physical stream habitat associations of herpetofauna. Some related topics are discussed in other chapters. For example, see Chapter 3 for a description of fluvial process interactions with large wood and Chapter 8 for a thorough examination of influences and management that occur at the watershed scale.

2.2. Conceptual Context

The concept of equilibrium is one of the most important ideas in fluvial geomorphology (Thorn and Welford 1994; Grant et al. 2013). The equilibrium concept posits that rivers tend to work toward long-term equilibrium (Gilbert 1877 as cited by Grant et al. 2013). *Dynamic equilibrium* describes a state of relative stability that results from the interaction of opposing forces (e.g., flowing water and substrate resistance). That is, over the long term and assuming that process drivers like climate and land use remain unchanged (see Chapter 8), overall progression of the composition and structure of stream reaches in a watershed remains largely unchanged. A stream network may undergo significant changes during an extreme flood event, and yet return to equilibrium as smaller flows rework the sediment distributed by floodwaters to re-establish roughly the same relative abundance of stream reach types that existed prior to the flood event.

Lane (1955) conceptualized equilibrium within a stable channel as a balance among stream discharge, channel slope, sediment load, and sediment size (Figure 2.1). Lane's conceptual model was described by Heede (1980) as:

$$Q_s D \propto Q_w S$$

where Q_s is sediment load (i.e., sediment discharge), Q_W is water discharge, D is sediment size, and S is channel slope.

What remains "in balance" over time are the processes of streambed degradation (erosion) and aggradation (sediment deposition). If an increase occurs in stream discharge, for instance, then the resulting increase in stream power can cause an increase in streambed degradation. The channel "adjusts" by decreasing channel slope, which reduces stream power and causes a return to the balance between degradation and aggradation. If a shift in stream discharge or sediment supply occurs, then the channel returns to equilibrium through adjustments in one or more other variables. However, persistent changes in one or more variables of sufficient magnitude may exceed a threshold that causes an abrupt shift to a new equilibrium state (Schumm 1979).

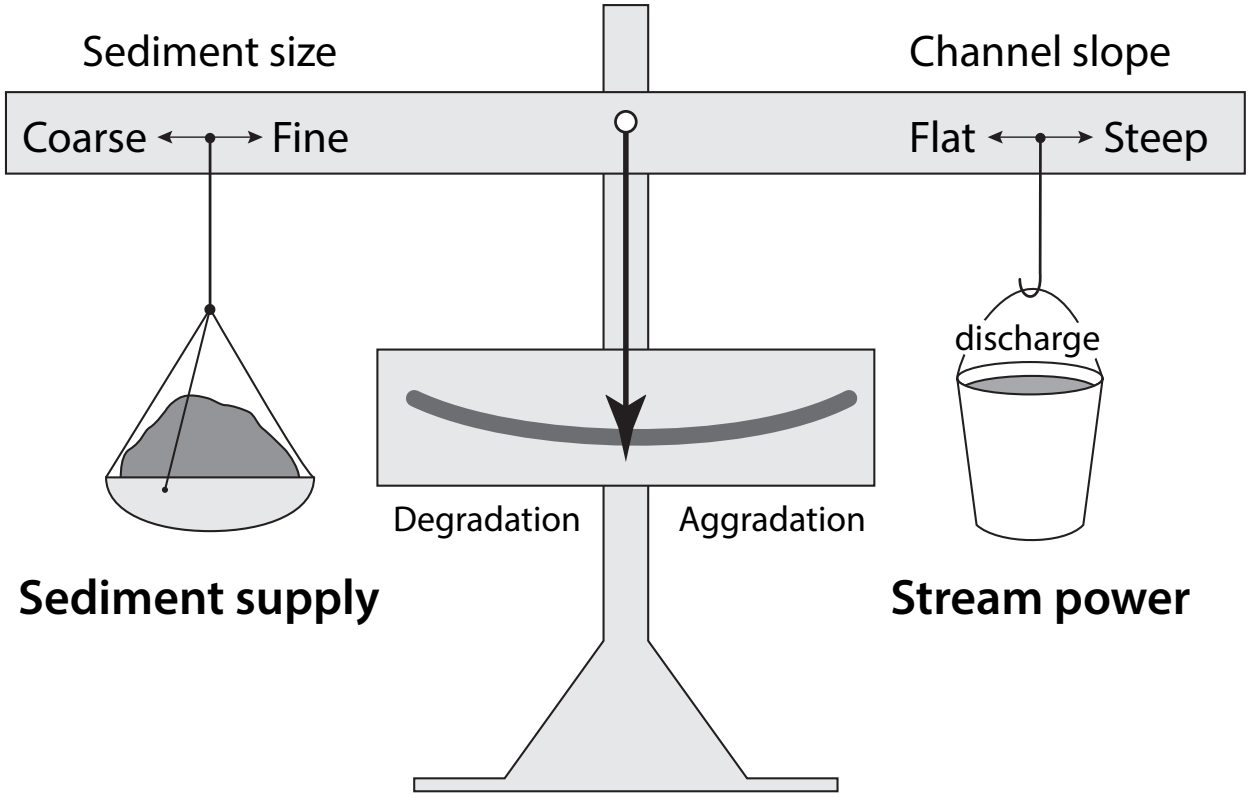


Figure 2.1. Lane's Balance illustrating the concept of channel adjustment (i.e., vertical aggradation or degradation of the streambed) in response to changes in water or sediment yield (from Dust and Wohl 2012).

While Lane's Balance is a useful conceptual model, it does not address complexity at the watershed scale nor the interactions between fluvial processes and riparian vegetation that affect channel morphology (Corenblit et al. 2007; Gurnell 2014) (Figure 2.2). These interactions are reciprocal and feedbacks exist between fluvial processes and vegetation composition and structure (Hupp and Osterkamp 1996; Osterkamp and Hupp 2010). Vegetation influences channel form and channel forming processes help shape riparian plant communities. Human activities that alter these interactions can cause significant changes to channel morphology and fish habitats.

Many geomorphic and ecosystem processes are coupled and occur in parallel at similar spatial and temporal scales. This results in mutual dependence between processes (Renschler et al. 2007). While such processes have received much attention from the scientific community in the last fifteen years, a theoretical synthesis within a holistic conceptual framework is still needed to address how riparian management interacts with this complex system (Smith et al. 2002; Stallins 2006). Interdisciplinary research of these interactions could result in better predictability of impacts caused by management. From an ecosystem management perspective, the choice of spatiotemporal boundaries—often dictated by geomorphic processes—is of profound importance to conceptualization of the system and its ecologic processes (Post et al. 2007).

We frame the hydrologic and physical processes as they shape the riverscape from the context of equilibrium and mutual dependence among water, sediment, and vegetation.

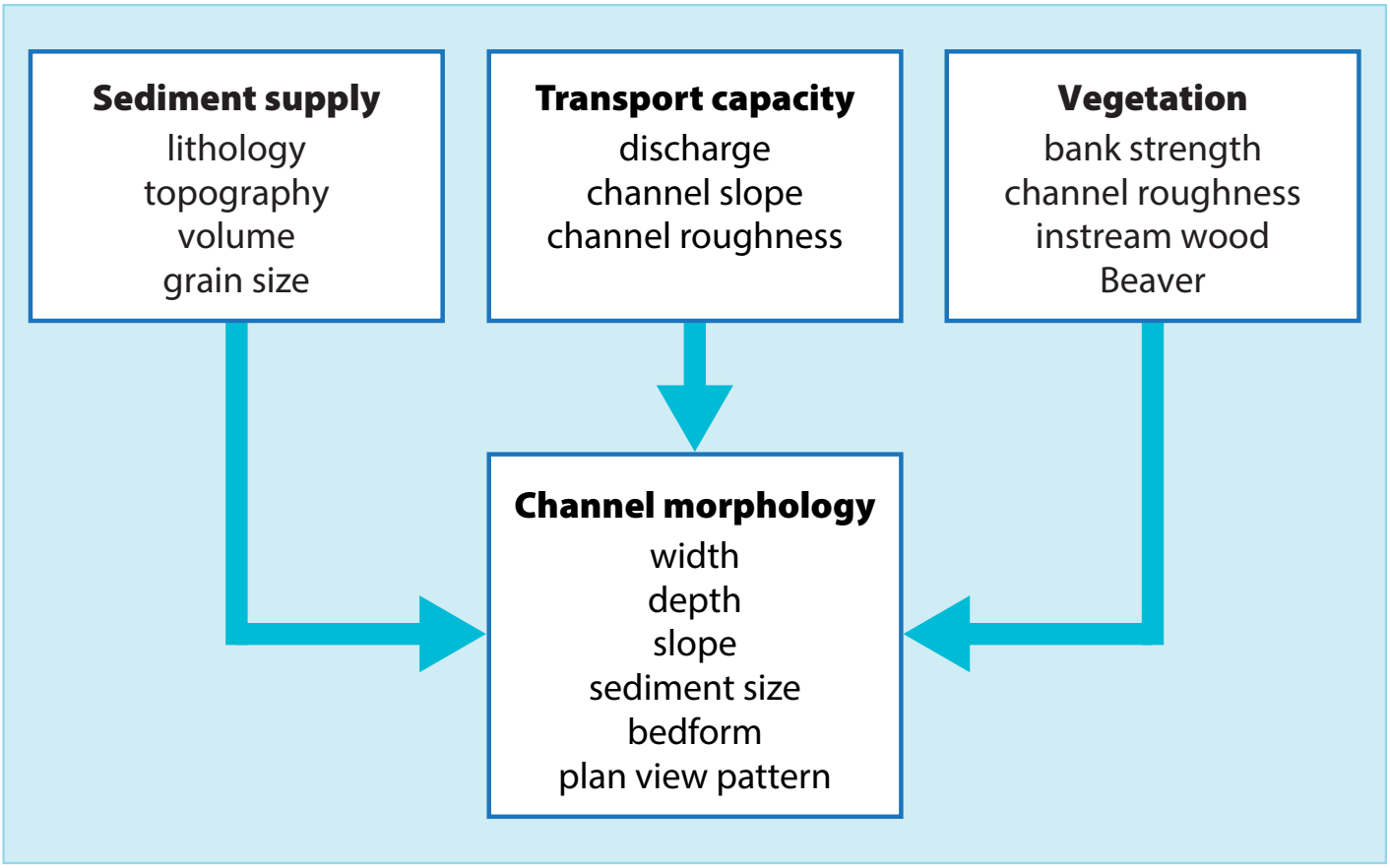


Figure 2.2. Influences on channel morphology (modified from Naiman and Bilby 1998).

2.3. Streamflow Processes

The pathways that water takes to reach a river exert a strong influence on the amount and timing of streamflow in the channel (Figure 2.3). Differences in the relative contributions of these pathways among locations and seasonal variability (e.g., presence or absence of snow) in environmental conditions produce a wide range of stream flow responses to precipitation events.

The fate of precipitation that is not lost through evaporation and transpiration is highly dependent on soil cover. Rain or melted snow that infiltrates the soil can flow downslope in the vadose zone (unsaturated), above the water table as through flow, or below the water table as groundwater in the phreatic zone (saturated).

When precipitation rates exceed soil infiltration rates (Horton 1933) or when local soils are saturated (Dunne and Black 1970a, 1970b; Dunne 1978), water moves downslope as surface runoff. Surface runoff or overland flow remains outside the confines of a channel, and is most common where vegetation is sparse. Human activities that compact soil or destroy permeable, near-surface soil layers reduce infiltration capacity and promote overland flow. A second type of runoff, saturated overland flow, occurs at convergent zones (such as hillslope concavities) and is a combination of direct precipitation onto saturated areas and return flow from the subsurface as it becomes saturated (Wohl 2014) (Figure 2.3).

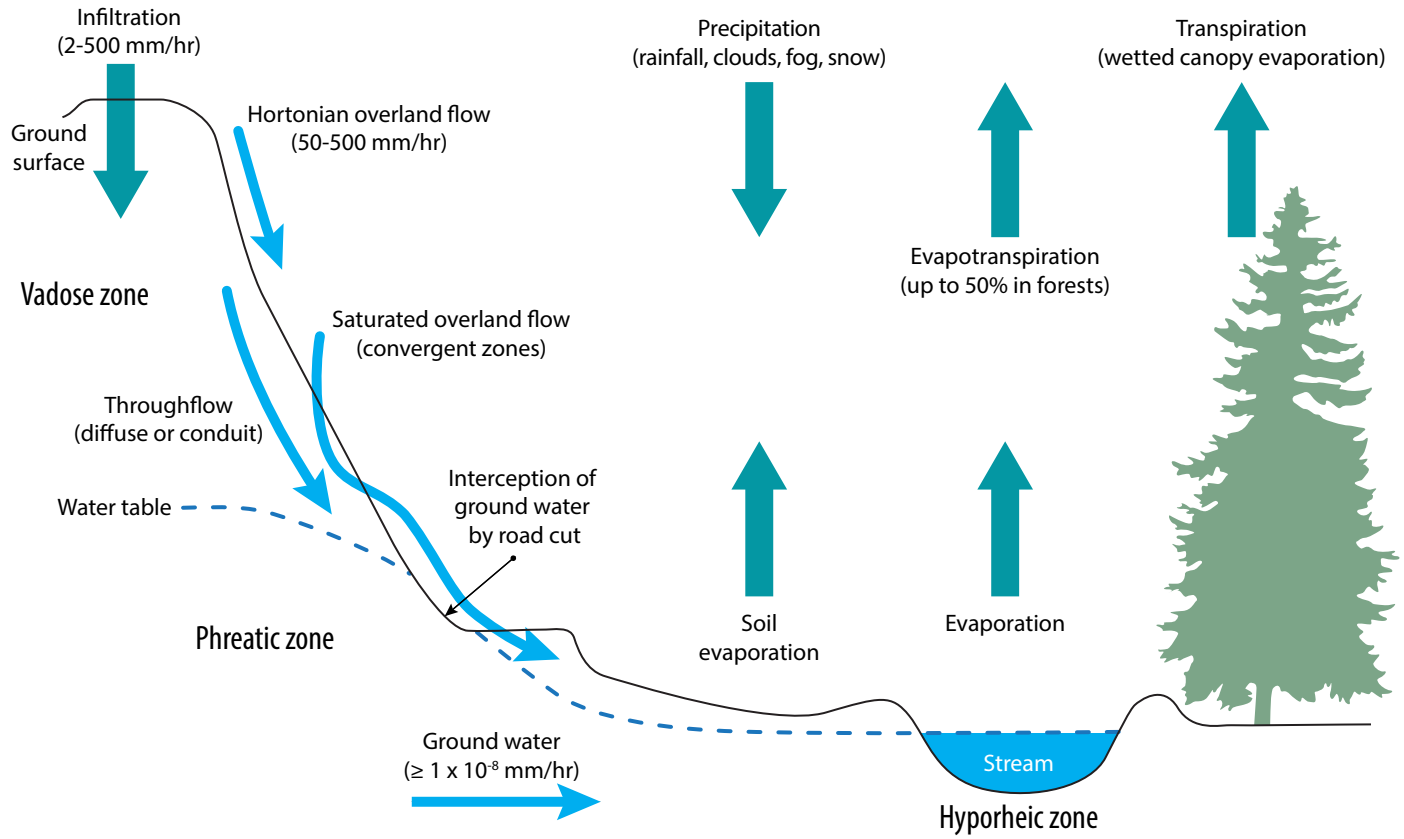


Figure 2.3. Illustration of different types and rates of downslope movement of water on a hillslope (modified from Ziemer and Lisle 1998, and Wohl 2014).

Runoff originates from variable source areas in response to precipitation and soil saturation conditions (Betson 1964; Hewlett and Nutter 1970). Conceptually, the amount of runoff within a single small drainage basin can be highly varied in space and time because many factors influence water infiltration and movement. Much of the variability in areas contributing water to the channel reflects the groundwater levels and activation[1] thresholds for lateral subsurface flow existing immediately after a precipitation event (McDonnell 2003).

Riparian vegetation influences preferential flow pathways in both surface and subsurface environments (Swanson et al. 1998; McDonnell 2003) and the manner in which surface flows create and maintain channel and floodplain morphology. During periods of active runoff, riparian areas quickly become saturated, and become the first areas within the watershed to contribute runoff into the channel (McDonnell 2003). Riparian areas account for the majority of the runoff at the beginning of a flood event, whereas hillslopes contribute more as the runoff tapers off at the end of an event. Flow resistance provided by riparian vegetation and related organic material slows water velocities, reduces peak discharge, and lengthens a flood's duration (Tabacchi et al. 2000; Nilsson and Svedmark 2002).

In a reciprocal manner, stream hydrology plays a large role in shaping riparian vegetation communities. The rate at which the river water surface lowers after a spring freshet influences seedling germination and recruitment (Mahoney and Rood 1998). Thus vegetation species composition and age structure vary due to flow frequencies that determine sediment mobilization and effective discharge (Pike and Scatena 2010).

[1] Activation of subsurface water means that subsurface water is flowing, i.e., the velocity deviates significantly from zero. Activation threshold often refers to the amount of precipitation needed to activate subsurface flow.

Interactions between stream water and groundwater occur in the hyporheic zone. In other words, the *hyporheic zone* is the ecotone between a surface stream and deeper groundwater (Boultan et al. 1998). The extent of the hyporheic zone is determined by the volume of sediment stored within the channel and active floodplain (Moore and Wondzell 2005). Two-way exchanges of water occurring in the hyporheic zone are important in regulating hydrological, biogeochemical, and thermal processes (Krause et al. 2011), which strongly influence the volume, chemistry, and temperature of streamflow. Along this ecotone, upwelling subsurface water supplies the stream ecosystem with mineral nutrients while downwelling stream water provides dissolved oxygen and organic matter to organisms inhabiting the interstitial spaces of alluvial sediments (Boultan et al. 1998). The hyporheic zone can account for a fifth of the invertebrate production in an aquatic ecosystem (Smock et al. 1992). Water flows laterally from the hyporheic zone into alluvial sediment deposits, and can extend out more than 1.2 miles (2 km) in wide valleys and to depths of 33 ft (10 m) (Stanford and Ward 1988). Hyporheic flows can also affect riparian vegetation, although the interactions between riparian communities and hyporheic conditions are not well understood (NRC 2002).



Cape Creek, Lane County, Oregon/Jane Atha, WDFW

2.4. Erosion and Sedimentation Processes

2.4.1. Sediment Sources and Delivery

Sediment sources and delivery within a watershed can vary significantly depending upon geology, climate, landform, soil erodibility, vegetation, and the magnitude and frequency of dominant disturbances. Delivery of sediment to channels by surface erosion is generally low in undisturbed watersheds, but can vary greatly by year (Swanston 1991). Annual differences are caused by variation in weather patterns, changes in exposed surface area, and changes in the amount of erodible material. Sediment can move downslope in aggregates through mass wasting (mass movement, mass failure, or slope movement) categorized as landslides, debris flows, or heaves. Mass wasting events are typically seasonal as a function of soil moisture and freeze-thaw processes (Hales and Roering 2009). Soil on a hillslope will remain stable if the sum of the applied shear stresses does not exceed the sum of the shear strengths of slope materials (soils, roots, etc.). Mass wasting is initiated when shear stress on a material exceeds its shear strength threshold (Ritter et al. 2002). The volume of material generated from hillslope mass wasting events can be very large, and is often the predominant source of sediment and large wood delivered to streams in the Pacific Northwest (Swanson et al. 1982).

Sediment can also move downslope through gradual, diffuse processes such as rainsplash and rills that form from overland flow. Rainsplash takes place when raindrops loosen the soil particles making them more



Skagit Valley agriculture/Jane Atha, WDFW

susceptible to entrainment by overland flow (Furbish et al. 2009; Dunne et al. 2010). Overland flow can be concentrated into small, narrow, shallowly incised micro-channels that are carved into hillslope soils (Selby 1993). These channels, termed rills and gullies (with gullies being deeper) can form effective conduits for sediment erosion into stream channels (Wohl 2014).

Sediment delivered from riparian areas can be generated by mechanisms other than direct streambank erosion. Riparian sediment sources can be associated with treefall that results in the uprooting of trees (root throw; Hairston-Strang and Adams 2000; Liquori 2006). The primary causes of treefall include wind along newly created edges in riparian forest (Liquori 2006; Reid and Hilton 1998), undercutting streambank erosion, and large-scale disturbances such as fire or pest infestation. Root throw can provide direct sediment inputs to the channel (Lewis 1998; Reid and Hilton 1998; Gomi et al. 2005). Harris (1977) found that windthrow-related sediment production along a stream in coastal Oregon was responsible for 33 tons of sediment per mile of stream per year (18.6 metric tons per kilometer per year) (as cited in Gomi et al. 2005).

Riparian vegetation can effectively trap and store sediment transported downslope from overland flow (Naiman et al. 2010). This topic is fully explored in Chapter 5, Pollutant Removal. Once the sediment is deposited in riparian areas, plant roots facilitate stabilization and continued storage of sediment (Allmendinger et al. 2005; Tal and Paola 2007).

2.4.2. Instream Sediment Transport and Deposition

Sediment that has entered the stream channel can be transported downstream as dissolved load, suspended load, or bed load. Dissolved load carries sediment within solution, which can be substantial in some rivers (Knighton 2014). The concentration of solute is highest in water entering the channel through subsurface pathways because slower rates of subsurface water

movement allow for longer reaction times with the surrounding environment. Solute concentrations through subsurface pathways tend to lessen with greater discharge (Wohl 2014). Suspended load refers to sediment carried as suspended particulates in the water, and originates predominantly from bank erosion and surface erosion from upland areas. The finest size fractions of suspended transport, known as wash load, are more likely to be supply limited, i.e., the amount in transport is limited by the amount available. In contrast, the coarser bed load, which consists of larger rocks that bounce along the channel bed, is typically limited by transport capacity of flowing water (stream energy). Bed load may not get suspended; it can roll and slide during low flows, saltate (bounce) at intermediate flows, and move as sheetflow during high flows (Wohl 2014). Bed load transport processes are surprisingly complicated because many factors, some of which interact, determine the threshold for movement. These factors include the range of sediment sizes, their spatial arrangement, and channel form within a reach (Knighton 1984).

Bedforms are bed undulations that result from sediment transport and deposition. Montgomery and Buffington (1997) classified stream channels based on common bedforms (i.e., cascade, step-pool, plane-bed, pool-riffle, and dune-riffle), their dominant sediment transport process, and behaviors of debris flows and instream wood. The role that sediment plays in aquatic habitat can differ dramatically among those classes. For example, sediment in headwater channels (often classified as cascade or step-pool) tends to be stored behind boulder and wood obstructions. In lower gradient channels, sediments become sorted into pools and riffles depending on instream wood load, gradient, and a wide variety of other factors (Benda et al. 2005; Gomi et al. 2005).

All bedforms are depositional features. Deposition occurs when the flow or shear velocity in the stream falls below the settling threshold velocity of the sediment particle. Settling thresholds are lower than entrainment thresholds, and deposition can be localized or extended across a channel length depending on fluctuations in flow velocity (Wohl 2014). Riparian vegetation can be especially instrumental in facilitating deposition within channels and along banks (Tal et al. 2004). Establishment of riparian vegetation can initiate a positive feedback process as plants trap and stabilize sediments and organic matter that provides sites for germination of plants, which can then reinforce the development of floodplains, instream islands, and other landforms.

Erosional forces in the streambed can be increased due to topographic constrictions or locally steep gradients. Where hydraulic forces overcome surface resistance, channel incision can occur (Wells et al. 2009). Channel incision that occurs at the channel head, known as a headcut, results in vertical faces that separate upslope unchanneled environments from downslope channels. Headcuts that destabilize or incise an otherwise stable channel bed result in significant increases in sediment yield (Meyer et al. 1975; Bryan 1990). Headcuts can also occur as an upstream-migrating "step" in the channel bed that forms as a result of hydraulic scour, often from manipulations to the channel or flow conditions (e.g., culverts, diversions, etc.). This type of headcut can migrate upstream and change channel form for long distances.

Establishment of riparian vegetation can initiate a positive feedback process as plants trap and stabilize sediments and organic matter that provide sites for germination of plants, which can then reinforce the development of floodplains, instream islands, and other landforms.

A combination of field, experimental, and theoretical research has dramatically advanced our understanding of sediment transport dynamics as well as the role of vegetation in stream morphology. Sophisticated flume experiments and computational models have confirmed the importance and complexity of interactions among water, sediment, wood, and vegetation (Gurnell 2014). Recent modeling efforts have placed these phenomena on solid theoretical footings and have allowed researchers to explore scale dependence. We know much less about these interactions at small scales (single plant), however, understanding smaller scale phenomena is crucial to fully understanding longer-term and larger-scale geomorphic form and process (Gurnell 2014).



Bank erosion along the upper Chehalis River/Jane Atha, WDFW

2.4.3. Streambank Erosion

Streambank erosion is a geomorphic process that is integral to a watershed's natural disturbance regime and necessary for long-term ecological sustainability (Florsheim et al. 2008). Bank erosion is a key process for maintaining the structural diversity of aquatic and riparian habitats; it initiates community succession that promotes ecological diversity of riparian areas, and contributes coarse sediment to streambeds that is an essential habitat element for benthic invertebrates and spawning salmon. Bank erosion commonly occurs on the outside of river bends, but it can also occur in straight channels where changes in water or sediment supply cause channel incision. Instream large wood or mid-channel gravel bars that divert flows toward a bank (Florshiem et al. 2008) can also cause bank erosion. Local bank erosion is a naturally occurring process that is often indicative of a channel in dynamic equilibrium. Despite this fact, bank erosion at any scale is commonly misinterpreted as a sign of channel instability. Human disturbances can increase rates of bank erosion, and thus, understanding whether bank erosion is triggered by human activities or natural geomorphic processes is important for site-scale management (Polvi et al. 2014).

Two types of processes result in bank erosion: fluvial erosion and mass wasting (ASCE 1998). Fluvial erosion is the separation of sediments from a streambank's surface by the forces of flowing water. Fluvial erosion may destabilize riparian vegetation by exposing plant roots or undercutting vegetation (Florsheim et al. 2008). Fluvial erosion can eventually lead to mass wasting ("bank failure"). Mass wasting at streambanks is caused by scour of the streambed and bank toe that increases bank height and angle. When gravitational forces on the bank (weight of soil, water, and overlying vegetation) exceed the shear strength of the bank material, a portion of the bank collapses along a failure plane (Simon et al. 2000). Both types of bank erosion occur mainly during peak flows, but the association between flow magnitude and amount of bank erosion varies greatly among



Building in danger from streambank erosion on Newaukum River/Kaysie Cox, WDFW

watersheds. Wolman (1959, as cited in ASCE 1998), for instance, reported that significant bank erosion on a creek in Maryland occurred more than ten times per year during relatively small but frequent peak flow events. Studies of other alluvial systems have found that significant bank erosion was caused mostly by large floods with recurrence intervals of decades or more (ASCE 1998).

The stability of streambanks is influenced by soil characteristics, groundwater, and vegetation (Hickin 1984; NRC 2002). Mass wasting failure mechanics, for example, are quite different for cohesive and noncohesive soils (ASCE 1998). Adjacent surface waters or ground water affects pore water pressure, and positive pore water pressure destabilizes banks by reducing cohesion and friction amongst soil particles. Water in soil also adds mass, thereby increasing gravitational forces acting on a streambank. Bank failure often occurs shortly after flood waters recede because soils are at or near saturation and the laterally confining hydraulic pressure of the floodwaters decreases to zero (Rinaldi et al. 2004).

Vegetation may have mechanical and hydrologic effects on bank stability, and these effects can be stabilizing or destabilizing (Simon and Collison 2002; Langendoen et al. 2009; Pollen-Bankhead and Simon 2010). Soil is generally strong in compression, but weak in tension. Woody and herbaceous plant roots are strong in tension, but weak in compression. Consequently, the root-permeated soil of streambanks behaves as a composite material with enhanced strength (Simon and Collision 2002; Pollen and Simon 2005). However, the additional bank strength provided by roots is species dependent (Polvi et al. 2014). Simon et al. (2006), for instance, found that Lemmons's Willow *Salix lemmonii* provided an order of magnitude more root reinforcement of streambanks than Lodgepole Pine *Pinus contorta*. Dense root networks also physically restrain or bind soil particles. In addition, exposed roots on the bank surface increase channel roughness, which dampens stream flow velocities, thereby reducing fluvial erosion (Griffin et al. 2005; Gorrick and Rodríguez 2012). In fact, fluvial erosion of well-vegetated banks is 10 to 100 times less than erosion of unvegetated banks (ASCE

1998). Reduction of stream velocities by roots may also cause sediment deposition, which further stabilizes streambanks.

Vegetation has destabilizing mechanical effects as well (ASCE 1998; Simon and Collison 2002). The weight of vegetation adds a "surcharge"[2] load to soil. Hence, the weight of vegetation increases the vertical shear stress near a streambank and adds to the lateral earth pressure[3] at the streambank surface, however, these effects can be minimal relative to soil's weight (Simon et al. 2006). Additionally, tall, stiff vegetation may impose destabilizing forces on streambanks during windstorms (ASCE 1998).

The hydrologic effects of plants on streambank stability are those that influence soil moisture. Through canopy interception, vegetation reduces the amount of precipitation that reaches soil. Transpiration, which extracts water from the soil column within the root zone, creates negative pore water pressures (matric suction) that increase soil shear strength (Simon and Collison 2002). Plants destabilize streambanks by facilitating infiltration of water into soil via flow pathways ("macropores") created by live and decayed roots. In addition, stemflow tends to concentrate precipitation around the base of stems, creating higher local pore water pressure. The net hydrological effect of vegetation can be significant. Simon and Collision (2002), for instance, found in their study conducted in northern Mississippi that following a very dry period the stabilizing hydrological effect of tree cover was two times greater (220%) than tree cover's stabilizing mechanical effect. However, this result was reversed following a wet period; the stabilizing mechanical effect of tree cover was 159% of tree cover stabilizing hydrological effect.

The bank stability function of riparian vegetation has important implications for riparian area management. FEMAT (1993:V-27) created a generalized curve of root strength versus distance from channel based on expert opinion informed by scientific literature. The radius of Douglas-fir *Pseudotsuga menziesii* root networks are highly correlated with tree crown radius (Smith 1964).[4] Hence, FEMAT (1993) assumed the contribution of root strength to maintaining streambank integrity declines at distances greater than one-half a crown diameter. Using linear regression, Roering et al. (2003) derived a power-law relationship for coniferous trees between root network radius and tree diameter. This relationship suggests that large diameter conifers (36 to 48 inches [91 to 122 cm] diameter breast height) have root network radii that measure 16 to 33 ft (5 to 10 m). Hence, in an undisturbed old-growth riparian forest, the full contribution of root strength to streambank stability is provided by trees within approximately 33 ft (11 m) of the streambank.

2.4.4. Lateral Channel Migration

Lateral channel migration affects sediment erosion and deposition, local topographic relief, flood inundation patterns, river planform, alluvial architecture, and riparian vegetation patterns, which in turn results in a complex arrangement of aquatic and riparian habitats across a river's floodplain (Naiman et al. 1993). Lateral channel migration occurs through the processes of meander bend development, avulsions, and channel widening and narrowing (Rapp and Abbe 2003). These processes occur through fluvial erosion of intact bank material and mass failure of streambanks under gravity, followed by mobilization and transport of the disturbed material (Burckhardt and Todd 1998).

2 A surcharge load is any load imposed upon the soil surface close enough to a streambank to cause lateral pressure to act on the bank. "Surcharge" denotes an extra force in addition to the weight of the soil.

3 Lateral earth pressure is the pressure (i.e., force per area) that soil exerts in the horizontal direction.

4 The ratio of root spread to crown width for small Douglas-fir and Western Hemlock *(Tsuga heterophylla)* (mean dbh about 13 inches [33 cm]) was reported by Smith (1964) to be about 1. Data in Eis (1987) for these same tree species suggest a ratio of about 2.

One mechanism of channel migration is meandering, which is one of the most common river-channel patterns (Güneralp and Marston 2012). Given time, and lacking physical obstructions, a natural unimpeded meandering channel can swing and shift across its valley in the downstream direction, completely disturbing the floodplain (Schumm 1977). The floodplains of meandering rivers are low-lying depositional features that store large volumes of sediment, and reflect the history of erosion and deposition of a river occupying the valley floor (Dunne and Leopold 1978). The time needed for a channel to migrate and occupy its entire floodplain is expressed as a "floodplain turnover rate," which may take tens to thousands of years in western Washington. Beechie et al. (2006) found, for example, that braided channels in rivers of the Cascades and Olympic mountains had a turnover rate of 25 years. In contrast, O'Connor et al. (2003) estimated turnover rates for two large rivers on the Olympic Peninsula to be approximately 200 to 2000 years. The channel migration rates for the rivers in O'Connor et al.'s study ranged from 13 ft (4.0 m) to 42 ft (12.7 m) per year.

Sediment erosion and deposition patterns that result in channel migration are caused by complex flow patterns along meander bends. Water tends to develop a horizontal swirling flow as a result of greater roughness along the banks than in the center of the channel. This swirling flow, termed "helical flow", is generated by the super elevation of the water's surface as it flows along the outside of a bend (Callander 1978). Helical flow creates large cross-stream variation in velocity (Dietrich et al. 1984), and the reduced velocity and bed shear stress at the inside of a bend creates pointbar deposition. In addition, pointbars deflect flow laterally toward the cutbank, creating topographically driven secondary flow that further induces an outward velocity shift toward the cutbank (Güneralp and Marston 2012).

Movements of individual meanders are described as: 1) simple migration (or translation), which is a downstream shift without significant shape change; 2) extension (or growth), where the amplitude of the bend extends by migrating across the valley; 3) rotation, in which the bend axis changes orientation; and 4) lobing and compound growth, where the bends become less regular and symmetrical (Hooke 1984). Individual bends along a meandering channel can have different styles and rates of migration, and typically deform and become asymmetrical with migration. Meander migration that increases the amplitude and tightness of bends can lead to a cutoff channel that creates a shorter flow path across the inside of a pointbar or a neck cutoff at the base of the bend. The increase in channel gradient from the cutoff causes it to become the main channel, and the longer flow path becomes a secondary or overflow channel on the floodplain. Secondary channels may function as side channels that are important rearing habitat for juvenile salmonids (Rosenfeld et al. 2008) or



Chehalis River meander bend/Jane Atha, WDFW



Mid-channel bar/Jane Atha, WDFW

oxbow lakes, which are habitat for amphibians (Henning and Schirato 2006). The increased habitat diversity for aquatic and riparian organisms can persist for decades to centuries depending on rates of sediment filling.

Another mechanism for channel migration is avulsion, which is the rapid abandonment of a river channel and the formation of a new river channel. Avulsions can occur with little erosion of the land between the old and new channel locations (Allen 1965; Butler 2004). An avulsion can cause rapid, dramatic shifts in channel location from one side of the valley bottom to the other, and can occur during a single flood event. Avulsions are often associated with aggrading channels, but this is not a necessary requirement (Tooth et al. 2007). Meander cutoffs, for example, are a type of avulsion not derived from aggradation. In the Pacific Northwest, wood jams often cause and mediate avulsions, acting to maintain a multiple-channel pattern. Wood jams can cause avulsions by plugging channels and diverting flow into a relict channel that then becomes the main channel (Collins and Montgomery 2002).

Along alluvial rivers, spatial and temporal patterns of riparian vegetation composition and structure are controlled by rates of channel migration and vegetation response to disturbance (Figure 2.4). As channels migrate laterally, pointbars create conditions for recruitment of early successional plant species. Over long periods, pointbar growth is followed by the succession of terrestrial plant communities. Consequently, a pointbar may support a chronological series of successional stages arranged from youngest closest to the active channel to oldest farthest from the channel (Shankman 1993). A limited number of species consistently dominate the accreting edge of pointbar landforms, while progressively more species establish as the pointbar aggrades to a higher surface elevation (Meitzen 2009). Opposite these pointbars, eroding cutbanks expose and remove previously established mature vegetation, but also open edge habitat for colonization by new plant species. Kupfer and Malanson (1993) found that cutbank edge forests have higher stem densities and greater species richness than floodplain interior forests.

Lateral channel migration and related streambank erosion processes can pose risks to human communities located near rivers and large streams. Likewise, human actions intended to limit channel migration can degrade aquatic and riparian habitats. For these reasons, geomorphologists have developed protocols for determining the channel migration zone (CMZ). A CMZ includes the outer extent of historical channels, plus the area where future channel migration could occur over some time period (e.g., 100 years). CMZ delineation considers the historical migration zone, i.e., the area encompassing all historical channels; the avulsion hazard zone, i.e., areas not in the historical record that are at risk of avulsion; and the erosion hazard area, i.e., the area at risk of bank erosion from stream flow or mass wasting over the time horizon of the CMZ (Rapp and Abbe 2003). The CMZ typically encompass floodplains and some portion of terraces (landform remnants of the former floodplain). The CMZ also includes channels and terrace banks that are at risk of mass wasting due to erosion of the toe.

Lateral channel migration produces a spatially dynamic riparian ecosystem. Because the riparian ecosystem (i.e., the riparian zone and zone of influence) is defined by proximity to water, as the active channel moves back

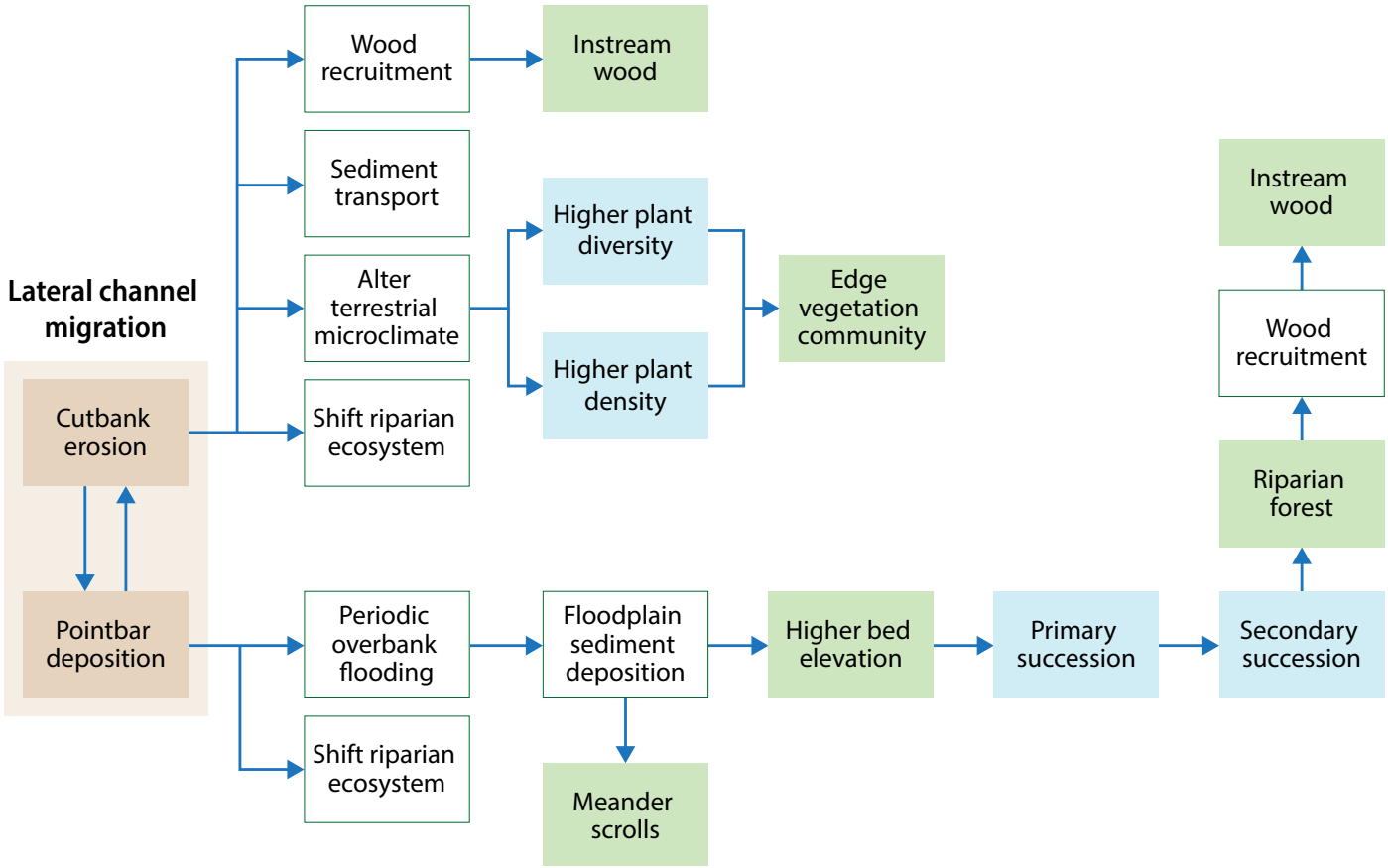
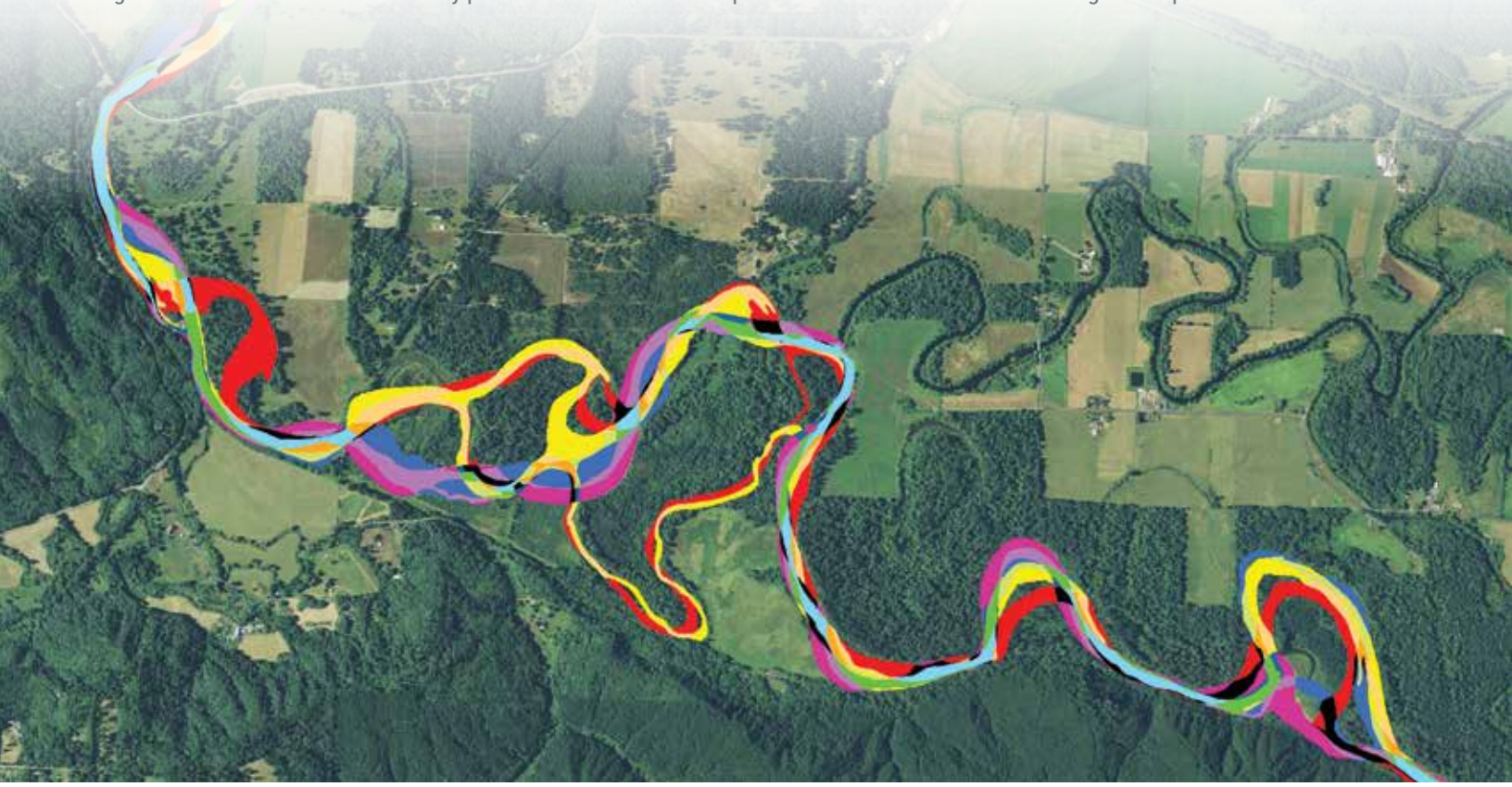


Figure 2.4. A conceptual model of lateral channel migration processes and riparian forest responses (modified from Meitzen 2009). Arrows indicate the hypothesized directions of causal relationships. Brown boxes represent proximal processes leading to channel migration. White boxes are secondary processes. Green boxes depict structures. Blue boxes are biological responses.



Chehalis River meander paths between 1938 and 2013/Ken Pierce, WDFW

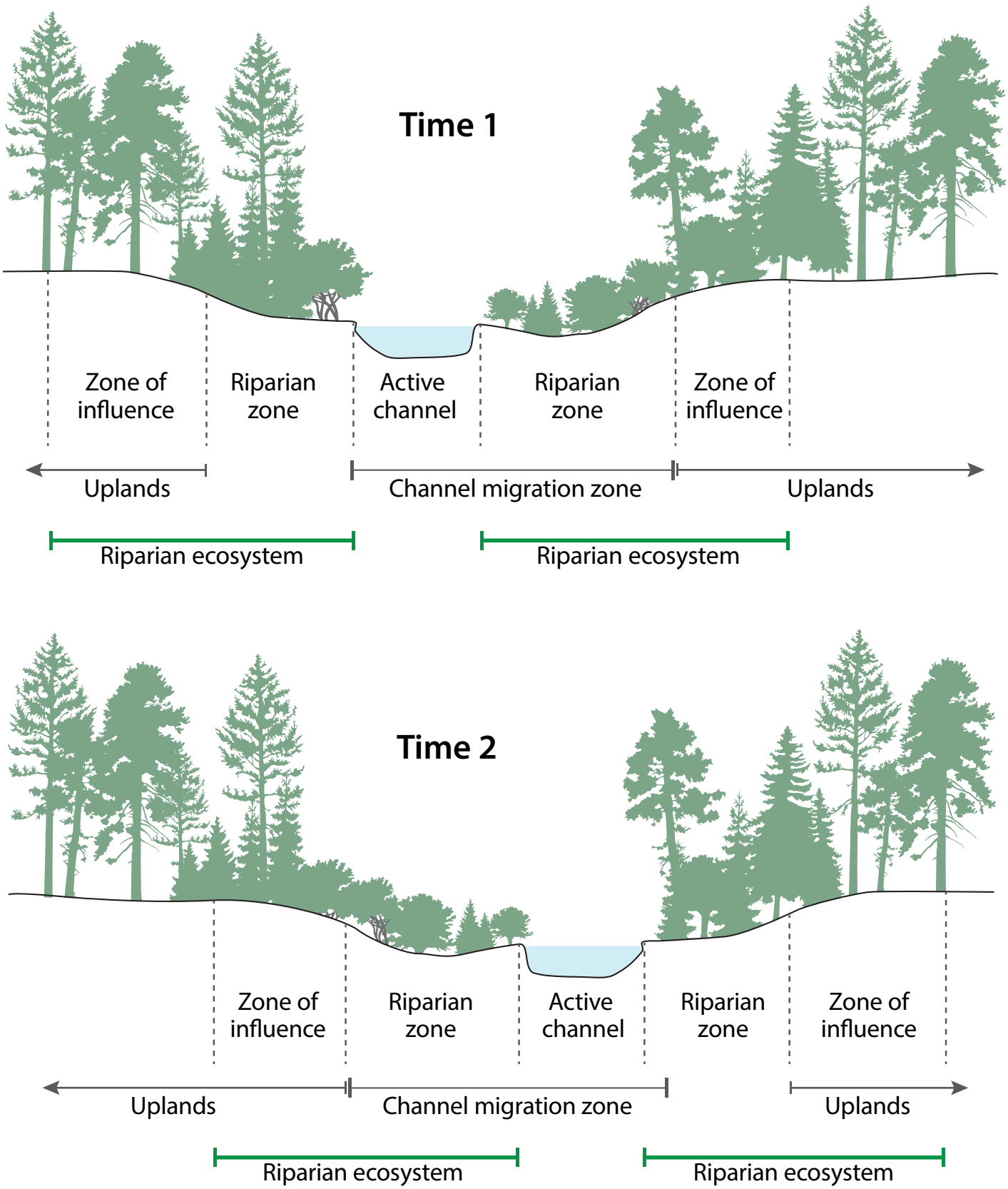


Figure 2.5. Spatial relationships between the riparian ecosystem and channel migration zone (CMZ) over time. As the active channel moves laterally within the CMZ the riparian ecosystem moves with it. Time 1 and time 2 could be separated by days or centuries.



Quinault River/Jane Atha, WDFW

and forth across the CMZ, the riparian ecosystem moves with it (Figure 2.5). Consequently, over long periods of time, a riparian ecosystem will occupy different parts of the CMZ. Furthermore, when an active channel reaches the outside limit of its CMZ, the riparian ecosystem lies outside and adjacent to the CMZ. Hence, to maintain riparian ecosystem functions, management must anticipate and protect future locations of the riparian ecosystem.

2.5. Disturbances

2.5.1. Geomorphic Process Domains

The spatial variability of sediment sources and the varying capacity of water to transport sediment result in a mosaic of different channel forms within a watershed. Channel forms can be described by attributes such as bed and bank sediment size distributions, pool and riffle depths, bankfull widths, gradient, and sinuosity. The classification of channel forms has been refined over the last 30-40 years beginning with Schumm (1977), who distinguished a headwater production zone, mid-basin transfer zone, and downstream depositional zone. This longitudinal arrangement is also reflected in more recent work that defines geomorphic *process domains*. Process domains characterize differences in the types and frequency of disturbance events, and provide a way to represent spatial differences in disturbance regimes (Montgomery 1999).

Six common geomorphic process domains have been identified for forested watersheds of Washington State: hillslope, unchanneled hollows, debris-flow channels, bedrock-fluvial channels, coarse-bed alluvial channels, and fine-bed alluvial channels (Montgomery et al. 1996; Sklar and Dietrich 1998; Montgomery 1999). These process domains are important to distinguish since they

each function differently in terms of sediment dynamics and transport capacity. Note that although geomorphic process domains often occur in a regular longitudinal sequence, there are many exceptions in Washington State where this is not the case.

Hillslopes are unchannelized and are typically dominated by diffusive transport or rain-facilitated transport of sediment downslope. Unchanneled hollows are hillslope concavities that serve as sediment storage sites and source zones for hillslope mass movement (Dietrich and Dunne 1978; Montgomery et al. 2009). Debris-flow channels are dominated by mass wasting sediment dynamics but channel geometry may still be influenced by fluvial processes. Bedrock-fluvial channels have underlying exposed bedrock that limits boundary erosion. In these channels, overlying alluvium is transported by scour during higher flows, and transport capacity exceeds sediment supply, resulting in exposed bedrock. Coarse-bed alluvial channels are dominated by unconsolidated gravels, cobbles, and boulders and are more likely to be supply limited, rather than stream energy limited. Lastly, fine-bed alluvial channels have non-cohesive sand-sized sediment and are more likely to be transport limited by flow energy rather than sediment supply (Wohl 2014).

Using process domains, it is possible to identify within a watershed where different geomorphic processes, disturbance regimes, and responses to disturbance dominate, and predict riparian vegetation dynamics (Naiman et al. 2000; Polvi et al. 2011). Channel morphology correlates well with bed gradient and sediment supply (Montgomery and Buffington 1997). The differences in the balance of hydraulic forces and available sediment among these channels likely lead to differences in overbank processes that can affect vegetation establishment, growth, and mortality. For example, in higher gradient channels, energy is expended on transporting sediment downstream and is not available to reshape the riparian area.

Disturbances are relatively discrete disruptive events that change the physical environment or resource availability, and are essential for developing habitat to support native biota.

2.5.2. Natural Disturbance Regimes

From an ecological perspective, disturbances are relatively discrete disruptive events that change the physical environment or resource availability (Pickett and White 1985); thereby creating opportunities for other species to become established (Nakamura and Swanson 2003). Natural disturbances result in dynamic habitats of varying physical conditions that allow for a variety of species to coexist. Community succession theory recognizes that large-scale disturbances, such as low frequency, high magnitude floods, continually reinitiate community succession in riparian areas (Pickett et al. 1987; Corenblit et al. 2007). The cycle of disturbance and succession occurring throughout a watershed maintains compositional and structural diversity in aquatic and riparian ecosystems. Disturbances that influence streams and riparian areas include wildfire, floods, landslides, tree infestations by insects, and human-induced disturbances such as residential development, timber harvest, and road construction.

Disturbance processes are essential for developing the range of habitat conditions necessary to support native biota (Swanson et al. 1998; Tabacchi et al. 2000). For example, the coarse sediments and large wood delivered to streams via mass wasting are thought to be essential components of freshwater salmonid habitats (Reeves et al. 1995). A natural disturbance regime can be characterized by frequency (how often), magnitude

(how big), duration (how long), and predictability. Wildfires of a given magnitude, for example, occur with a particular statistical probability in the absence of human manipulation of a watershed (Agee 1993). In general, smaller, frequent, and varied disturbances increase the heterogeneity of channel forms, leading to an environment that is more diverse and species rich (Kauffman and Martin 1989; Malanson 1993; Tabacchi et al. 2000; Everett et al. 2003). For example, the dynamics of stream channels that result from frequent, low intensity wildfires determine short-term patterns such as seed germination and animal foraging behavior (Hughes 1997). The influence of moderate and frequent disturbances such as fire (Wright and Bailey 1992) or insect-induced tree mortality (Mattson and Addy 1975) may lead to minor reductions in the riparian canopy, but more diverse habitat conditions that are generally beneficial for salmonids (Naiman and Bilby 1998). By contrast, disturbances that are large and infrequent tend to lead to widespread alterations that have larger and longer-lasting physical impacts. Large disturbances could cause a geomorphic threshold to be exceeded, and the resulting fluvial response could manifest a new geomorphic state with different physical conditions that support a different biological community (Hughes 1997).

Human activities can either dampen or amplify disturbance processes. While natural disturbance processes are ongoing, they are modified by human alterations (e.g., dams eliminate or dampen flood flows and land management can reduce the frequency and severity of fires). Too little or too much disturbance may have detrimental impacts on the physical structure of streams and riparian areas. For example, too little flooding can lead to cementation of the streambed or loss of riparian vegetation, especially in arid regions. Conversely, too much flooding caused by land cover change, for example, can lead to less habitat complexity due to excessive scouring of the channel. The past and current management of a site–and of its greater watershed–may alter the natural disturbance regime resulting in ecosystem states that did not exist historically.

Process domains within a watershed exhibit different disturbance regimes which manifest different aquatic and riparian ecosystems. Disturbances, and where they occur within a watershed, play key roles in structuring ecosystems. Important advances have shifted focus from single channel reaches and disturbance events to processes occurring at larger geographic extents over longer periods of time, that establish linkages between watershed-scale conditions and natural disturbance regimes (Naiman and Bilby 1998; Nakamura and Swanson 2003).

2.5.3. Human Alteration Impacts

Thus far, this chapter has largely focused on the hydrologic and geomorphic processes and their interactions with riparian area vegetation as they naturally occur within a watershed. However, human influences on channel form are ubiquitous, and therefore should be considered in management of riparian areas.

How a channel responds to human alterations of the landscape or riparian areas depends on its sensitivity and resilience (Brunsden and Thornes 1979).



Narrow riparian buffers along Badger Creek/Jennifer Nelson, WDFW

A sensitive channel reach changes in response to human alterations. A resilient channel reach also changes in response to human alterations but will return to its prior condition at some later time. The idea that some parts of a river are more or less sensitive or resilient is critical to predicting channel adjustments. For example, stream reaches with high transport capacity may adjust relatively quickly to an increase in upstream sediment yield but a similar change in sediment yield may cause significant changes in channel morphology in reaches with low transport capacity. The shape, hydraulics, and natural disturbance regime of a reach may indicate its sensitivity to anthropogenic disturbance. For example, a channel that is degrading (lowering bed elevation) may be more sensitive to riparian large wood additions than a channel that is in equilibrium. In addition, sensitivity to changes in hydrology is inversely proportional to channel gradient (Wohl et al. 2007). Hence, managers should anticipate that high gradient streams will be more sensitive to changes in stream flow than lower gradient streams. Other drivers such as the flow regime or controls such as lithology might also be used to determine a reach's sensitivity and resilience, and thereby inform management decisions.

Forestry

An extensive body of scientific literature documents the effects of forestry on stream channels (see Foley et al. 2005; Scanlon et al. 2007; and Wohl 2013 for thorough reviews). Cutting of trees and road building associated with forestry can greatly increase sediment yields and affects water yields over multiple decades as vegetation recovers (Wohl 2014). Impacts from road networks—for logging and otherwise—are numerous and are discussed below. Changes in sediment supply and water yield due to logging can alter the streamflow, stream chemistry, and channel morphology of a stream reach (Liquori et al. 2008). In addition, the resilience of channels in response to such alterations can be quite variable. For example, Madej and Ozaki (1996) found that channel recovery (defined as returning to a former bed-elevation) after a sediment wave following extensive logging in Redwood Creek basin, Northern California varied from 8 years in one creek to 15 years in another. A third channel had not yet recovered.



Clearcut hillslope/Jane Atha, WDFW



Big Beef Creek, Kitsap Peninsula/Ned Pittman, WDFW

There is substantial agreement among scientists as to the potential magnitude and consequences of peak flow changes due to forestry. Grant et al. (2008) assessed the effects of forestry on peak flows and consequent channel response in the Pacific Northwest in a state of the science report. Their findings, primarily synthesized from long-term monitoring, show that responses are complex, and vary with runoff type (snowmelt, rainfall or rain-on-snow), local hydrology, harvest treatment, and channel type. The authors generally noted that geomorphic changes from harvest-related peak flow effects are limited to low-gradient channels (below 2% grade) and are generally minor as compared to other anthropomorphic impacts. Other literature reviews (e.g., Liquori et al. 2008; Grant et al. 1999) had similar conclusions.

The degree to which forestry practices alter water and sediment yields depends on where the logging occurs within a drainage basin. In one study, logging at lower elevations in snowmelt-dominated basins of southwestern Canada caused little to no change in peak flow because of relatively small snowpack, whereas in the higher elevations the peak flow changed significantly (Whitaker et al. 2002). Similarly, characteristics such as climate, topography, and soils also determine landscape sensitivity to forestry. Several studies have shown that mean annual precipitation is a reasonable indicator of impact (e.g. Anderson et al. 1976; Coe 2006; CBOF-TAC 2008). A road network may deliver 20% of sediment to stream channels in areas with 22 in (500 mm) per year average precipitation compared with 50% of the sediment when precipitation exceeds 118 in (3,000 mm) per year (Coe 2006). In areas of high topographic relief, it is particularly challenging for researchers to differentiate channel adjustments induced by logging from change that would have occurred without interference (Marston 2008).

Conversion of riparian areas from forest to other land uses can cause channel narrowing and deepening (Anderson et al. 2004; Sweeney et al. 2004; Faustini et al. 2009). Furthermore, streams without riparian forests often exhibit channels with less wood that are narrower, deeper, have fewer obstructions, less variability in active channel width, higher proportions of run and glide habitats, and lower habitat diversity (Jackson et al. 2014).

Road Infrastructure

Road networks are similar to stream networks in that they are often widely distributed, transport energy and material across a landscape, and have a high edge length per unit area enabling interaction with adjacent hillslopes (Jones et al. 2000). Stream networks and road networks commonly occur in similar densities in wet-climate forested mountains where logging has occurred (Wemple et al. 1996).

The biggest impact of unpaved roads on aquatic systems is sedimentation. Road construction and maintenance disturbs a layer of soil on the road tread, adjacent drainage ditch, and cutslopes that becomes easily eroded material (Megahan 1974). In conjunction with other loose material on roads, higher erodibility increases the total sediment yield from a road segment (Luce and Black 1999). In managed forests of Washington State, unpaved roads and trails are the most significant management activity that affects

sediment production and delivery into streams (Lewis 1998; Gomi et al. 2005; CBOF TAC 2008). Roads can initiate mass movements that tend to result in longer runout zones and more sediment than their naturally occurring counterparts do (May 2002). Sediment generated from roads can be delivered to streams via ditches and gullies below cross-draining culverts that concentrate and route runoff. Road sediment production varies substantially with the type of surfacing material, road slope, mean annual precipitation, geology, traffic type and volumes, and road area (Cafferata and Munn 2002; MacDonald et al. 2004; Coe 2006). Roads and water crossings with improper design or maintenance are often the most significant sources of erosion and sediment delivery to streams in forested watersheds (Madej 2001; Cafferata and Munn 2002). Jones et al. (2000) found that unpaved roads continue to contribute sediment fines to channels long after harvested vegetation has reestablished.

Agriculture

Agriculture, in the form of livestock grazing or crop production, can reduce and alter vegetation cover, compact soils,and reduce water infiltration. It can also increase runoff and sediment yield, and cause associated changes in streamflow, channel morphology, and channel stability.

Cattle grazing can severely degrade riparian areas particularly through vegetation reduction and trampling of streambanks. Grazing animals can create ramps along streambanks and trails along the floodplain that enhance localized erosion (Trimble and Mendel 1995). Grazing-disturbed streams are usually characterized by a lack of overhanging banks, wide and shallow channels, smaller pool area, high sediment yields and turbidity, steep gradients, and channel beds typified by long stretches of glides or runs. Along streams with enclosures that kept cattle out of riparian areas, Magilligan and McDowell (1997) found that channel widths became narrower due to increased roughness by grassy riparian vegetation, which ultimately traps sediment leading to width reductions. The channel narrowing effects of grassy vegetation were also reported by Sweeney et al. (2004) and Allmendinger et al. (2005).

Understanding a channel's state of equilibrium (or disequilibrium) and its potential future states is critical for restoration and protection of salmon habitats.

A common effect of planting crops is increased sediment yield and associated changes in channel pattern and stability (Wohl 2014). The magnitude of these changes is dependent on the type and extent of crops, as well as the topographic and soil characteristics at a site. Numerous case studies indicate that soil erosion from conventional agriculture exceeds rates of natural erosion by up to several orders of magnitude (Montgomery 2007).

Urban/Suburban

Research on the effects of urbanization on sediment yield and channel response date back almost 50 years and is global in reach (Wolman 1967). The results of this research draw similar conclusions regarding the sequence of changes that occur within a drainage basin, with differences occurring only in the magnitude and timing (Chin 2006).

Erosion rates can reach up to 40,000 times pre-disturbance rates on land surfaces cleared for building that remain bare for up to a year (Harbor 1999). Construction sites can dramatically increase sediment yield from an urbanizing basin (Fusillo et al. 1977). For example, sediment production from Issaquah Creek



Mill Creek, Walla Walla, Washington/Jane Atha, WDFW

watershed in western Washington had two- to five-fold increases when only 0.3% of its 55.6 mi^2 (144 km^2) drainage area was under construction (Nelson and Booth 2002). Upon completion of construction, sediment yield usually decreases to negligible amounts as urbanizing areas are stabilized beneath roads, buildings, and lawns.

Research on the effects of urbanization on hydrology and flooding is also extensive, and dates back at least 50 years. Collectively, this research clearly shows that urban development, and associated increases in impervious surfaces, leads to larger and more frequent floods (Leopold 1968). The key metrics of change are peak discharge, lag time, flood frequency, and total runoff or water yield. Morphological adjustments have been studied in response to hydrologic changes, with most studies showing increases in channel width (Chin 2006).

Stream Channel Modifications

Humans have been directly altering stream flow and channel form for centuries (Poff et al. 1997). Flow regulation, through dams, reduces the size and variation of annual peak flows (Williams and Wolman 1984), increases minimum flows (Hirsch et al. 1990), shifts the timing of seasonal flows, and can alter diurnal flow fluctuations if the dam is used for hydroelectric power generation (Magilligan and Nislow 2001).

Dams can have dramatic effects on aquatic and riparian systems (Nilsson et al. 1997; Nilsson and Berggren 2000; Katz et al. 2005; Merritt and Wohl 2006). Dams disconnect the channel from the floodplain by reducing peak flows. This decreases or eliminates freshly scoured surfaces necessary for seedling establishment in riparian areas. Flow regulation can disrupt downstream transport of seeds to germination sites, and seedlings established on gravel bars may die from prolonged submersion when managed flows are higher than natural flows. Changes in sediment size distributions and moisture content can also adversely impact riparian vegetation. The cumulative effects on riparian communities downstream of dams can result in fewer plant species and lower plant density (Jansson et al. 2000).

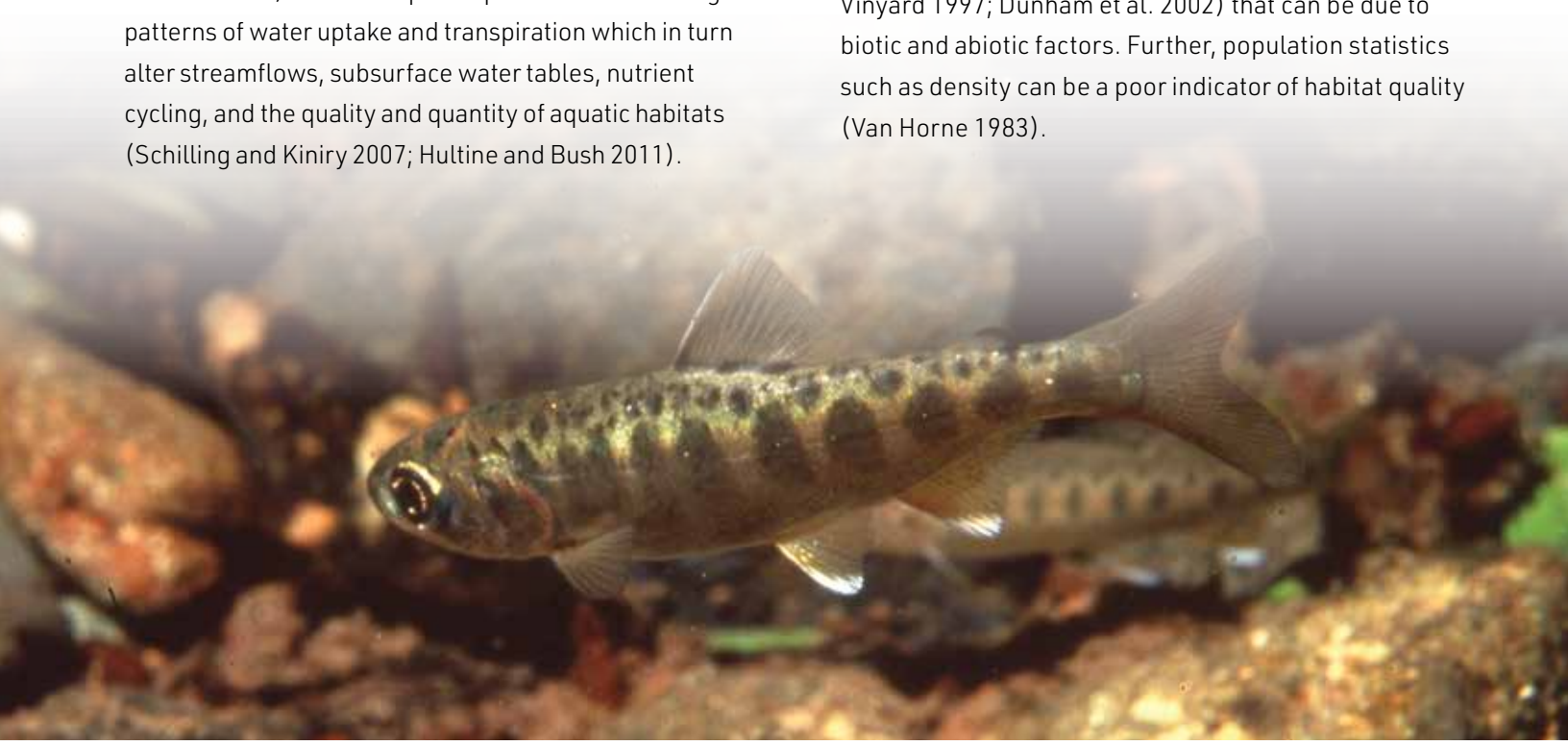
Humans regularly alter channel form through dredging, channel straightening, removing instream wood or Beaver dams, building check dams, extending channel networks via canals, burying or laterally shifting inconvenient channels, and simply reconfiguring a channel to be more esthetically pleasing. (Wohl 2014). Levees are a direct form of channel alteration particularly ubiquitous in lowland rivers. Levees are mounds built parallel to stream channels that limit overbank flooding, and are also known as dikes or embankments (Petroski 2006). Levees severely reduce or eliminate channel-floodplain exchanges, facilitate higher magnitude floods, and exacerbate flooding in downstream areas without levees. Disconnection between the channel and floodplain reduces deposition of sediment and organic matter in floodplains, leading to loss of habitat, reduced animal abundance, and lower biodiversity in riparian areas (Hohensinner et al. 2004).

Lastly, humans can indirectly and severely alter channel form by introducing invasive, exotic species to riparian areas. Invasive plants may displace native riparian plants and thus impact streambank resistance to erosion and overbank sedimentation dynamics (Graf 1978; Allred and Schmidt 1999). Invasive riparian plants can also change patterns of water uptake and transpiration which in turn alter streamflows, subsurface water tables, nutrient cycling, and the quality and quantity of aquatic habitats (Schilling and Kiniry 2007; Hultine and Bush 2011).

2.6. Fish and Wildlife Habitat

2.6.1. Fish

The fisheries and fish ecology literature are replete with studies that report relationships between fish and physical habitat conditions. Such studies demonstrate the profound importance of instream conditions for fish and they have helped guide habitat management and restoration. For example, Nickelson et al. (1992) found seasonal differences in the use of pool and riffle habitat by juvenile Coho Salmon *Oncorhynchus kisutch* and suggested that additional pool habitats might improve their survival. Such correlative approaches have been expanded by considering shifts in habitat use within species and differential habitat requirements among species in attempts to identify optimal habitat type configurations (Rosenfeld 2003; Bain and Jai 2012). However, the success of such approaches has been limited by high spatiotemporal variability in, for example, habitat-density relations among streams (Dunham and Vinyard 1997; Dunham et al. 2002) that can be due to biotic and abiotic factors. Further, population statistics such as density can be a poor indicator of habitat quality (Van Horne 1983).



Juvenile Chinook Salmon Oncorhynchus tshawytscha/*David Price, WDFW*

Recent scientific advances regarding the protection and restoration of fish habitats (and habitats for other vagile aquatic species) include the following: 1) acknowledgement of the importance and frequency of fish movement (Schlosser 1991, 1995; Gowan et al. 1994), 2) greater acknowledgement of the importance of habitat heterogeneity and spatial variability in fish-habitat relationships (Torgersen et al. 2006), and 3) the concept of riverscapes (Ward 1998; Fausch et al. 2002; Allan 2004), which describes a dynamic mosaic of habitat types and environmental gradients that are characterized by high connectivity and complexity.

The riverscape concept expands on the classic stream continuum concept of Vannote et al. (1980) mostly by explicitly incorporating spatial and temporal heterogeneity, discontinuities, and connectivity between stream reaches (longitudinal), the stream and uplands (lateral), and the stream and groundwater (vertical). Fausch et al. (2002) provide several principles for effective research and management given the riverscape concept. These include: 1) conduct research (and management) at appropriate scales for the question, 2) the importance of physical and ecological processes are revealed at different spatiotemporal scales and processes will interact among scales, 3) rare or unique features can be very important, and 4) unintended consequences of habitat degradation propagate in all directions, including upstream. Cumulatively, these principles and the vast research that supported their development suggest that the spatial extent and temporal duration of research and management must be matched to the scales at which populations of species use habitat and at which suitable habitat conditions are created and maintained. Further, they emphasize the importance of maintaining and restoring longitudinal and lateral connectivity of stream systems (Sedell et al. 1989) to allow for proper functioning of habitat forming processes and maintenance and restoration of supplementary and complimentary habitats to account for expected variability in local suitability.

Conducting research and management that incorporates the riverscape concept is challenging because it often requires study at large spatial and long temporal extents as well as monitoring biotic and abiotic processes at fine spatial and temporal resolutions. Perhaps the best examples of such work in Washington are the Intensively Monitored Watersheds (IMW) projects that are designed to assess the efficacy of stream restoration for increasing the freshwater survival and production of salmon (Bilby et al. 2005). The IMW projects are conducted at the spatial extent of watersheds and over the course of several salmon life cycles. Important physical and ecological processes are monitored within and among individual stream reaches with the intent of identifying rare features and measuring changes in habitat complexity and connectivity (Bennett et al. 2016). This approach should yield reliable inferences regarding the efficacy of restoration efforts that can be used to inform decisions via adaptive management (Bennett et al. 2016).

2.6.2. Amphibians and Reptiles

Amphibians are less conspicuous inhabitants of instream habitats than fish, but in much of the Pacific Northwest, particular groups of stream-breeding amphibian species that include giant salamanders (*Dicamptodon* spp.), tailed frogs (*Ascaphus* spp.), and torrent salamanders (*Rhyacotriton* spp.) dominate fishless headwater

The riverscape concept expands on Vannote et al.'s (1980) classic stream continuum concept by including lateral and vertical connectivity and incorporating spatial and temporal heterogeneity.



Coastal Tailed Frog Ascaphus truei *in metamorphosis/Marc Hayes, WDFW*

streams. Headwater streams represent a large majority (up to 80%) of the overall stream network based on its length (Meyer and Wallace 2001). Stream-breeding amphibian dominance in headwaters partly reflects the flow conditions in headwater habitats and the suitable physical conditions those flows create. Amphibian abundance is highest in step-pool and cascade reach morphologies characterized by armored beds, stable bedforms, refuge spaces amongst coarse bed material, and reduced tractive forces as a result of tumbling flow (Dupuis and Friele 2006). For example, torrent salamanders, the only stream-breeding amphibian group that does not attach their eggs to rocky substrates, deposit and conceal them in the lowest flow headwater ends of streams and their tributaries; higher flow habitats will dislodge or damage their eggs. In contrast, giant salamanders and tailed frogs, which glue their eggs to coarse rocky substrates, use concealed oviposition sites in stable step structures typically found further downstream in the headwater network (Hayes et al. 2006). Stream-breeding amphibians seem to become less abundant below headwater streams at least in part because substrate and flow conditions that provide either oviposition or refuge sites become less frequent (Brummer and Montgomery 2003). Other conditions, such as predation by fishes, also play a role.

The freshets (high water events) in larger streams or rivers that have an alluvial floodplain, when coupled with wood, are also critical to both creation and maintenance of off-channel amphibian habitats (Amoros and Bornette 2002). Off-channel habitats comprise among the most important lowland stillwater habitats representing key breeding and rearing areas for the largest group of native amphibians (stillwater breeders) (Richter 2005) and the garter snakes (*Thamnophis* spp.) that feed on them. Such off-channel habitats are also critical rearing and foraging habitat for native turtles (Holland 1994).

2.7. Conclusions

The interactions of water, sediment, wood, and riparian vegetation create complex channel morphologies and diverse aquatic habitat conditions. Reach-scale differences in sediment erosion, transport, and deposition result in a mosaic of aquatic habitat conditions within and among stream reaches.

Understanding a channel's state of equilibrium (or disequilibrium) and its potential future states is critical for restoration and protection of salmon habitats. Consistent with the idea of process domains, not all stream reaches within a watershed are equally sensitive or resilient to human land uses or other anthropogenic disturbances. Describing a channel's historical range of natural variability can aid in understanding a reach's potential response to human disturbance. A historical perspective may also aid in identifying biological communities that are in most need of habitat restoration (McDonald et al. 2004; Brierley and Fryirs 2009). By adopting a historical perspective, we may be able to move closer to the ecosystem composition and structure, and the resulting habitat heterogeneity, essential for fish and wildlife.

Historically, disturbance and successional processes were key drivers for the creation of aquatic habitats (Reeves et al. 1995). Now and into the future, both natural and anthropogenic disturbances will affect the creation, maintenance, destruction, and recreation of aquatic habitats. Management may most reliably result in high quality habitat when it emulates historical disturbances and their effects on a watershed (Poff et al. 1997). An idea offered by Naiman et al. (2000) is to base management on historical patterns of watershed conditions and natural disturbances. If flooding was a major natural disturbance in a watershed, then with empirical data and/or models on the extent to which flooding has affected the watershed, one could describe the dynamic equilibrium conditions of channels and floodplains over time, and then tailor riparian management to the unique conditions of that watershed. If wildfires followed by landslides were the historical disturbance pattern in a watershed, then watershed-scale, long-term forest management plans might schedule timber harvests such that historical natural patterns are partially emulated (Reeves et al. 1995; Bisson et al. 2009). Emulating flood or wildlife disturbances for the benefit of salmon and other aquatic species will be a much more complicated project in residential (i.e., rural, suburban, urban) areas.

The importance of riparian ecosystems in maintaining channel, off-channel, and floodplain habitats is increasingly well supported by the scientific literature. In particular, the importance of longitudinal, lateral, and vertical connectivity to the quality of habitat conditions and the importance of riparian vegetation to stream channel stability are increasingly emphasized. Management of riparian ecosystems should consider connectivity among the geomorphic process domains, the influences of natural disturbance, the historical range of natural variability, and the inextricable influence that riparian vegetation has on geomorphic processes.



Bridge on Strait of Juan de Fuca Highway/Ned Pittman, WDFW

2.8. Literature Cited[5]

Agee, J.K. 1993. Fire ecology of Pacific Northwest forests. Island Press, Washington, D.C. (i)

Allan, J.D. 2004. Landscapes and riverscapes: the influence of land use on stream ecosystems. Annual Review of Ecology, Evolution, and Systematics 35:257-284. (i)

Allen, J.R.L. 1965. A review of the origin and characteristics of recent alluvial sediments. Sedimentology 5:89-191. (i)

Allmendinger, N.E., J.E. Pizzuto, N. Potter, T.E. Johnson, and W.C. Hession. 2005. The influence of riparian vegetation on stream width, eastern Pennsylvania, USA. Geological Society of America Bulletin 117:229-243. (i)

Allred, T.M., and J.C. Schmidt. 1999. Channel narrowing by vertical accretion along the Green River near Green River, Utah. Geological Society of America Bulletin 111:1757-1772. (i)

Amoros, C., and G. Bornette. 2002. Connectivity and biocomplexity in waterbodies of riverine floodplains. Freshwater Biology 47:761-776. (i)

Anderson, J.R., E.E. Hardy, J.T. Roach, and R.E. Witmer. 1976. A land use and land cover classification system for use with remote sensor data. Geological Survey Professional Paper 964. U.S. Geological Survey, Arlington, Virginia. (viii)

Anderson, R.J., B.P. Bledsoe, and W.C. Hession. 2004. Widths of streams and rivers in response to vegetation, bank material, and other factors. Journal of the American Water Resources Association 40:1159-1172. (i)

ASCE (American Society of Civil Engineers Task Committee on Hydraulics, Bank Mechanics, and Modelling of River Width Adjustment). 1998. River width adjustment. I: processes and mechanisms. Journal of Hydraulic Engineering 124:881-902. (i)

Bain, M.B., and H. Jai. 2012. A habitat model for fish communities in large streams and small rivers. International Journal of Ecology 2012:962071. (i)

Beechie, T.J., M. Liermann, M.M. Pollack, S. Baker, and J. Davies. 2006. Channel pattern and river-floodplain dynamics in forested mountains river systems. Geomorphology 78:124-141. (i)

Benda, L., M.H. Hassan, M. Church, and C.L. May. 2005. Geomorphology of steepland headwaters: the transition from hillslopes to channels. Journal American Water Resources Association 41:835-851. (i)

Bennett, S., G. Pess, N. Bouwes, P. Roni, R.E. Bilby, S. Gallagher, J. Ruzycki, T. Buehrens, K. Krueger, W. Ehinger, J. Anderson, C. Jordan, B. Bowersox, and C. Greene. 2016. Progress and challenges of testing the effectiveness of stream restoration in the Pacific Northwest using intensively monitored watersheds. Fisheries 41:92-103. (i)

Betson, R.P. 1964. What is watershed runoff? Journal of Geophysical Research 69:1541–1552. (i)

Bisson, P.A., J.B. Dunham, and G.H. Reeves. 2009. Freshwater ecosystems and resilience of Pacific salmon: habitat management based on natural variability. Ecology and Society 14(1):45. (i)

Bilby, R., W. Ehinger, T. Quinn, G. Volkhardt, K. Krueger, D. Seiler, G. Pess, C. Jordan, M. McHenry, and D. Poon. 2005. Study evaluates fish response to management actions. Western Forester 50:14-15. (i)

Boulton, A.J., S. Findlay, P. Marmonier, E.H. Stanley, and H.M. Valett. 1998. The functional significance of the hyporheic zone in streams and rivers. Annual Review Ecology and Systematics 29:59-81. (i)

Brierley, G., and K. Fryirs. 2009. Don't fight the site: three geomorphic considerations in catchment-scale river rehabilitation planning. Environmental Management 43:1201-1218. (i)

Brummer, C.J., and D.R. Montgomery. 2003. Downstream coarsening in headwater channels. Water Resources Research 39:1-13. (i)

Brunsden, D., and J.B. Thornes. 1979. Landscape sensitivity and change. Transactions of the Institute of British Geographers 4:463-484. (i)

Bryan, R. 1990. Knickpoint evolution in rillwash. Catena Supplement 17:111-132. (i)

[5] References are classified according to RCW 34.05.271 (see Appendix 1) denoted by a lower case roman numeral (i – viii) in parentheses at the end of the citation.

Burckhardt, J.C., and B.L. Todd. 1998. Riparian forest effect on lateral stream channel migration in the glacial till plains. Journal of the American Water Resources Association 34:179-184. (i)

Butler, B. 2004. Channel migration zones. Chapter 4 *in* Best available science, volume 1: a review of science literature. King County, Seattle. (viii)

Cafferata, P.H., and J.R. Munn. 2002. Hillslope monitoring program: monitoring results from 1996 through 2001. Monitoring Study Group Final Report prepared for the California State Board of Forestry and Fire Protection. Sacramento, California. (viii)

Callander, R.A. 1978. River meandering. Annual Review of Fluid Mechanics 10:129-158. (i)

CBOF-TAC (California Board of Forestry and Fire Protection Technical Advisory Committee). 2008. Primer on water riparian exchanges related to forest management in the western U.S., Version 2.0. Sacramento, California. (viii)

Chin, A. 2006. Urban transformation of river landscapes in a global context. Geomorphology 79:460-487. (i)

Coe, D. 2006. Sediment production and delivery from forest roads in the Sierra Nevada, California. Master's thesis. Colorado State University, Fort Collins. (i)

Collins, B.F., and D.R. Montgomery. 2002. Forest development, wood jams, and restoration of floodplain rivers in the Puget Lowland, Washington. Restoration Ecology 10:237-247. (i)

Corenblit, D., E. Tabacchi, J. Steiger, and A.M. Gurnell. 2007. Reciprocal interactions and adjustments between fluvial landforms and vegetation dynamics in river corridors: a review of complementary approaches. Earth-Science Reviews 84:56-86. (i)

Dietrich, W., and T. Dunne. 1978. Sediment budget for a small catchment in a mountainous terrain. Pages 31- 48 *in* O. Slaymaker, editor. Fluvial geomorphology. Rutledge, New York. (i)

Dietrich, W.E., J.D. Smith, and T. Dunne. 1984. Boundary shear stress, sediment transport, and bed morphology in a sand-bedded river meander during high and low flow. Pages 632-639 *in* C.M. Elliot, editor. River meandering: proceedings of the conference rivers '83. American Society of Civil Engineers, New York. (viii)

Dunham, J.B., B.S. Cade, and T.W. Terrell. 2002. Influences of spatial and temporal variation on fish-habitat relationships defined by regression quantiles. Transactions of the American Fisheries Society 131:86-98. (i)

Dunham, J.B., and G.L. Vinyard. 1997. Incorporating stream level variability into analyses of site level fish habitat relationships: some cautionary examples. Transactions of the American Fisheries Society 126:323-329. (i)

Dunne, T. 1978. Field studies of hillslope flow processes. Pages 227-293 *in* M.J. Kirby, editor. Hillslope hydrology. John Wiley, Chichester, United Kingdom. (i)

Dunne, T., and R.D. Black. 1970a. Partial-area contributions to storm runoff in a small New England watershed. Water Resources Research 6:1296-1311. (i)

Dunne, T., and R.D. Black. 1970b. An experimental investigation of runoff production in permeable soils. Water Resources Research 6:170-191. (i)

Dunne, T., and L.B. Leopold. 1978. Water in environmental planning. WH Freeman and Company, San Francisco. (i)

Dunne, T., D.V. Malmon, and S.M. Mudd. 2010. A rain splash transport equation assimilating field and laboratory measurements. Journal of Geophysical Research 115:F01001. (i)

Dupuis, L, and P. Friele. 2006. The distribution of the Rocky Mountain Tailed Frog (*Ascaphus montanus*) in relation to the fluvial system: implications for management and conservation. Ecological Research 21:489-502. (i)

Dust, D., and E. Wohl. 2012. Conceptual model for complex river responses using an expanded Lane's relation. Geomorphology 139:109-121. (i)

Eis, S. 1987. Root systems of older immature hemlock, cedar and Douglas-fir. Canadian Journal of Forest Research 17:1348-1354. (i)

Everett, R., R. Schellhaas, P. Ohlson, D. Spurbeckand, and D. Keenum. 2003. Continuity in fire disturbance between riparian and adjacent sideslope Douglas-fir forests. Forest Ecology and Management 175:31-47. (i)

FEMAT (Forest Ecosystem Management Assessment Team). 1993. Forest ecosystem management: an ecological, economic and social assessment. U.S. Department of Agriculture and U.S. Department of the Interior, Portland, Oregon. (viii)

Fausch, K.D., C.E. Torgersen, C.V. Baxter, and H.W. Li. 2002. Landscapes to riverscapes: bridging the gap between research and conservation of stream fishes. BioScience 52:1-16. (i)

Faustini, J.M., Kaufmann, P.R., and A.T. Herlihy. 2009. Downstream variation in bankfull width of wadeable streams across the conterminous United States. Geomorphology 108:292-311. (i)

Florsheim, J.L., J.F. Mount, and A. Chin. 2008. Bank erosion as a desirable attribute of rivers. BioScience 58:519-529. (i)

Foley, J.A., R. DeFries, G.P. Asner, C. Barford, G. Bonan, S.R. Carpenter, F.S. Chapin, M.T. Coe, G.C. Daily, and H.K. Gibbs. 2005. Global consequences of land use. Science 309:570-574. (i)

Frissell, C.A., W.J. Liss, C.E. Warren, and M.D. Hurley. 1986. A hierarchical framework for stream classification: Viewing streams in a watershed context. Environmental Management 10:199-214. (i)

Furbish, D.J., E.M. Childs, P.K. Haff, and M.W. Schmeeckle. 2009. Rain splash of soil grains as a stochastic advection dispersion process, with implications for desert plant soil interactions and land surface evolution. Journal of Geophysical Research 114:F00A03. (i)

Fusillo, T.V., G. Nieswand, and T. Shelton. 1977. Sediment yields in a small watershed under suburban development. Pages 34-88 *in* Proceedings from the international symposium on urban hydrology, hydraulics, and sediment control. University of Kentucky Press, Lexington. (viii)

Gilbert, G.K. 1877. Report on the geology of the Henry Mountains. U.S. Government Printing Office, Washington, D.C. (viii)

Gomi, T., R.D. Moore, and M. Hassan. 2005. Suspended sediment dynamics in small forest streams of the Pacific Northwest. Journal of the American Water Resources Association 41:877-898. (i)

Gorrick, S., and J.F. Rodrígue. 2012. Sediment dynamics in a sand bed stream with riparian vegetation. Water Resources Research 48:W02505. (i)

Gowan, C., M.K. Young, K.D. Fausch, and S.C. Riley. 1994. Restricted movement of resident stream salmonids: a paradigm lost. Canadian Journal of Fisheries and Aquatic Sciences 51:2626-2637. (i)

Graf, W.L. 1978. Fluvial adjustments to the spread of tamarisk in the Colorado Plateau region. Geological Society of America Bulletin 89:1491-1501. (i)

Grant, G.E., S.L. Lewis, F.J. Swanson, J.H. Cissel, and J.J. McDonnell. 2008. Effects of forest practices on peak flows and consequent channel response: a state-of-the-science report for western Oregon and Washington. PNW-GTR-760. U.S. Forest Service, Pacific Northwest Research Station, Portland, Oregon. (viii)

Grant, G., W. Megahan, and R. Thomas. 1999. A re-evaluation of peak flows: do forest roads and harvesting cause floods? Paper presented at the 1999 NCASI west coast regional meeting. National Council for Air and Stream Improvement, Corvallis, Oregon. (viii)

Grant G.E., J.E. O'Connor J.E., and M.G. Wolman. 2013. A river runs through it: conceptual models in fluvial geomorphology. Pages 6-21 *in* J.F. Shroder, editor. Treatise on geomorphology, volume 9. Academic Press, San Diego, California. (i)

Griffin, E., J. Kean, K. Vincent, J. Smith, and J. Friedman. 2005. Modeling effects of bank friction and woody bank vegetation on channel flow and boundary shear stress in the Rio Puerco, New Mexico. Journal of Geophysical Research: Earth Surface 110:F04023. (i)

Güneralp, I., and R.A. Marston. 2012. Process-form linkages in meander morphodynamics: bridging theoretical modeling and real world complexity. Progress in Physical Geography 36:718-746. (i)

Gurnell, A. 2014. Plants as river system engineers. Earth Surface Processes and Landforms 39:4-25. (i)

Hairston-Strang, A.B., and P.W. Adams. 2000. Riparian management area condition for timber harvests conducted before and after the 1994 Oregon water protection rules. Western Journal of Applied Forestry 15:147-153. (i)

Hales, T., and J. Roering. 2009. A frost "buzzsaw" mechanism for erosion of the eastern Southern Alps, New Zealand. Geomorphology 107:241-253. (i)

Harbor, J. 1999. Engineering geomorphology at the cutting edge of land disturbance: erosion and sediment control on construction sites. Geomorphology 31:247-263. (i)

Harris, D.D. 1977. Hydrologic changes after logging in two small Oregon coastal watersheds. Water Supply Paper 2037. U.S. Geological Survey, Washington, D.C. (i)

Hayes, M., T. Quinn, D. Dugger, T. Hicks, M. Melchiors, and D. Runde. 2006. Dispersion of Coastal Tailed Frog (*Ascaphus truei*): a hypothesis relating occurrence of frogs in non-fish-bearing headwater basins to their seasonal movements. Journal of Herpetology 40:533-545. (i)

Heede, B.H. 1980. Stream dynamics: an overview for land managers. PNW-GTR-72. U.S. Forest Service. Rocky Mountain Research Station, Fort Collins, Colorado. (viii)

Henning, J.A., and G. Schirato. 2006. Amphibian use of Chehalis River floodplain wetlands. Northwestern Naturalist 87:209-214. (i)

Hewlett, J.D., and W.L. Nutter. 1970. The varying source area of streamflow from upland basins. Pages 65-83 *in* Proceedings of the symposium on interdisciplinary aspects of watershed management. American Society of Civil Engineers, New York. (viii)

Hickin, E.J. 1984. Vegetation and river channel dynamics. Canadian Geographer 28:111-126. (i)

Hirsch, R., J. Walker, J. Day, and R. Kallio. 1990. The influence of man on hydrologic systems. Pages 329–359 *in* M.G. Wolman and H.C. Riggs, editors. Surface water hydrology. Geological Society of America, Boulder, Colorado. (viii)

Hohensinner, S., H. Habersack, M. Jungwirth, and G. Zauner. 2004. Reconstruction of the characteristics of a natural alluvial river-floodplain system and hydromorphological changes following human modifications: the Danube River (1812-1991). River Research and Applications 20:25-41. (i)

Holland, D.C. 1994. The Western Pond Turtle: habitat and history. Final Report to the U.S. Department of Energy, Bonneville Power Administration, Portland, Oregon. (viii)

Hooke, J.M. 1984. Changes in river meanders: a review of techniques and results of analyses. Progress in Physical Geography 8:473-508. (i)

Horton, R.E. 1933. The role of infiltration in the hydrologic cycle. Transactions American Geophysical Union, 14:446-460. (i)

Hultine, K., and S. Bush. 2011. Ecohydrological consequences of non-native riparian vegetation in the southwestern United States: a review from an ecophysiological perspective. Water Resources Research 47:W07542. (i)

Hughes, F.M.R. 1997. Floodplain biogeomorphology. Progress in physical geography 21:501–529. (i)

Hupp, C.R., and W.R. Osterkamp. 1996. Riparian vegetation and fluvial geomorphic processes. Geomorphology 14:277-295. (i)

Jackson, C., D. Leigh, S. Scarbrough, and J. Chamblee. 2014. Herbaceous versus forested riparian vegetation: narrow and simple versus wide, woody and diverse stream habitat. River Research and Applications 31:847-857. (i)

Jansson, R., C. Nilsson, M. Dynesius, and E. Andersson. 2000. Effects of river regulation on river-margin vegetation: a comparison of eight boreal rivers. Ecological applications 10:203-224. (i)

Jones, J.A., F.J. Swanson, B.C. Wemple, and K.U. Snyder. 2000. Effects of roads on hydrology, geomorphology, and disturbance patches in stream networks. Conservation Biology 14:76-85. (i)

Katz, G.L., J.M. Friedman, and S.W. Beatty. 2005. Delayed effects of flood control on a flood-dependent riparian forest. Ecological Applications 15:1019-1035. (i)

Kauffman, J.B., and R.E. Martin. 1989. Fire behavior, fuel consumption, and forest floor changes following prescribed understory fires in Sierra Nevada mixed conifer forests. Canadian Journal of Forest Resources 19:455-462. (i)

Kiffney, P.M., C.M. Greene, J.E. Hall, and J.R. Davies. 2006. Tributary streams create spatial discontinuities in habitat, biological productivity and diversity in mainstem rivers. Canadian Journal of Fisheries and Aquatic Sciences 63:2518-2530. (i)

Knighton, D. 2014. Fluvial forms and processes: a new perspective. Routledge, London. (i)

Krause, D., D.M. Hannah, J.H. Fleckenstein, C.M. Heppell, D Kaeser, R. Pickup, G. Pinay, A.L. Robertson, and P.J. Wood. 2011. Inter-disciplinary perspectives on processes in the hyporheic zone. Ecohydrology 4:481-499. (i)

Kupfer, J., and G.P. Malanson. 1993. Observed and modeled directional change in riparian forest composition at a cutbank edge. Landscape Ecology 8:185-199. (i)

Lane, E.W. 1955. The importance of fluvial morphology in hydraulic engineering. Proceedings of American Society of Civil Engineers 81:1-17. (i)

Langendoen, E.J., R.R. Lowrance, and A. Simon. 2009. Assessing the impact of riparian processes on streambank stability. Ecohydrology 2:360-369. (i)

Leopold, L.B. 1968. Hydrology for urban land planning: A guidebook on the hydrologic effects of urban land use. Geological Survey Circular 554. U.S. Geological Survey, Reston, Virginia. (i)

Leopold, L.B., and G. Wolman. 1957. River channel patterns: braided, meandering and straight. U.S. Geological Survey Professional Paper 282-B. U.S. Government Printing Office, Washington, D.C. (i)

Lewis, J. 1998. Evaluating the impacts of logging activities on erosion and sediment transport in the Caspar Creek watersheds. Pages 55-69 *in* R.R. Ziemer, technical coordinator. Proceedings of the conference on coastal watersheds: the Caspar Creek story. PSW-GTR-168. U.S. Forest Service, Pacific Southwest Research Station, Albany, California. (viii)

Liquori, M.K. 2006. Post-harvest riparian buffer response: implications for wood recruitment modeling and buffer design. Journal of American Water Resources Association 42(1):177-189. (i)

Liquori, M.K., D. Martin, R. Coats, L. Benda, and D. Ganz. 2008. Scientific literature review of forest management effects on riparian functions for anadromous salmonids. Sound Watershed Consulting, Oakland, California. (viii)

Luce, C.H., and T.A. Black. 1999. Sediment production from forest roads in western Oregon. Water Resources Research 35:2561-2570. (i)

MacDonald, L.H., D.B. Coe, and S.E. Litschert. 2004. Assessing cumulative watershed effects in the central Sierra Nevada: hillslope measurements and catchment-scale modeling. Pages 149-157 *in* D.D. Murphy and P.A. Stine, editors. Proceedings of the Sierra Nevada science symposium. PSW-GTR-193. U.S. Forest Service, Pacific Southwest Research Station, Albany, California. (viii)

Madej, M.A. 2001. Erosion and sediment delivery following removal of forest roads. Earth Surface Processes and Landforms 26:175-190. (i)

Madej, M.A., and V. Ozaki. 1996. Channel response to sediment wave propagation and movement, Redwood Creek, California, USA. Earth Surface Processes and Landforms 21:911-927. (i)

Magilligan, F.J., and P.F. McDowell. 1997. Stream channel adjustments following elimination of cattle grazing. Journal of the American Water Resources Association 33:867-878. (i)

Magilligan, F.J., and K.H. Nislow. 2001. Long-term changes in regional hydrologic regime following impoundment in a humid-climate watershed. Journal of the American Water Resources Association 37:1551-1569. (i)

Mahoney, J.M., and S.B. Rood. 1998. Streamflow requirements for cottonwood seedling recruitment -an integrative model. Wetlands 18:634-645. (i)

Malanson, G.P. 1993. Riparian Landscapes. Cambridge University Press, Cambridge, United Kingdom. (i)

Marston, R.A. 2008. Land, life, and environmental change in mountains. Annals of the Association of American Geographers 98:507-520. (i)

Mattson, W.J., and N.D. Addy. 1975. Phytophagous, insects as regulators of forest primary production. Science 190:515-522. (i)

May, C.L. 2002. Debris flows through different forest age classes in the central Oregon Coast Range, Journal of the American Water Resources Association 38:1097-1113. (i)

McDonald, A., S.N. Lane, N.E. Haycock, and E. Chalk. 2004. Rivers of dreams: on the gulf between theoretical and practical aspects of an upland river restoration. Transactions of the Institute of British Geographers 29:257-281. (i)

McDonnell, J.J. 2003. Where does water go when it rains? Moving beyond the variable source area concept of rainfall-runoff response. Hydrological Processes 17:1869-1875. (i)

Megahan, W.F. 1974. Erosion over time on severely disturbed granitic soils: a model. INT-156. U.S. Forest Service, Intermountain Forest & Range Experiment Station, Ogden, Utah. (i)

Meitzen, K.M. 2009. Lateral change migration effects on riparian forest structure and composition, Congaree River, South Carolina, USA. Wetlands 29:465-475. (i)

Merritt, D.M., and E.E. Wohl. 2006. Plant dispersal along rivers fragmented by dams. River Research and Applications 22:1-26. (i)

Meyer, L., G. Foster, and S. Nikolov. 1975. Effect of flow rate and canopy on rill erosion. Transactions of the American Society of Agricultural Engineers 18:905-911. (i)

Meyer, J.L., and J.B. Wallace. 2001. Lost linkages and lotic ecology: rediscovering small streams. Pages 295-317 *in* M.C. Press, N.J. Huntly, and S. Levin, editors. Ecology: achievement and challenge. Blackwell Science, Oxford, United Kingdom. (i)

Montgomery, D.R. 1999. Process domains and the river continuum. Journal of the American Water Resources Association 35:397-410. (i)

Montgomery, D.R. 2007. Is agriculture eroding civilization's foundation? GSA Today 17(10):4-9. (i)

Montgomery, D.R., T.B. Abbe, J.M. Buffington, N.P. Peterson, K.M. Schmidt, and J.D. Stock. 1996. Distribution of bedrock and alluvial channels in forested mountain drainage basins. Nature 381:587-589. (i)

Montgomery, D.R., and J.M. Buffington. 1997. Channel-reach morphology in mountain drainage basins. Geological Society of America Bulletin 109:596-611. (i)

Montgomery, D.R., K.M. Schmidt, W.E. Dietrich, and J. McKean. 2009. Instrumental record of debris flow initiation during natural rainfall: implications for modeling slope stability. Journal of Geophysical Research 114:F01031. (i)

Moore, R.D., and S.M. Wondzell. 2005. Physical hydrology and the effects of forest harvesting in the Pacific Northwest: a review. Journal of the American Water Resources Association 41:763-784. (i)

Naiman, R.J., and R.E. Bilby. 1998. River ecology and management: lessons from the Pacific Coastal Ecoregion. Springer-Verlag, New York. (i)

Naiman, R.J., R.E. Bilby, and P.A. Bisson. 2000. Riparian ecology and management in the Pacific coastal rain forest. BioScience 50:996-1011. (i)

Naiman, R.J., H. Decamps, and M.E. McClain. 2010. Riparia: ecology, conservation, and management of streamside communities. Academic Press, London. (i)

Naiman, R.J., H. Decamps, and M. Pollock. 1993. The role of riparian corridors in maintaining regional biodiversity. Ecological Applications 3:209-212. (i)

Nakamura, F., and F.J. Swanson. 2003. Dynamics of wood in rivers in the context of ecological disturbance. Pages 279-298 *in* S.V. Gregory, K.L. Boyer, and A.M. Gurnell, editors. The ecology and management of wood in world rivers. American Fisheries Society, Bethesda, Maryland. (i)

NRC (National Research Council). 2002. Riparian areas: strategies for management. National Academies Press, Washington, D.C. (i)

Nelson, E.J., and D.B. Booth. 2002. Sediment sources in an urbanizing, mixed land-use watershed. Journal of Hydrology 264:51-68. (i)

Nickelson, T.E., J.D. Rodgers, S.L. Johnson, and M.F. Solazzi. 1992. Seasonal changes in habitat use by juvenile Coho Salmon (*Oncorhynchus kisutch*) in Oregon coastal streams. Canadian Journal of Fisheries and Aquatic Sciences 49:783-789. (i)

Nilsson, C., and K. Berggren. 2000. Alterations of riparian ecosystems caused by river regulation. BioScience 50:783-792. (i)

Nilsson, C., R. Jansson, and U. Zinko, U., 1997. Long-term responses of river-margin vegetation to water-level regulation. Science 276:798-800. (i)

Nilsson, C., and M. Svedmark. 2002. Basic principles and ecological consequences of changing water regimes: riparian plant communities. Environmental Management 30:468-80. (i)

O'Connor, J.E., M.A. Jones, and T.L. Haluska. 2003. Floodplain and channel dynamics of the Quinault and Queets Rivers, Washington, USA. Geomorphology 51:31-59. (i)

Osterkamp, W.R., and C.R. Hupp. 2010. Fluvial processes and vegetation – glimpses of the past, the present, and perhaps the future. Geomorphology 116:274-285. (i)

Petroski, H. 2006. Levees and other raised ground. American Scientist 94(1):7-11. (i)

Pickett, S., S. Collins, and J. Armesto. 1987. A hierarchical consideration of causes and mechanisms of succession. Vegetatio 69:109-114. (i)

Pickett, S.T., and P.S. White. 1985. The ecology of natural disturbance and patch dynamics. Academic Press, San Diego, California. (i)

Pike, A.S., and F.N. Scatena. 2010. Riparian indicators of flow frequency in a tropical montane stream network. Journal of Hydrology 382:72-87. (i)

Poff, N.L., J.D. Allan, M.B. Bain, J.R. Karr, K.L. Prestegaard, B. Richter, R. Sparks, and J. Stromberg. 1997. The natural flow regime: a new paradigm for riverine conservation and restoration. BioScience 47:769-784. (i)

Pollen, N., and A. Simon. 2005. Estimating the mechanical effects of riparian vegetation on stream bank stability using a fiber bundle model. Water Resources Research 41:W07025. (i)

Pollen-Bankhead, N., and A. Simon. 2010. Hydrologic and hydraulic effects of riparian root networks on streambank stability: is mechanical root-reinforcement the whole story? Geomorphology 116:353–362. (i)

Polvi, L.E., E.E. Wohl, and D.M. Merritt. 2011. Geomorphic and process domain controls on riparian zones in the Colorado Front Range. Geomorphology 125:504-516. (i)

Polvi, L.E., E.E. Wohl, and D.M. Merritt. 2014. Modeling the functional influence of vegetation type on streambank cohesion. Earth Surface Processes and Landforms 39:1245-1258. (i)

Post, D.M., M.W. Doyle, J.L. Sabo, and J.C. Finlay. 2007. The problem of boundaries in defining ecosystems: a potential landmine for uniting geomorphology and ecology. Geomorphology 89:111-126. (i)

Rapp, C.F., and T.B. Abbe. 2003. A framework for delineating channel migration zones. Ecology Publication #03-06-027. Washington State Department of Ecology and Washington State Department of Transportation, Olympia. (viii)

Reeves, G.H., L.E. Benda, K.M. Burnett, P.A. Bisson, and J.R. Sedell. 1995. A disturbance-based ecosystem approach to maintaining and restoring freshwater habitats of evolutionarily significant units of anadromous salmonids in the Pacific Northwest. American Fisheries Society Symposium 17:334-349. (i)

Reid, L.M., and S. Hilton. 1998. Buffering the buffer. Pages 71-80 *in* R.R. Ziemer, technical coordinator. Proceedings of the conference on coastal watersheds: the Caspar Creek story. PSW-GTR-168. U.S. Forest Service, Pacific Southwest Research Station, Albany, California. (i)

Renschler, C.S., M.W. Doyle, and M. Thomas. 2007. Geomorphology and ecosystems: challenges and keys for success in bridging disciplines. Geomorphology 89:1-8. (i)

Richter, K.O. 2005. Wetlands. Pages 22-23 *in* L.L.C. Jones, W.P. Leonard, and D.J. Olson, editors. Amphibians of the Pacific Northwest. Seattle, Audubon Society, Seattle. (vi)

Rinaldi, M., N. Casagli, S. Dapporto, and A. Gargini. 2004. Monitoring and modelling of pore water pressure changes and riverbank stability during flow events. Earth Surface Processes and Landforms 29:237-254. (i)

Ritter, D.F., R.C. Kochel, and J.R. Miller. 2002. Process geomorphology. McGraw-Hill, Boston. (i)

Roering, J.J., K.M. Schmidt, J.D. Stock, W.E. Dietrich, and D.R. Montgomery. 2003. Shallow landsliding, root reinforcement, and the spatial distribution of trees in the Oregon Coast Range. Canadian Geotechnical Journal 40:237-253. (i)

Rosenfeld, J. 2003. Assessing the habitat requirements of stream fishes: an overview and evaluation of different approaches. Transactions of the American Fisheries Society 132:953-968. (i)

Rosenfeld J.S., E. Raeburn, P.C. Carrier, and R. Johnson. 2008. Effects of side channel structure on productivity of floodplain habitats for juvenile Coho Salmon. North American Journal of Fisheries Management 28: 1108–1119. (i)

Scanlon, B.R., I. Jolly, M. Sophocleous, and L. Zhang. 2007. Global impacts of conversions from natural to agricultural ecosystems on water resources: quantity versus quality. Water Resources Research 43:W03437. (i)

Schilling, K., and J. Kiniry. 2007. Estimation of evapotranspiration by Reed Canarygrass using field observations and model simulations. Journal of Hydrology 337:356-363. (i)

Schlosser, I.J. 1991. Stream fish ecology: a landscape perspective. BioScience 41:704-712. (i)

Schlosser, I.J. 1995. Critical landscape attributes that influence fish population dynamics in headwater streams. Hydrobiologia 303:71-81. (i)

Schumm, S.A. 1977. The fluvial system. Wiley, New York. (i)

Schumm, S.A. 1979. Geomorphic thresholds: the concept and its applications. Transactions of the Institute of British Geographers 4:485-515. (i)

Sedell, J.R., J.E. Richey, and F.J. Swanson. 1989. The river continuum concept: a basis for the expected ecosystem behavior of very large rivers? Pages 49-55 *in* D.P. Dodge, editor. Proceedings of the international large river symposium. Department of Fisheries and Oceans, Ottawa, Canada. (i)

Selby, M.J. 1993. Hillslope forms and processes, 2nd edition. Oxford University Press, United Kingdom. (i)

Shankman, D. 1993. Channel migration and vegetation patterns in the Southeastern Coastal Plain. Conservation Biology 7:176-183. (i)

Simon, A., and A.J.C. Collison. 2002. Quantifying the mechanical and hydrologic effects of riparian vegetation on streambank stability. Earth Surface Processes and Landforms 27:527-546. (i)

Simon, A., A. Curini, S.E. Darby, and E.J. Langendoen. 2000. Bank and near-bank processes in an incised channel. Geomorphology 35:193-217. (i)

Simon, A., N. Pollen, and E. Langendoen. 2006. Influence of two woody riparian species on critical conditions for streambank stability: upper Truckee River, California. Journal of the American Water Resources Association 42:99-113. (i)

Sklar, L., and W.E. Dietrich. 1998. River longitudinal profiles and bedrock incision models: stream power and the influence of sediment supply. Geophysical Monograph Series 107:237-260. (i)

Smith, J.H.G. 1964. Root spread can be estimated from crown width of Douglas-fir, Lodgepole Pine, and other British Columbia tree species. Forestry Chronicle 40:456-473. (i)

Smith, B., P. Warkeand, and W. Whalley. 2002. Landscape development, collective amnesia and the need for integration in geomorphological research. Area 34:409-418. (i)

Smock, L.A., J.E. Gladden, J.L. Riekenberg, L.C. Smith, and C.R. Black. 1992. Lotic macroinvertebrate production in three dimensions: channel surface, hyporheic, and floodplain environments. Ecology 73:876-886. (i)

Stallins, J.A. 2006. Geomorphology and ecology: unifying themes for complex systems in biogeomorphology. Geomorphology 77:207-216. (i)

Stanford, J.A., and J.V. Ward. 1988. The hyporheic habitat of river ecosystems. Nature 335:64-66. (i)

Stanford, J.A., and J.V. Ward. 2001. Revisiting the serial-discontinuity concept. Regulated Rivers: Research & Management 17:303-310. (i)

Swanson, F.J., R.L. Fredriksen, and R.M. McCorison. 1982. Material transfer in a western Oregon forested watershed. Pages 233-266 *in* R.L. Edmonds, editor. Analysis of coniferous forest ecosystems in the western United States. Hutchinson Ross, Stroudsburg, Pennsylvania. (viii)

Swanson, F.J., S.L. Johnson, S.V. Gregory, and S.A. Acker. 1998. Flood disturbance in a forested mountain landscape. BioScience 48:681-689. (i)

Swanston, D.N. 1991. Natural Processes. Pages 139-179 *in* W. Meehan, editor. Influences of forest and rangeland management on salmonid fishes and their habitats. American Fisheries Society, Bethesda, Maryland. (i)

Sweeney, B.W., T.L. Bott, J.K. Jackson, L.A. Kaplan, J.D. Newbold, L.J. Standley, W.C. Hession, and R.J. Horwitz. 2004. Riparian deforestation, stream narrowing, and loss of stream ecosystem services. Proceedings of the National Academy of Sciences101:14132-14137. (i)

Tabacchi, E., L. Lambs, H. Guilloy, A.M. Planty-Tabacchi, E. Muller, and H. Decamps. 2000. Impacts of riparian vegetation on hydrological processes. Hydrological Processes 14:2959-2976. (i)

Tal, M., K. Gran, A.B. Murray, C. Paola, and D.M Hicks. 2004. Riparian vegetation as a primary control on channel characteristics in multi-thread rivers. Pages 43-58 *in* A.J. Bennet and A. Simon, editors. Riparian vegetation and fluvial geomorphology. American Geophysical Union, Washington, D.C. (i)

Tal, M., and C. Paola. 2007. Dynamic single-thread channels maintained by the interaction of flow and vegetation. Geology 35:347-350. (i)

Thorn, C.E., and M.R. Welford. 1994. The equilibrium concept in geomorphology. Annals of the Association of American Geographers 84:666-696. (i)

Tooth, S., H. Rodnight, G.A. Duller, T.S. McCarthy, P.M. Marren, and D. Brandt. 2007. Chronology and controls of avulsion along a mixed bedrock-alluvial river. Geological Society of America Bulletin 119:452-461. (i)

Torgersen, C., E., C.V. Baxter, and H.W. Li. 2006. Landscape influences on longitudinal patterns of river fishes: spatially continuous analysis of fish-habitat relationships. American Fisheries Society Symposium 48:473-492. (i)

Trimble, S.W., and A.C. Mendel. 1995. The cow as a geomorphic agent—a critical review. Geomorphology 13:233-253. (i)

Van Horne, B. 1983. Density as a misleading indicator of habitat quality. Journal of Wildlife Management 47:893-901. (i)

Vannote, R.L., G.W. Minshall, K.W. Cummins, J.R. Sedell, and C.E. Cushing. 1980. The river continuum concept. Canadian Journal of Fisheries and Aquatic Sciences 37:130-137. (i)

Ward J.V. 1998. Riverine landscapes: biodiversity patterns, disturbance regimes, and aquatic conservation. Biological Conservation 83:269-278. (i)

Wells, R.R., C.V. Alonso, and S.J. Bennett. 2009. Morphodynamics of headcut development and soil erosion in upland concentrated flows. Soil Science Society of America Journal 73:521-530. (i)

Wemple, B.C., J.A. Jones, and G.E. Grant. 1996. Channel network extension by logging roads in two basins, western Cascade, Oregon. Journal of the American Water Resources Association 32:1195-1207. (i)

Whitaker, A., Y. Alila, J. Beckers, and D. Toews. 2002. Evaluating peak flow sensitivity to clear-cutting in different elevation bands of a snowmelt-dominated mountainous catchment. Water Resources Research 38:1172. (i)



School of Bull Trout Salvelinus confluentus/*William Meyer, WDFW*

Williams, G.P., and M.G. Wolman. 1985. Effects of dams and reservoirs on surface-water hydrology – changes in rivers downstream from dams. U.S. Geological Survey, Washington, D.C. (i)

Wohl, E. 2013. Mountain rivers revisited. American Geophysical Union, Washington, D.C. (i)

Wohl, E. 2014. Rivers in the landscape: science and management. Wiley, Hoboken, New Jersey (i)

Wohl, E., D. Cooper, L. Poff, F. Rahel, D. Staley, and D. Winters. 2007. Assessment of stream ecosystem function and sensitivity in the Bighorn National Forest, Wyoming. Environmental Management 40:284-302. (i)

Wolman, M.G. 1959. Factors influencing erosion of cohesive river banks. American Journal of Science 25:204-216. (i)

Wolman, M.G. 1967. A cycle of sedimentation and erosion in urban river channels. Geografiska Annaler 49A:385-395. (i)

Wright H.A., and A.W. Bailey. 1982. Fire ecology: United States and southern Canada. Wiley, New York. (i)

Ziemer, R.R., and T.E. Lisle. 1998. Hydrology. Pages 43-68 *in* R.J. Naiman and R.E. Bilby, editors. River ecology and management: lessons from the Pacific Coastal Ecoregion. Springer-Verlag, New York. (i)

Chapter 3. Wood

By: George F. Wilhere and Anne Marshall

3.1. Introduction

The scientific study of wood in rivers and streams began about 50 years ago (Gregory 2003) and the vital ecological role of instream wood has been known for at least 40 years (Swanson et al. 1976). Over that 50 year period, the substantial quantity of research on instream wood has motivated numerous authoritative reviews of the scientific literature, such as Bisson et al. (1987), Maser et al. (1988), Gurnell et al. (1995), Bilby and Bisson (1998), Gurnell et al. (2002), Naiman et al. (2002a), and Hassan et al. (2005). A comprehensive, in-depth review of the ecology of wood in aquatic ecosystems is provided by Gregory et al. (2003). Although we have a solid understanding of wood's role in aquatic ecosystems and the pathways through which wood enters and moves through a stream network, some important questions remained unanswered.



Wood, rocks, and roots – roughness elements that enhance habitat diversity by increasing hydraulic complexity/Jane Atha, WDFW

This chapter focuses on the roles and recruitment of wood in aquatic ecosystems. It does not cover stream restoration using large wood. For information on that, see Dominguez and Cederholm (2000), Reich et al. (2003), Bisson et al. (2003), Carah et al. (2014), and Roni et al. (2014). For information on riparian forest management see Boyer et al. (2003) and Spies et al. (2013).

3.2. The Ecological Role of Instream Wood

Wood plays critical roles in the composition, structure, and function of riparian and aquatic ecosystems. In forested regions, wood is an important determinant of channel form and dynamics, especially in small streams (Montgomery and Buffington 1997; Bilby and Bisson 1998). However, the importance of wood's effects differs with channel dimensions, slope, sediment supply, and stream discharge (Gurnell et al. 1995). Large wood causes widening and narrowing, deepening and shallowing, stabilization and destabilization at different points along a stream or river channel (Swanson et al. 1976). The many effects of large wood create a variety of channel morphologies–dam pools, plunge pools, riffles, glides, undercut banks, and side channels–which provide a diversity of aquatic habitats. Pools are deposition sites for sediment and fine organic matter. Sediment is essential substrate for salmonid spawning, and stored sediments become mobilized over time to replenish downstream spawning areas.

Sediment and fine organic matter deposits are productive areas for invertebrates and are important food production sites for juvenile salmonids (Bisson et al. 1987). Pools provide rearing habitats and essential refuge from high flows for fish and other aquatic fauna. Instream large wood provides fish with cover from predators, and by increasing a water body's effective space, wood structures may increase fish densities (Bisson et al. 1987).

3.2.1. Small Wood

Wood is often divided into large and small size categories. Large wood is usually defined as having diameter greater than 4 in (10 cm) and length greater than 6 ft (≈2 m) (Bilby and Ward 1991; Schuett-Hames et al. 1999).[1] Small wood[2] consists of branches and other woody material not classified as large wood. Small wood plays essential and unique roles in lotic ecosystems. For instance, accumulations of small wood enhance a stream's retention of leaves and particulate organic matter (Gregory et al. 1991), which are vital food sources for many aquatic invertebrates. Small wood also effects channel morphology. Plunge and dammed pools are often associated with accumulations of small wood, and large wood with dense accumulations of small wood retain sediment significantly more frequently than large wood with sparse small wood accumulations (Bilby and Ward 1991).

Small wood exerts tremendous effects on hydrology and channel morphology through actions of the American Beaver *Castor canadensis* (Naiman et al. 1988). Beaver dams can store large quantities of sediment, reduce channel incision, remove excess nutrients from water, increase water retention and base flows, reduce peak flows, and by spreading flow events over longer periods, increase groundwater recharge, and increase the salmonid habitat capacity of small streams (Pollock et al. 2015). Beaver dams consist mainly of mud and small wood. Published information on small wood sizes in dams of Beaver is lacking. However, Beaver most often forage on trees ranging from 1.2 - 3.2 in (3 - 8 cm) in diameter (Collen and Gibson 2001), and a large proportion of woody stems used as food are also used in dam construction (Barnes and Mallik 1996). In Maryland, Blersch and Kangas (2014) found that 98% of sticks (i.e., small wood) in a Beaver dam were less than 4 in (10 cm) in diameter and that 46% of those sticks were probably placed in the dam by Beaver. The other 54% of sticks in the dam were due to passive capture of transported wood. For more information on the role of Beaver and Beaver dams in aquatic ecosystems, see Pollock et al. (2015).

3.2.2. Roles of Instream Large Wood

The main role of large wood in aquatic ecosystems is large roughness elements (Bisson et al. 1987) (Figure 3.1). Roughness elements are obstacles in a channel that deflect flow and change its velocity. The size, shape, and strength of large wood make it very effective at redirecting hydraulic forces and the flow of materials (Figure 3.2), such as sediment and fine organic matter. Instream large wood increases hydraulic complexity, i.e., creates a wider range of flow velocities, which causes pool formation, streambed scour, sediment deposition, and channel migration. The net result is a diversity of aquatic habitats.

[1] Large wood is also known as large woody debris (LWD) or coarse woody debris. There is no universal definition of LWD. Another definition is greater than 4 in (10 cm) in diameter and greater than 3 ft (≈1 m) in length. The system of measurement used effects the size of large wood. The definition using English units (4 in wide and 6 ft long) results in a piece of smaller volume than the definition using metric units (10 cm wide and 2 m long).
[2] Small wood is also known as small woody debris or fine woody debris

The influences of instream large wood on aquatic ecosystems are a function of wood size relative to channel size. For instance, as much as 80% of pools in small streams can be associated with wood (Montgomery et al. 1995); however, the frequency of wood-associated pools decreases with increasing stream size (Bilby and Ward 1989, 1991; Montgomery et al. 1995). The latter relationship is due to the increased capacity of larger streams to transport large wood downstream.

In low order streams, "key pieces" of large wood affect channel morphology. Key pieces are defined as large wood that is independently stable within the bankfull channel (i.e., not held or trapped by other material) and have the potential to retain other pieces of large wood (WFPB 2011). Key piece size increases as channel width increases (Table 3.1). In large rivers, wood influences channel morphology through tangled accumulations of wood known as woody debris jams.

Stable structural features can promote channel stability (Sullivan et al. 1987). In large rivers, for instance, woody debris jams contribute to floodplain stabilization by initiating the formation of mid-channel bars that eventually become forested islands (Fetherston et al. 1995; Abbe and Montgomery 1996). In small streams, persistent large wood structures trap sizable amounts of sediment thereby increasing channel stability (Figure 3.3). Of all structures capable of storing sediment (i.e., wood, boulders) in small non-fish-bearing streams of northwest Washington, 93% were composed of large wood (Grizzel and Wolff 1998). Thirty to 80% of a stream's drop in elevation can be influenced by large wood (Keller and Swanson 1979), and log steps can reduce average channel gradients by 8 to 22% (Heede 1972). Reducing channel gradient dissipates stream power which mobilizes less sediment and increases sediment storage which can subsequently increase channel stability.

Table 3.1. Minimum volume of large wood key pieces for different channel widths. Example dimensions for key piece length and diameter yield minimum volume. Diameter is measured at piece midpoint. One meter is approximately 3.3 ft.

		Example dimensions (m)	
Bankfull width (m)	Minimum volume (m^3)	Length	Diameter
0-5[a]	1	2.5	0.71
5-10[a]	2.5	7.5	0.65
10-15[a]	6	12.5	0.78
15-20[a]	9	17.5	0.81
20-30[b]	9.75	17.5	0.84
30-50[bc]	10.5	17.5	0.87
50-100[bc]	10.75	17.5	0.88

[a] WFPB (2011), [b] Fox and Bolton (2007), [c] Must have an attached root wad.

Studies where wood has been experimentally removed from streams further reveal the significant role of large wood for storing sediment. For instance, Bilby (1981) measured a 72% reduction in sediment storage following removal of large wood from 575 ft (175 m) of streambed. Beschta (1979) observed a similar effect after woody debris dams were removed from a moderate gradient headwater stream in western Oregon where 6,500 yd^3 (5,000 m^3) of sediment was lost from 820 ft (250 m) of streambed over a period of about 10 months.

Large wood can also cause transient channel instability. Keller and Swanson (1979) and Nakamura and Swanson (1993) describe stream reaches where large wood caused local erosion that increased channel width by more than 50%. In one case a woody debris jam increased channel width by 230%. These two studies also describe reaches where large wood caused lateral migration of the main channel and formation of side

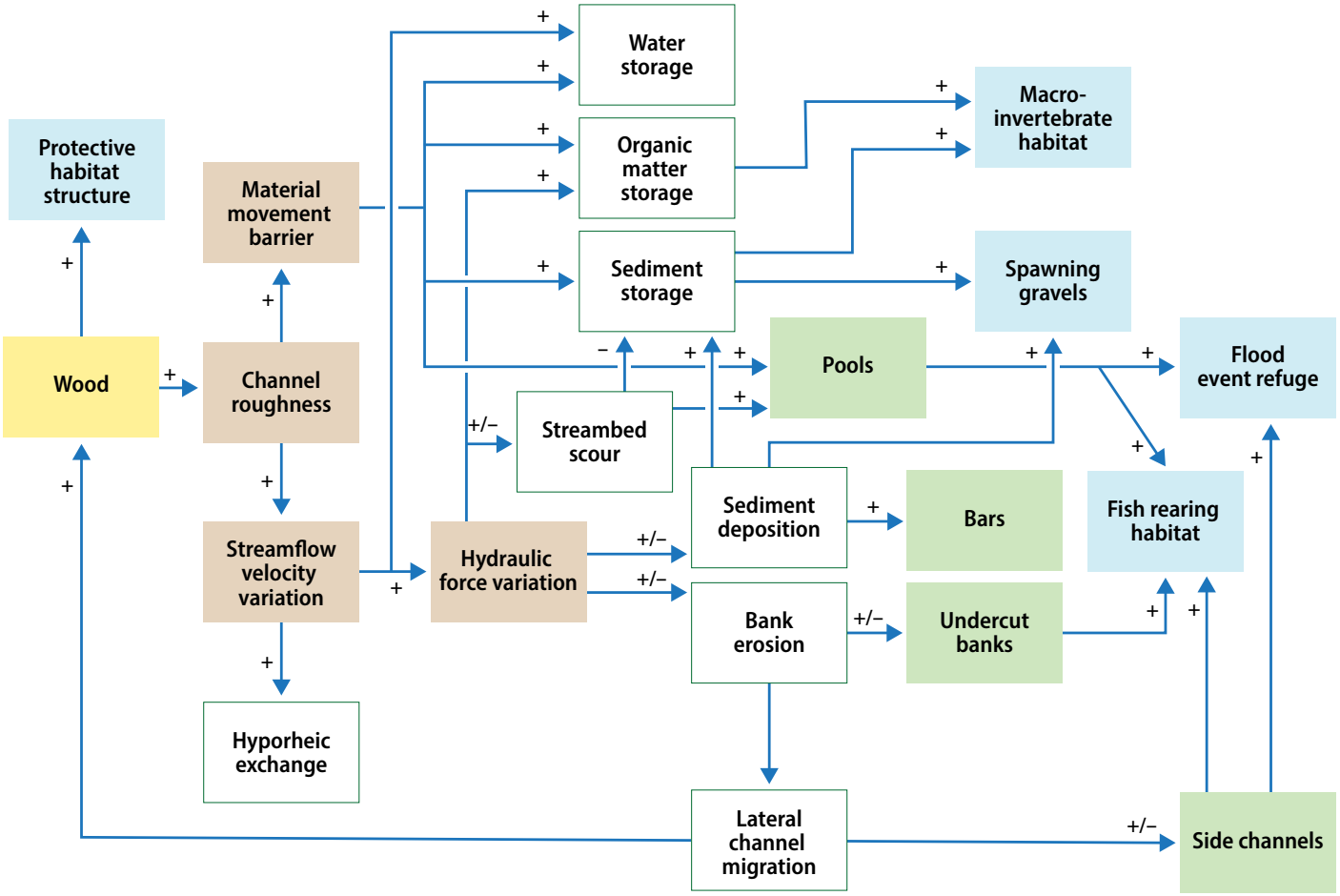


Figure 3.1. Conceptual model depicting the effects of wood on fluvial systems and fish habitats. Arrows indicate the hypothesized directions of causal relationships; pluses and minuses indicate the hypothesized slope of each relationship. Brown boxes represent direct effects of wood on fluvial processes. White boxes are secondary processes. Green boxes depict channel structures. Blue boxes are habitat features. Diagram does not include most feedback loops.

channels. Over time, these types of disturbances create a shifting mosaic of aquatic and riparian habitats.

Wood influences nutrient dynamics in two major ways: wood contains nutrients that are released through decomposition, and large wood influences the rate and timing of organic materials transport (Bilby 2003). The latter is the more important effect. Instream large wood traps and retains organic matter, such as leaves and other plant detritus, which are essential to the aquatic food web. Trapped organic materials are food sources for aquatic microorganisms, such as bacteria and certain fungi, and invertebrates, such as insects, crustaceans, and mollusks.



Figure 3.2. Sediment and nutrient storage and gravel bar formation behind large wood/Jane Atha, WDFW



Figure 3.3. Large wood altering channel morphology by creating dam pool, step drop, and plunge pool/Jane Atha, WDFW

The relationship between instream large wood and nutrient storage is well established. Larger quantities of wood per unit area in small streams lead to higher rates of storage of fine organic matter (Bilby and Likens 1980; Bilby and Bisson 1998; Brookshire and Dwire 2003). The mass of coarse particulate organic matter in streams in the McKenzie River watershed of Oregon was positively related to amounts of instream wood (Naiman and Sedell 1979). Bilby (1981) reported dramatic increases in downstream export of fine particulates during periods of high discharge following woody debris removal.

Carcasses of adult anadromous salmon provide nutrients to aquatic ecosystems (Cederholm et al. 1989; Reimchen et al. 2003). On the Olympic Peninsula, a positive correlation was observed between the number of Coho Salmon *Oncorhynchus kisutch* carcasses retained in streams and the amount of large wood in the stream (Cederholm and Peterson 1985).

By creating dams, instream large wood regulates water flow and storage. For example, surface water volume increased by 168%, five years after restoration of instream large wood in a coastal Oregon stream (Crispin et al. 1993), and third-order streams in Indiana with woody debris dams held surface water 1.5 to 1.7 times longer than those with minimal large wood (Ehrman and Lamberti 1992, cited by Gurnell et al. 1995). Hydrological effects such as these may alter high flow events by reducing peak discharge and increasing the event's duration (Gurnell et al. 1995). Pools created by woody debris dams raise the water table in adjacent streambanks (Gurnell et al. 1995), and that affects riparian vegetation composition. For instance, at some sites, wet riparian soils may be maintained through seepage from pools, and wet soils are more suitable for Red Alder *Alnus rubra,* Red Ceder *Thuja plicata,* and Alaska Yellow Ceder *Chamaecyparis nootkatensis* than other tree species. Red Alder is known to contribute enormous amounts of beneficial nitrogen to soils and streams (Naiman et al. 2002b).

The hyporheic zone is the saturated sediment beneath stream channels and riparian areas where groundwater and instream water mix. Large wood diverts surface water flow into the hyporheic zone, and by trapping and storing sediments, large wood increases the volume of the hyporheic zone (Naiman et al. 2000). Greater hyporheic exchange can also reduce a streams thermal sensitivity (Chapter 4).

3.3. Recruitment of Instream Large Wood

The quantity of instream large wood is determined by the processes of wood recruitment, decomposition, and transport (Figure 3.4). "Recruitment" refers to the process of wood moving from the terrestrial environment to the stream channel. "Transport" refers to wood import to, movement within, and export from stream reaches. For comprehensive reviews of the dynamics of instream large wood, including decomposition and transport, see Benda et al. (2003), Bilby (2003), Gurnell (2003), and Piegay (2003).

3.3.1. Wood Recruitment Mechanisms

Large wood recruitment is often caused by bank erosion, windthrow, landslides, debris flows, snow avalanches, and tree mortality due to fire, ice storms, insects, and disease (Swanson et al. 1976; Maser et al. 1988). At any given site, more than one mechanism may contribute to recruitment. However, the dominant mechanism is determined by channel morphology, slope steepness, slope stability, forest composition and structure, and local wind patterns (Murphy and Koski 1989; McDade et al. 1990; May and Gresswell 2003; Johnston et al. 2011; Benda and Bigelow 2014). In large low-gradient rivers, for instance, wood is commonly recruited via bank erosion. Steep-sloped riparian forests along confined streams can recruit instream large wood via several mechanisms; however, landslides and windthrow are the dominant recruitment mechanisms in such settings (Nakamura and Swanson 1993; May and Gresswell 2003). Fox (2001) reported that smaller channels are likely to obtain a significant proportion of instream large wood by stem breakage and individual tree mortality due to insects or disease because smaller streams recruit less wood through lateral bank avulsion. Beaver recruit small wood to small, low-gradient streams (Pollock et al. 2003).

Instream wood originating from bank erosion increases as channel confinement decreases (Murphy and Koski 1989; Nakamura and Swanson 1993; Martin and Benda 2001; Johnston et al. 2011). In relatively unconfined third-order channels surrounded by mature and old-growth forests in British Columbia, bank erosion was the dominant route of large wood delivery, especially in wider channels (Johnston et al. 2011). Along Alaska's southeastern coast, bank erosion dominated large wood recruitment in alluvial channels, while windthrow was dominant in bedrock channels (Murphy and Koski 1989). Over a 63 year period, the Queets River (bankfull width = 420 ft [128 m]) recruited 95% of wood pieces ≥ 3 ft (1 m) in diameter through bank erosion that occurred as its channel meandered across its wide floodplain (Latterell and Naiman 2007).

The relative importance of each instream wood recruitment mechanism is highly variable (Table 3.2). Johnston et al. (2011) found tree mortality was the most common recruitment mechanism followed by (in descending order) bank erosion, windthrow, and landslides. In contrast, Murphy and Koski (1989) found that tree mortality was the third most common mechanism, and their rank ordering was bank erosion, windthrow, tree mortality, and landslides. Johnston et al. (2011) found that windthrow contributed 4% of instream large wood, but May and Gresswell (2003) found windthrow contributed 59%, on average. Benda et al. (2003) found that landslides contributed, on average, 17% of instream wood volume, but at the site-level, the contribution from landslides ranged from 0 to 66%. In the Oregon Coast Range, 65% of instream pieces of large wood and 46% of wood volume in a fourth order stream were delivered by landslide or debris flow (Reeves et al. 2003).



Large wood suspended over water creates a refuge for fish from avian predators/Jane Atha, WDFW

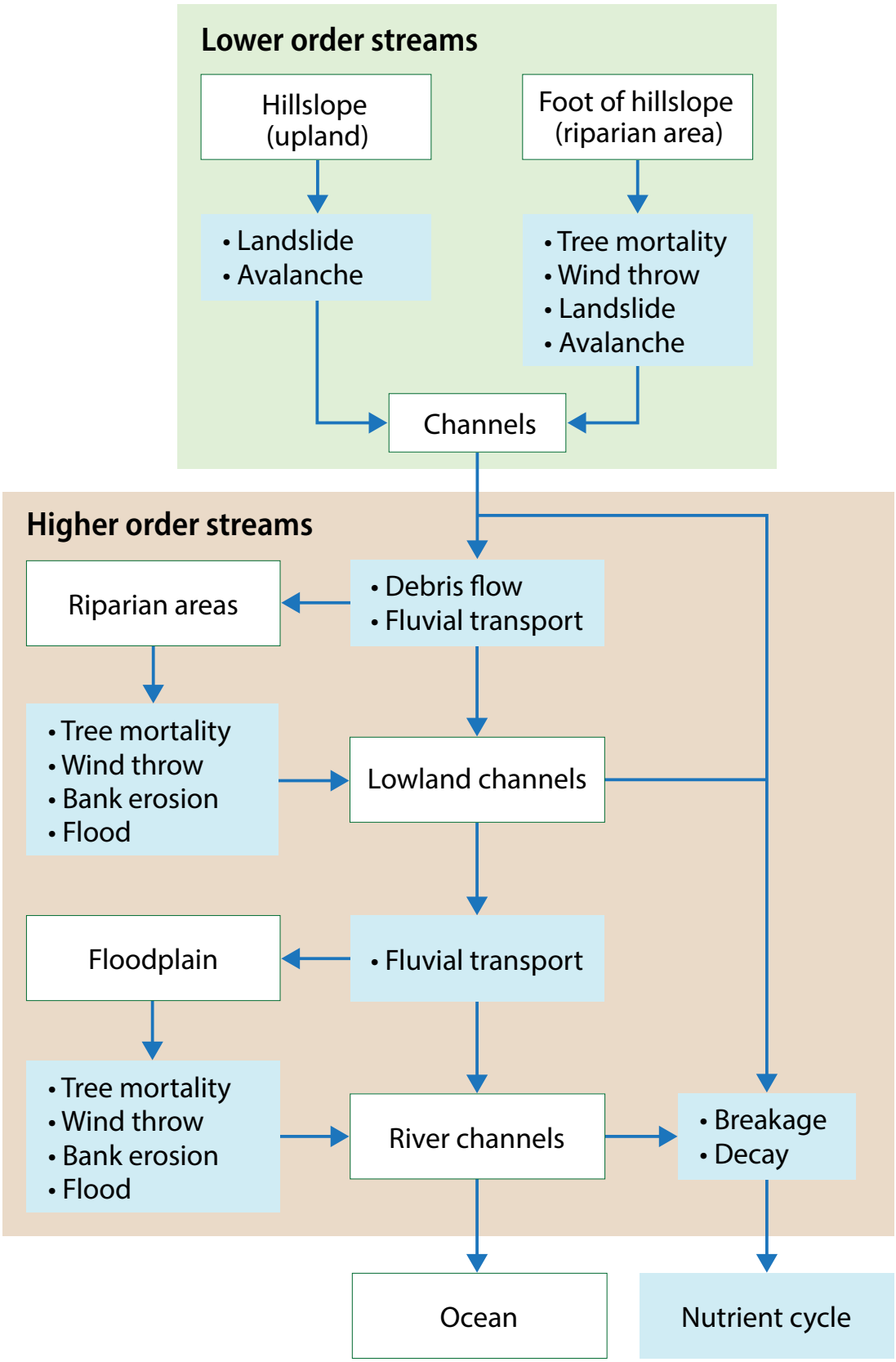


Figure 3.4. Wood recruitment mechanisms and wood transport pathways (adapted from Hassan et al. 2005). Lower order streams are first and second order headwaters. White and blue boxes are ecosystem structures and processes, respectively.

Table 3.2. Mean percentage of instream large wood contributed by various recruitment mechanisms in unmanaged old-growth conifer forests. For Johnston et al. (2011), stem breakage could be lumped with the windthrow or tree mortality categories. One meter is approximately 3.3 feet.

		Southeast Alaska[1]	South & Central British Columbia[2]	Coast Range Oregon[3]	Northern California[4]
	Stream length (m)	10,280	8,129	3,220	4,470
	Wood units	% of wood pieces	% of wood pieces	% of wood pieces	% of wood volume
Recruitment mechanism	bank erosion	42	18	6	29
	windthrow	33	4	59	--
	tree mortality	22	65	6	53
	stem break	--	12	--	--
	landslide	3	1	29	17

1 = Murphy and Koski 1989, 2 = Johnston et al. 2011, 3 = May and Gresswell 2003, 4 = Benda et al. 2003

A site's recruitment mechanisms determine the magnitude and timing of wood recruitment events. Recruitment can be continual or episodic. In large, meandering rivers wood may be recruited through continual bank erosion. Soil creep along the eroding base of a hillslope may also contribute to continual wood recruitment. However, most wood recruitment occurs through episodic events such as floods, landslides, debris flow, or windstorms. For example, if a 100-year flood causes a river to migrate across its floodplain, then a huge volume of wood that would have taken decades to be recruited under smaller flows could be recruited overnight. In smaller confined streams, the main recruitment mechanism may be windthrow, which can recruit wood incrementally (single tree per event) or catastrophically (100s of trees per event).

3.3.2. Recruitment Distances

Forests adjacent to streams provide the majority of large wood delivered to stream channels (Murphy and Koski 1989; McDade et al. 1990), however, trees far removed from riparian areas may also be delivered via landslides (Reeves et al. 2003) or channel migration (Latterell and Naiman 2007). Johnston et al. (2011) found that mean recruitment distances were greatest for wood entering by way of landslides, followed by (in descending order by distance) windthrow, stem breakage, falling of dead trees, and bank erosion.

Source distances are affected by channel geomorphology. The source distance of instream large wood differed significantly ($P < 0.05$) when comparing alluvial streams to colluvial channels draining steep hillslopes in Oregon's Coast Range (May and Gresswell 2003). In this study, 80% of wood pieces and total wood volume originated from forests within 160 ft (50 m) of colluvial channels confined by steep hillslopes, whereas in unconfined alluvial channels, 80% of instream large wood originated from within 98 ft (30 m) of the channel (May and Gresswell 2003). Along steep second growth redwood forests in northern California, landslides resulted in recruitment distances extending over 197 ft (60 m) (Benda et al. 2002). In the Oregon Coast Range, large wood from pristine steeply sloped conifer-deciduous forest was delivered to a fourth order stream by landslide or debris flow from distances of more than 295 ft (90 m) upslope of the channel (Reeves et al. 2003).

Table 3.3. Recruitment distances of instream large wood from unmanaged old-growth conifer riparian forests.

Location	Stream order or width	Maximum recruitment distance	Dominant recruitment process	Recruitment from intermediate distances	Source*
Southeast Alaska	second- to fifth-order	> 100 ft > 30 m	bank erosion	99% of pieces from < 100 ft (30 m). 45% of pieces from within 3 ft (1 m) of streambank. Average tree height = 130 ft (40 m)‡.	1
Western Oregon & Washington	first- to third-order	180 ft 55 m	not reported	50% of pieces from within 33 ft (10 m) of streambank; 85% from within 100 ft (30 m); 90% from within 128 ft (39 m), horizontal distance. Average tree height = 189 ft (57.6 m).	2
Northern California	45-55 ft 14-17 m	180 ft 55 m	variable	90% of wood from < 100 ft (30 m), slope distance. Longer recruitment distances due to landsliding.	3
Coast Range Oregon	second- and third-order	230 < d < 262 ft 70 < d < 80 m	windthrow	In alluvial stream 80% of pieces from ≤ 100 ft (30 m). In colluvial streams ≈50% of pieces from ≤ 100 ft (30 m). For both types ≈75% of volume from ≤ 165 ft (50 m).	4
Coast Range Oregon	fourth-order	> 300 ft > 90 m	landslide & debris flow	About 65% of pieces and 46% of wood volume were from upslope sources by landslides or debris flows.	5
Olympic Peninsula	sixth-order	> 1,475 ft > 450 m	channel migration	95% of wood from < 870 ft (265 m). 50% of pieces from within 300 ft (92 m).	6
Southeast Alaska	16-94 ft 5-30 m	115 < d < 130 ft 35 < d < 40 m	variable	96% of all large wood from within 65 ft (20 m) and 89% of from within 33 ft (10 m). Average tree height = 74 ft (22.6 m).	7
South & Central British Columbia	3-55 ft 1-17 m	425 ft 65 m	tree mortality	90% of large wood pieces and volume delivered to stream channels from within 33 and 30 ft (10 and 9 m), respectively. Average tree height = 120 ft (37 m).	8

* 1 = Murphy and Koski 1989, 2 = McDade et al. 1990, 3 = Benda et al. 2002; 4 = May and Gresswell 2003; 5 = Reeves et al. 2003, 6 - Latterell and Naiman 2007, 7 - Martin and Grotefendt 2007, 8 - Johnston et al. 2011.

‡ Tree height from Spence et al. (1996).

Source distances are affected by tree size. In one study, source distances for approximately 90% of instream large wood from mature and old-growth conifer riparian forest in western Washington and Oregon were within 85 and 130 ft (26 m and 40 m) of the streambank, respectively (McDade et al. 1990). The difference in source distances was largely attributed to taller trees in old-growth riparian forest (mean height = 189 ft [58 m]) compared to trees in mature riparian forest (mean height = 157 ft [48 m]). Likewise, recruitment distances measured in Alaska (e.g., Murphy and Koski 1989; Martin and Grotefendt 2007) are generally shorter than those measured in Oregon (e.g., McDade et al. 1990; May and Gresswell 2003) because trees of the same species are generally shorter in Alaska than in Oregon (Table 3.3). Johnston et al. (2011) also found that large wood source distances increased with increasing tree height. For a more thorough discussion of factors affecting source distances see Benda and Bigelow (2014).

The stereotypic recruitment function describing the amount of instream wood versus recruitment distance is nonlinear (Figure 3.5). That is, areas closer to the

stream channel provide relatively more wood than areas farther from the stream channel. In southeast Alaska, for instance, 100% of large wood was recruited from within 98 ft (30 m) of the streambank, but 45% of large wood originated from within 3.3 ft (1 m) (Murphy and Koski 1989). Likewise, in a study from Oregon and Washington, 100% of large wood with an identified source was recruited from within 180 ft (55 m), but 50% of large wood with an identified source originated from 33 ft (10 m; McDade et al. 1990) (Table 3.3). The shape of the wood recruitment function, and in particular, the shape under different watershed and site-level conditions, is an important question for riparian forest management.

Although most wood is recruited from areas close to a stream (Table 3.2), areas farther from a stream cannot be discounted, especially along larger alluvial streams. Along a fourth order stream in Oregon, the sources for 65% of large wood originated on hillslopes prone to landslides and lay beyond 295 ft (90 m) from the stream channel (Reeves et al. 2003). In Washington, 50% of large wood in a fifth-order river was recruited by lateral channel migration from forests on floodplains and fluvial terraces that lay beyond 300 ft (92 m) from the riverbank (Latterell and Naiman 2007).

3.3.3. Wood Recruitment in Intensively Managed Forests

An important question for riparian area management is how does wood recruitment in second-growth or intensively managed forests differ from recruitment in unmanaged, "natural" riparian forests? The answer to this question is essential for understanding the effects of contemporary forest management on fish habitats, however, useful answers are difficult to obtain because forest practices today are much different from those of the past.

The current conditions of instream wood and riparian areas in second-growth forests are the result of past management, and over the past 100 years management practices have changed dramatically. In the early 20th century splash dams were built on small streams to sluice logs downstream (Bisson et al. 1987), a practice that flushed naturally occurring large wood from the channel. During the 1950s and 1960s wood was routinely removed from streams to "improve" fish passage (Sedell et al. 1988), and this practice continued until the 1980s (Bilby 1984). Until the 1970s, logging to the streambank was common in Oregon

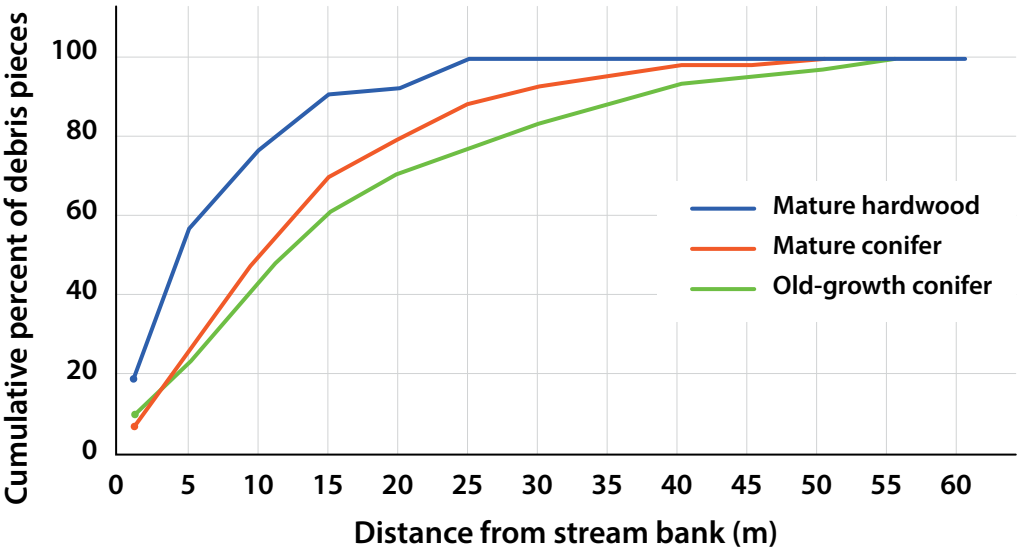


Figure 3.5. Distribution of source distances from tree origin to streambank. Empirically derived curves for old-growth conifer, mature conifer, and mature hardwood stands in western Oregon and Washington (from McDade et al. 1990). Empirically derived curves based on large wood with an identified source. One meter is equivalent to 3.3 feet.

and Washington; a practice that changed shortly after passage of the Clean Water Act of 1972. From 1987 to 2000, the Washington Forest Practices Rules required 23 to 65 trees per acre in riparian areas (WFPB 1987). In contrast, old-growth riparian areas may have 160 or more trees per acre (Acker et al. 2003). The current forest practices rule (WDNR 2005) require much wider stream-side buffers with much higher tree densities in riparian areas than pervious rules. The current regulations should result in a stand basal area equal to that of a mature conifer forest when the riparian stand is 140 years old. In short, over the past 100 years, riparian areas in intensively managed forests of Washington have been subjected to many different types of management, and over the next 100 years these same riparian areas will change dramatically.

Past forest practices are known to have severely degraded instream wood (Bilby and Ward 1991; Ralph et al. 1994), but current forest practice regulations are expected to improve instream wood (WDNR 2005). Whether current regulations will result in enough instream wood to create fish habitats that meet policy goals is unknown, and resolving that issue will be difficult until riparian areas attain their desired future conditions a century or more from now. Nevertheless, theoretical and empirical evidence suggest two main differences in large wood recruitment between second-growth, intensively managed forests and unmanaged mature and old-growth riparian forests.

Past forest practices are known to have severely degraded instream wood, but current forest practice regulations are expected to improve instream wood. Whether current regulations will result in enough instream wood to create fish habitats that meet policy goals is unknown.

First, the size of wood recruited from intensively managed forests is smaller than wood recruited from old-growth forests. Benda et al. (2002) found that the diameter of wood recruited from old-growth sites was, on average, up to twice the diameter of wood found in 50-year-old second-growth sites. Czarnomski et al. (2008) found significantly higher numbers of large wood pieces in stream segments adjacent to unmanaged mature and old-growth sites than in segments adjacent to 30- to 50-year-old intensively managed sites. From a theoretical perspective, these results are unsurprising—the dominant trees in a 200-year-old stand are much larger than the dominant trees in a 50-year-old stand. A similar relationship was also reported by McDade at al. (1990) who found that the size, both length and diameter, of instream large wood was related to forest age—wood was significantly smaller in younger forests (i.e., unmanaged mature forest versus old-growth forest).

Second, both theoretical models and empirical evidence show that maximum wood recruitment distances for intensively managed forest are less than the maximum recruitment distance for old-growth forests (McDade at al. 1990; Robison and Beschta 1990; Benda and Bigelow 2014). Again, these results are due to relative tree sizes—taller trees can contribute large wood from longer distances. The models show that the maximum recruitment distance for large wood is slightly less than the height of dominant trees; however, these models do not incorporate the recruitment processes of landslides and lateral channel migration which could substantially lengthen the maximum recruitment distance. For instance, in Benda et al. (2002) the theoretical maximum recruitment distance for their sixteen 50-year-old second-growth sites was about 98 ft (30 m), but due to landslides two sites had large wood recruited from beyond that distance—105 ft (32 m) and 210 ft (65 m). The results of Benda et al. (2002) and Benda and



Bank erosion recruits large wood into stream/Ned Pittman, WDFW

Bigelow (2014) also show that regardless of stand age or management, recruitment distances are primarily determined by recruitment processes. Riparian areas where bank erosion is the dominant process will, on average, have shorter recruitment distances, riparian areas where landslides dominate will have longer recruitment distances, and areas where other forms of tree mortality (e.g., windthrow, suppression, disease) dominate will have intermediate recruitment distances. In short, spatial variability in large wood recruitment is a function of many factors, including stream size and channel morphology, forest management, and natural disturbances such as landslides, floods, and windthrow.

3.4. Abundance of Instream Wood

3.4.1. Forested Regions of Washington

The abundance of instream large wood was much greater historically than it is today, especially in large rivers. One hundred fifty years ago, some woody debris jams on large rivers were nearly 1-mile-long (Sedell and Luchessa 1981), but

these impressive natural structures were cleared for purposes of river navigation. For instance, during the latter part of the 19th century, over 5,500 pieces of wood between 5 and 9 ft (1.5 and 2.7 m) in diameter were pulled from a 50-mile (80-km) section of the Willamette River (Sedell and Luchessa 1981). Collins et al. (2002) estimated that wood in some lowland Puget Sound rivers was 10 to 100 times greater prior to European settlement.

In contrast to large rivers, the abundance of large wood in small streams of unmanaged watersheds may still be representative of historical conditions. Fox and Bolton (2007) studied the quantities of instream large wood in natural, unmanaged forested watersheds in Washington. Ninety-six percent of their 150 sites had a stand age between 200 and 800 years (Fox 2001). In these watersheds, the processes of recruitment, decomposition, and transport were presumably undisturbed by human activities. Their findings, which are presented for forest zones and channel widths, could serve as reference or target conditions for instream large wood (Table 3.4).

3.4.2. Non-forested Regions of Washington

Fox and Bolton (2007) studied forested watersheds in forested regions (sensu Franklin and Dryness 1988), and, in fact, nearly all we know about instream wood is based on studies conducted in forested watersheds. This is unfortunate because our knowledge of instream wood for non-forested regions of Washington, such as semi-arid grasslands (i.e., steppe or Palouse) and shrub-steppe, is limited. Nevertheless, instream wood was likely to have been more abundant than it is today for two reasons.

First, in basins with headwaters in forested regions, such as the Yakima, Wenatchee, and Walla Walla basins, wood was transported downstream to shrub-steppe and grassland streams. This process is known to have occurred in other semi-arid and arid regions of the United States. Minckley and Rinne (1985) present historical evidence for the movement of large wood in rivers of the desert southwest: wood originated in forested headwaters, moved sporadically through desert riparian areas during flood events, and was ultimately deposited at the mouth of the Colorado River in Mexico. Minckley and Rinne (1985) identify interception of large wood by dams as a major cause of large wood reduction in semi-arid and arid river basins. At artificial reservoirs in eastern Washington, such as Keechelus, Kachess, Cle Elum, Bumping, Clear, and Rimrock lakes, large wood that could potentially interfere with dam operations is removed and burned (W. Meyer and B. Renfrow, Washington Department of Fish and Wildlife, personal communications). Some small water diversion dams do the same with large wood. This practice diminishes the quantity and quality of fish habitat in the Yakima and Tieton rivers, especially in their semi-arid shrub-steppe sections.

Second, riparian areas in grassland and shrub-steppe regions are inhabited by a wide variety of woody plants—Black Cottonwood *Populus balsamorhiza*, Quaking Aspen *Populus tremuloides*, White Alder *Alnus rhombifolia*, Thinleaf Alder *Alnus incana*, Water Birch *Betula occidentalis*, Black Hawthorne *Crataegus douglasii*, and Yellow Willow *Salix lutea* (Crawford 2003), and the historical abundance of woody plants in riparian areas is thought to have been much greater than it is today (Wissmar et al. 1994; Kauffman et al. 1997; Wissmar 2004). Reductions in woody plant abundance are mainly due to hydrological changes caused by water diversions for irrigation (Jamieson and Braatne 2001) and livestock grazing. Restoration projects can indicate the density of woody plants that historically existed in riparian areas prior to intensive livestock grazing. Only two years after the cessation of grazing within riparian areas in northeastern Oregon, the mean crown volume of willows and Thinleaf Alder tripled in size and that of Black Cottonwood increased 9-fold (Case and Kauffman

1997). Furthermore, shrub density increased by 50%. One possible reason for the severe impacts of grazing is that riparian vegetation in the semi-arid grassland and shrub-steppe regions of Washington evolved with little grazing by large herbivores (Mack and Thompson 1982).

With the exception of Black Cottonwood, woody plants in grassland and shrub-steppe regions do not contribute key pieces of large wood to stream channels (Table 3.1). Historically, much wood in stream channels of semi-arid regions was likely to have been small wood, and much of that small wood may have been recruited to and stored in the channel through Beaver activity. Prior to 1864, Beaver are known to have been abundant in the shrub-steppe region of central Oregon, and the eradication of Beaver from central Oregon is thought to have caused a cascade of effects: gradual disintegration of Beaver dams led to incision of streambeds, lowering of water

Table 3.4. Distributions of large wood per 100 m of stream channel by forest regions in Washington State and by bankfull width (BFW) class (Fox and Bolton 2007). Large wood was defined as pieces exceeding 10 cm (4 in) in diameter and 2 m (≈6 ft) in length. Key piece sizes are defined in Table 3.1. One meter is approximately 3.3 feet.

Forest zones	BFW Class (m)	75th Percentile	Median	25th Percentile
		Number of pieces per 100 m		
Sitka Spruce *Picea sitchensis*, Western Hemlock *Tsuga heterophylla*, Silver Fir *Abies alba*, and Mountain Hemlock *T. mertensiana*	0-6	> 38	29	< 26
	> 6-30	> 63	52	< 29
	> 30-100	> 208	106	< 57
Subalpine Fir *Abies lasiocarpa* and Grand Fir *A. grandis*	0-3	> 28	22	< 15
	> 3-30	> 56	35	< 25
	> 30-50	> 63	34	< 22
Douglas-fir *Pseudotsuga menziesii* and Ponderosa Pine *Pinus ponderosa*	0-6	> 29	15	< 5
	> 6-30	> 35	17	< 5
		Number of key pieces per 100 m		
Sitka Spruce, Western Hemlock, Silver Fir, and Mountain Hemlock	0-30	> 11	6	< 4
	> 30-100	> 4	1.3	< 1
Subalpine Fir and Grand Fir	0-15	> 4	2	< 0.5
	>15-50	> 1	0.3	< 0.5
Douglas-fir and Ponderosa Pine	0-30	> 2	0.4	< 0.5
		Volume (m^3) per 100 m		
Sitka Spruce, Western Hemlock, Silver Fir, and Mountain Hemlock	0-30	> 99	51	< 28
	> 30-100	> 317	93	< 44
Subalpine Fir and Grand Fir	0-3	> 10	8	< 3
	> 3-50	> 30	18	< 11
Douglas-fir and Ponderosa Pine	0-30	> 15	7	< 2



Wood jams are habitat features and are less common now than they were historically/Ned Pittman, WDFW

tables, loss of riparian vegetation, and subsequently deeper incision of channels (Buckley 1993). According to Pollock et al. (2007), the exact mechanism that caused widespread incision of streambeds remains uncertain, however, incision almost invariably coincided with widespread trapping of Beaver and the onset of intensive livestock grazing.

For the semi-arid grassland and shrub-steppe regions of Washington, we currently lack data with which to describe reference conditions for instream wood and for riparian plant communities. Historical reconstruction using General Land Office survey notes and historical photos is one way to develop qualitative descriptions of riparian plant communities (McAllister 2008); however, more quantitative descriptions would benefit development of management objectives. Much remains unknown about historical conditions of riparian areas in non-forested regions.

3.5. Fish, Wildlife, and Instream Wood

Authoritative reviews of the scientific literature regarding relationships between instream wood and fish or wildlife species have been written by Bisson et al. (1987), Benke and Wallace (2003), Dolloff and Warren (2003), Zalewski et al. (2003), Steel et al. (2003), and Wondzell and Bisson (2003). Certain small mammal and bird species are known to be associated with wood in stream channels (Steel et al. 2003). However, we discuss only fish, amphibians, reptiles, and invertebrates; taxonomic groups known to have strong associations with instream wood.

3.5.1. Fish

For salmonids, especially juvenile Coho Salmon, there is no more important structural component than instream wood (Bisson et al. 1987). In Puget Sound lowland streams, measures of salmonid rearing habitat were strongly linked to instream large wood abundance (May et al. 1997). In headwater streams, step pools formed by large wood were important for Dolly Varden *Salvelinus malma,* juvenile Coho Salmon, steelhead, and Cutthroat Trout *Oncorhynchus clarkii* in reaches with gradients less than 4% to greater than 10% (Bryant et al. 2007). Adult spawning Sockeye Salmon *Oncorhynchus nerka* densities were positively correlated with cover provided by large wood and undercut banks, pool area, and large wood (Braun and Reynolds 2011). The instream abundance of juvenile salmonids often is directly related to the amount of large wood (Murphy et al. 1986; Bisson et al. 1987). Stream reaches where large wood was artificially added were used by higher densities of juvenile Coho Salmon in summer and winter, and Cutthroat Trout and steelhead in winter in 30 western Oregon and Washington streams when compared to reaches where large wood was not enhanced (Roni and Quinn 2001). Spawning Coho Salmon abundance increased after instream wood structures were restored (Crispin et al. 1993). A study in British Columbia found that the biomass of yearling and older salmonids was positively correlated with stream pool volume (R^2 = 0.92) and that over 70% of pool volume was formed by large wood (Fausch and Northcote 1992).

Large wood provides both direct and indirect benefits to fish (Bisson et al. 1987). Indirect benefits are related to wood's role as a roughness element, and this role is especially obvious in smaller streams where wood

can bridge much of a channel (Zalewski et al. 2003). Large wood within a small channel dissipates flow velocity, which reduces the energy fish expend as they move upstream (Zalewski et al. 2003). Bisson et al. (1987) state that sediment storage by large wood benefits fish primarily by buffering the stream network against rapid changes in sediment load that would degrade habitats, such as rapid sediment increases due to landslides. Wood also benefits fish by increasing habitat diversity. In seeking a path around large wood obstructions, water creates complex hydraulic patterns that carve pools and side channels, form falls, and enhance channel sinuosity, imposing numerous variations in a stream's hydrology and geomorphology. Another indirect benefit of instream large wood is its influences on the availability of prey for fish in the form of macroinvertebrates. Large wood provides habitat for invertebrates, which then supplies fish with a source of food (Bisson et al. 1987).

The direct benefits of instream large wood to fish are also important. Large pieces of instream wood provide fish with refuge from high velocity flows during floods and provide hiding cover from predators (Sedell et al. 1985; Bisson et al. 1987; Braun and Reynolds 2011). Upturned tree roots and logs were the most common type of cover used by juvenile Coho Salmon and steelhead in an unlogged, west coast Vancouver Island stream (Bustard and Narver 1975). The deep pools often formed around these features made for good cover, particularly for older juveniles (Bustard and Narver 1975). After logging, almost all Coho Salmon that remained in channels over the winter sheltered in stream segments jammed with logs, with undercut banks, and in pools filled with upturned tree roots and other forest debris (Tschaplinski and Harman 1983). Hartman (1965) also found overwintering Coho Salmon fry preferring cover near logs, roots, and banks in streams in coastal British Columbia. Large wood increases fish density by visually isolating individual fish, which reduces inter- and intra-species competition (Dolloff and Reeves 1990; Crook and Robertson 1999).

3.5.2. Amphibians and Reptiles

Amphibians can be a dominant biotic component in Pacific Northwest streams (Olson et al. 2007), but in contrast to fishes and invertebrates, studies that characterize the importance of instream large wood for amphibians are sparse (Wondzell and Bisson 2003). However, diverse sources of data on stream-associated amphibian species life histories indicate that instream wood contributes to the creation and maintenance of breeding, rearing, and foraging habitats, and likely overwintering habitats as well. In particular, large wood can serve as the instream substrate for amphibian oviposition (Henry and Twitty 1940; Jones et al. 1990). Wood also forms steps in streams that promote sediment wedges (May and Gresswell 2003) that serve as variable but often extensive habitat matrices for oviposition and rearing (Nussbaum 1969; Wilkins and Peterson 2000). Moreover, wood-formed steps often create dam and plunge pools that are important for amphibian foraging or refuge (Wilkins and Peterson 2000; Welsh and Lind 2002). The basis of the former is that many aquatic invertebrates eaten by stream-associated amphibians occur in the habitat matrices created by wood-formed steps (Parker 1994; Steele and Brammer 2006; see next section). In coastal Washington headwater streams, the density of stream-associated amphibians



Van Dyke's Salamander Plethodon vandykei *use large wood for cover/ Eric Lund, WDFW*

was positively correlated with the amount of functional large wood (R^2 = 0.50), and torrent salamander (family Rhyacotritonidae) densities were positively correlated with the percentage of pools, indicating the importance of habitat complexity that large wood creates (Jackson et al. 2007). In Olympic National Park, large wood was a significant variable in explaining the densities of all three stream-associated amphibian species that were present, but its relative importance varied between species and was less important than one or more of aspect, gradient, and substrate in habitat use models for tailed frogs (family Ascaphidae) and torrent salamanders (Adams and Bury 2002).

Instream large wood is especially important for one Pacific Northwest reptile order: turtles. In the Northwest, water temperatures, even in the lowland stillwater habitats in which our two native turtle species occur, is often limiting (Holland 1994). Hence, the ability to bask securely (i.e., in a relatively predator-free environment) at temperatures that exceed those of water is critical to the normal processes of digestion and for female turtles, successfully yolking up eggs. Large floating or anchored-downed logs with enough area extending above the water surface are the key structures on which basking can occur (Holland 1994). Such structures are especially important in stillwater side- and off-channel habitats of large streams.

3.5.3. Aquatic Invertebrates

The distribution and abundance of aquatic invertebrates are influenced by instream wood and certain taxa are dependent on instream wood. In streams of all sizes, areas of wood accumulation are often also invertebrate biodiversity hot spots (Benke and Wallace 2003; Wondzell and Bisson 2003). Many aquatic invertebrates use the numerous grooves, splits, and fissures in large wood as refuges from predators and harsh environments. Other invertebrate uses of wood include



Large wood in Deschutes River/Noll Steinweg, WDFW

oviposition, case making, and emergence, especially when submerged pieces are decayed rather than firm (Harmon et al. 1986). Several families of caddisfly use wood for case construction. Of ninety-two case-making caddisfly genera reviewed by Wiggins (1977), roughly a quarter exploit bark or wood to varying degrees for case construction. Instream wood also is used as sites for oviposition above and below the water line. Many caddisflies in the family Limnephilidae deposit their egg masses on moist wood. In the Coast Range of Oregon, Wisseman and Anderson (1984) found oviposition by a number of caddisfly taxa on overhanging logs. The surfaces of instream wood also are used as nursery areas for early instars, and for resting, molting, and pupation (Anderson et al. 1978).

Large wood is especially important as substrate for invertebrates to attach to in rivers with limited sources of stable substrate (Benke and Wallace 2003). Trees that have fallen into the main channels of low-gradient rivers frequently are the only stable habitat (Benke and Wallace 2003). In these streams, wood can be especially important for periphyton and macroinvertebrate taxa to attach themselves (Benke and Wallace 2003). In contrast to smaller rivers, instream large wood shifts to channel margins and floodplains of larger rivers (Bisson et al. 1987), and hence, in these main-stem locations invertebrate densities peak (Ward et al. 1982). In headwater streams, large wood and gravel habitats supported higher densities and biomass of benthic invertebrates than cobble habitats (Hernandez et al. 2005). Coe et al. (2009) saw significantly higher densities of invertebrates in Pacific Northwest streams where engineered logjams were added. They attributed this to increased overall habitat surface area, and thereby the potential for increased productivity relative to reaches with low levels of wood. Instream large wood also supported a richer and more diverse invertebrate fauna than either cobble or gravel substrates.

Wood provides invertebrates with access to a wide variety of food sources. Large wood traps and stores



Large wood on Cedar River/Hal Beecher, WDFW

organic matter, and wood can be directly consumed by some invertebrates (Benke and Wallace 2003). Trapped organic materials are food sources for bacteria, fungi, mollusks, insects, and crustaceans. Although only a small fraction of aquatic insect taxa exploit woody debris as a source of food (Harmon et al. 1986), direct wood consumption by aquatic invertebrates in the Pacific Northwest has been observed in some species of caddisfly, mayfly, beetles, and snails (Anderson et al. 1978; Dudley and Anderson 1982; Pereira and Anderson 1982; Pereira et al. 1982). Submerged large wood may also support surface films of micro-organisms (e.g., diatoms, bacteria, fungi) that efficiently take up instream nitrogen and form a food web base for aquatic invertebrates (Dudley and Anderson 1982; Johnson et al. 2003), that in turn support vertebrate species (Ashkenas et al. 2004). By moderating pulses of fine sediment (Entrekin et al. 2009), instream large wood also acts to reduce the accumulation of sediment on algae (Richardson 2008), which is an important food to many macroinvertebrate taxa.

3.5.4. Fish and Wildlife Summary

The vital ecological role of instream wood has been known for at least 40 years (Swanson et al. 1976). Relationships between high quality salmonid habitats and instream large wood are well established (Bisson et al. 1987; Dollof and Warren 2003). Invertebrate taxa,

such as aquatic insects, are also known to rely on large wood as a habitat substrate and food source. Juvenile salmonids prey on aquatic insects. Amphibians and turtles also depend on the channel morphology and wood structure created by instream large wood.

3.6. Land Use Effects

The major human land uses in Washington–urban/suburban, agriculture, and forestry–have altered or removed extensive areas of riparian forest and have adversely impacted instream wood size, abundance, and distribution, and left many streams with a chronic deficiency of instream large wood compared to historical conditions (Maser et al. 1988; Bilby and Ward 1991; Stouder et al. 1997; May et al. 1997).

In general, the three major land uses impact instream large wood in similar ways–they diminish the amount of instream wood by reducing the number and size of trees in riparian areas. Furthermore, large wood is often purposefully removed from rivers and streams because it can block culverts or damage other human-made structures such as bridges, dams, or levees; cause streambank erosion that destroys private property; and present hazards to navigation or recreation. Culverts and dams also disrupt the transport of wood through a stream network and reduce the amount of wood in higher order streams and rivers.



Juvenile fish use large wood for shelter/WDFW

Most research on instream wood and riparian forests has occurred in unmanaged and managed forests, but much of the knowledge gained in forests–such as the functions of instream wood, natural amounts of instream wood, and recruitment mechanisms–is applicable to riparian areas in urban/suburban and agricultural settings as well, especially in forested ecoregions.

3.6.1. Forestry

Because mature conifer trees in the Pacific Northwest have large-diameter, decay-resistant boles, streams in this region have naturally high volumes of large wood compared to other parts of North America (Harmon et al. 1986). Nevertheless, harvest in and around riparian areas can result in immediate and long-term changes to the volume of instream wood. Czarnomski et al. (2008) found that instream wood volume and abundance varied significantly relative to timber harvest and adjacent tree stand age. They found instream wood volume and abundance were significantly higher in streams adjacent to unmanaged, mature and old-growth stands compared to streams along 30- to 50-year-old plantations, and significantly less in streams adjacent to 30- to 50-year-old plantations compared to those adjacent to 20- to 30-year-old plantations or mature and old-growth forest. Beechie et al. (2000) estimated that if a riparian buffer was established today in a 50-year-old stand of Douglas-fir, recovery of pool-forming large wood might take less than 100 years in small channels (e.g., ≤ 66 ft [20 m] wide), but could take as much as 200 years in larger channels.

The impacts of logging on instream large wood and aquatic habitats may not be realized for many decades after logging. In interior British Columbia, Chen et al. (2005) found that in the short term, instream large wood volume and biomass increased after logging. However, they concluded that in the long term, abundance of instream large wood may be greatly reduced as a

result of increased rates of decay, transport, and reduced recruitment from the adjacent riparian forest. With instream wood residence times averaging about 30 years, Hyatt and Naiman (2001) estimated that harvesting large riparian conifers would adversely impact aquatic habitats of large streams in about three to five decades. Murphy and Koski (1989) showed a 70% reduction of instream large wood 90 years after clearcutting without a riparian buffer. They also estimated a 250-year recovery time to pre-harvest levels.



Harvest near riparian areas can impact aquatic habitats/Marc Hayes, WDFW

The loss of riparian trees can come with long-term repercussions to functional aquatic habitat. Where riparian trees are absent, Beechie et al. (2000) predicted a lag of 7-49 and 15-91 years before pool-forming large wood could be recruited from Red Alder and Douglas-fir forests, respectively. The lag time for a given stream depends on multiple factors including channel width and the minimum size of pool-forming wood. In Alberta, instream large wood generated from stand-replacing fires was depleted within 100 years of the event but once the forests reestablished, new large wood recruitment was delayed by roughly 40 years (Powell et al. 2009).

A riparian management zone (RMZ) adjacent to logging differs in its ability to supply instream wood compared to riparian areas adjacent to unlogged uplands. On average, tree mortality was 50% greater in RMZs compared to riparian areas in unlogged landscapes, 3 to 15 years post-harvest (Martin and Grotefendt 2007). Differences in stand mortality between logged and unlogged tracts were primarily due to greater windthrow at a small proportion of RMZs in logged tracts. Additionally, downed tree recruitment from RMZ outer zones was more than double that of trees recruited in unlogged tracts. Consequently, wood recruitment increased by an average of 2 trees per 330 ft (100 m) in the buffered versus unlogged forested tracts (Martin and Grotefendt 2007).

Trees in RMZs with adjacent clear-cuts may be more susceptible to windthrow. Windthrow in RMZs (85 ft [26 m] wide on both side of streams) increased instream large wood by 34% within one to three years after logging in small streams (Grizzel and Wolff 1998). The authors of that study suggested that the RMZs adjacent to clearcuts served as a long-term source of large wood. They added that over a 10-year period, windthrow could add an average of 1.9 trees per 984 ft (300 m) of stream. Along second to fifth order streams, windthrow in RMZs was 26 times greater up to three years post-harvest compared to estimated mortality rates of trees in riparian stands in unlogged tracts (Liquori 2006). Post-harvest windthrow may reduce tree density in RMZs enough to significantly reduce competition-induced tree mortality, which in turn may lead to substantially different wood recruitment dynamics in buffers compared to unlogged forests (Liquori 2006).

3.6.2. Urban/Suburban

Very few studies have examined the impacts of development on instream large wood dynamics. In their analysis of the effects of urbanization, May et al. (1997) noted that as a basin's urbanization increased the quantity of large wood declined, as did related measures of habitat quality, namely loss of riparian forest area, reduced pool area, and decreased habitat complexity. Urban streams greater than 2% gradient and lacking large wood were found to be more susceptible to scour than less developed counterparts. Other than restoration sites where instream large wood had been replaced, high quantities of instream large wood were only found in undeveloped watersheds.

An analysis of relationships of channel characteristics, land ownership, land use, and land cover to instream large wood abundance in western Oregon showed that the most important predictor for large wood volume was land ownership, followed by stream gradient (Wing and Skaugset 2002). They also observed fewer large wood pieces in streams near rural residential areas compared to managed forests. In a study outside the Pacific Northwest, researchers in the Piedmont region of Georgia found that the absence of forest cover in catchments in suburban Atlanta corresponded to a decrease of instream large wood biomass (Roy et al. 2005).



Agricultural area in western Washington/Marlin Greene, One Earth Images

3.6.3. Agriculture

Many types of agriculture remove riparian forest, and consequently, reduce the recruitment of large wood to fish-bearing rivers and streams. Within the Nooksack River basin of northwest Washington, riparian forest along reaches accessible to anadromous fish were evaluated based on their ability to contribute instream wood large enough to form pools (Hyatt et al. 2004). Seventy-four percent of this basin's riparian forests that failed to meet this criterion were found in lowland rural-agricultural areas. In contrast, only 20% of the stands that failed to meet this threshold were in federal and commercial forestlands. This contrast is notable given that agricultural and rural areas comprised only about 22% of Nooksack basin (Hyatt et al. 2004). Similar results were observed in an analysis relating land use and land cover to instream wood abundance in western Oregon (Wing and Skaugset 2002). In this study, they found fewer pieces of large wood in streams near agricultural land uses compared to that of managed forestlands.

In shrub-steppe and grassland ecoregions of eastern Washington, livestock grazing in riparian areas significantly reduces the amount of woody vegetation. Significant reductions in woody vegetation lead to numerous adverse impacts to aquatic habitats: increased streambank erosion, increased overland flow and erosion within riparian areas, increased turbidity, reduced shade, higher water temperatures, loss of cover for fish due to reductions in overhanging vegetation and undercut banks, reduction in the amount of instream small wood, changes to channel morphology such as fewer pools, fewer meanders, and channel incision, lowering the water table, and reduction in essential nutrients derived from detritus (Belsky et al. 1999).

3.6.4. Land Use Effects Summary

Land uses that affect riparian forest also affect instream large wood. Of the three major land uses, contemporary forestry has the least effect on instream large wood. However, for all three land uses, the severity of effects depends largely on how riparian areas are managed.

3.7. Conclusions

Many effects of wood on aquatic ecosystems are well understood and not subtle, and therefore, ecologists are very confident about the critical role of wood in fish habitats. Ecologists are also confident about the role of riparian forests in supplying large wood to aquatic systems. Successful conservation of fish habitats and fish species in the forested regions of Washington depends on riparian forest management that delivers adequate wood to aquatic ecosystems. From a management perspective, the main scientific uncertainties are: 1) the shape of the wood recruitment function (e.g., Figure 3.5), especially the shape under different watershed and site-level conditions; and 2) the potential contributions from recruitment mechanisms outside the riparian forest, such as landslides, debris flows, or extreme channel migration. Addressing these uncertainties through research could lead to more ecologically effective and economically efficient management of riparian areas.

To maintain or restore 100% of a site's large wood recruitment potential, the site's composition and structure should be similar to that of an unmanaged riparian forest. Given current uncertainties, re-establishing riparian forest similar to unmanaged, mature or old-growth forests should be the most reliable way to provide instream large wood sizes and abundance that are similar to historical levels.

An important management question is: what are source distances for large wood recruitment from riparian areas to aquatic ecosystems? We know that source distances for wood in riparian areas are a function of tree height—source distances are longer for riparian forests with taller trees. We also know that tree heights for old-growth conifer forests can exceed 200 ft (60 m). In Washington State, Fox (2003) found that mean heights of canopy trees in old-growth riparian areas (i.e., stand age > 200 years old) ranged from 100 to 240 ft (30 to 73 m). Height variation among riparian areas was largely explained by forest zone and site productivity class. If large wood has a minimum diameter of 4 in (10 cm), then only that portion of a tree's stem greater than 4 in (10 cm) in diameter is large wood. From tree taper equations for Douglas-fir (Biging 1984), we know that for trees between 100 to 240 ft (30 and 73 m) tall about 15 to 3 percent of the stem is not large wood, respectively.[3] In other words, for the purpose of large wood recruitment, the "effective" tree height (*sensu* Robison and Beschta. 1990; Van Sickle and Gregory 1990) ranges from 85 to 230 ft (26 to 70 m), depending on site productivity class. Therefore, in forested ecoregions, 100% of a site's large wood recruitment potential, is located about 85 to 230 ft (26 to 70 m) from the stream channel, depending on site productivity class. These source distances only account for trees recruited via bank erosion, windthrow, or tree mortality. It does not account for large wood recruited to the stream channel through landslides or debris flows, nor does it account for recruitment through extreme channel migration in large river floodplains. In addition, this does not account for source distances of small wood. Source distances for small wood equal a full tree height from the stream channel.

Ecologists are confident about the critical role of wood in creating fish habitat and the role of riparian forests in supplying large wood to aquatic systems.

[3] Effective tree height calculations were done in Microsoft Excel with equations from Robison and Beschta (1990) and Biging (1984).

3.8. Literature Cited[4]

Abbe, T.B., and D.R. Montgomery. 1996. Large woody debris jams, channel hydraulics and habitat formation in large rivers. Regulated Rivers: Research & Management 12:201-221. (i)

Acker, S.A., S.V. Gregory, G. Lienkaemper, W.A. McKee, F.J. Swanson, and S.D. Miler. 2003. Composition, complexity, and tree mortality in riparian forests in the central western Cascades of Oregon. Forest Ecology and Management 173:293-308. (i)

Adams, M. J., and R. B. Bury. 2002. The endemic headwater stream amphibians of the American Northwest: associations with environmental gradients in a large forested preserve. Global Ecology & Biogeography 11:169-178. (i)

Anderson, N.H., J.R. Sedell, L.M. Roberts, and F.J. Triska. 1978. The role of aquatic invertebrates in processing of wood debris in coniferous forest streams. The American Midland Naturalist 100:64–82. (i)

Barnes, D.M., and A.U. Mallik. 1996. Use of woody plants in construction of Beaver dams in northern Ontario. Canadian Journal of Zoology 74:1781-1786. (i)

Beechie, T.J., G. Pess; P. Kennard, R.E. Bilby, and S. Bolton. 2000. Modeling recovery rates and pathways for woody debris recruitment in northwestern Washington streams. North American Journal of Fisheries Management 20:436-452. (i)

Belsky, A.J., A. Matzke, and S. Uselman. 1999. Survey of livestock influences on stream and riparian ecosystems in the western United States. Journal of Soil and Water Conservation 54:419-431. (i)

Benda, L., and P. Bigelow. 2014. On the patterns and processes of wood in northern California streams. Geomorphology 209:79-97. (i)

Benda, L.E., P. Bigelow, and T.M. Worsley. 2002. Recruitment of wood to streams in old-growth and second-growth redwood forests, northern California, U.S.A. Canadian Journal of Forest Research 32:1460-1477. (i)

Benda, L., D. Miller, J. Sias, D. Martin, R. Bilby, C. Veldhuisen, and T. Dunne. 2003. Wood recruitment processes and wood budgeting. Pages 49-74 *in* S.V. Gregory, K.L. Boyer, and A.M. Gurnell, editors. The ecology and management of wood in world rivers. American Fisheries Society, Symposium 37, Bethesda, Maryland. (i)

Benke, A.C., and J.B. Wallace. 2003. Influence of wood on invertebrate communities in streams and rivers. Pages 149-178 *in* S.V. Gregory, K.L. Boyer, and A.M. Gurnell, editors. The ecology and management of wood in world rivers. American Fisheries Society, Symposium 37, Bethesda, Maryland. (i)

Beschta, R.L. 1979. Debris removal and its effects on sedimentation in an Oregon Coast Range stream. Northwest Science 53:71-77. (i)

Biging, G.S. 1984. Taper equations for second-growth mixed conifers of northern California. Forest Science 30:1103-1117. (i)

Bilby, R.E. 1981. Role of organic debris dams in regulating the export of dissolved and particulate matter from a forested watershed. Ecology 62:1234-1243. (i)

Bilby, R.E. 1984. Removal of woody debris may affect stream channel stability. Journal of Forestry 82:609-613. (i)

Bilby, R.E. 2003. Decomposition and nutrient dynamics of wood in streams and rivers. Pages 135-148 *in* S.V. Gregory, K.L. Boyer, and A.M. Gurnell, editors. The ecology and management of wood in world rivers. American Fisheries Society, Symposium 37, Bethesda, Maryland. (i)

Bilby, R.E., and P.A. Bisson. 1998. Function and distribution of large woody debris. Pages 324-346 *in* R.J. Naiman and R.E. Bilby, editors. River ecology and management: lessons from the Pacific Coastal Ecoregion. Springer-Verlag, New York. (i)

Bilby, R.E., and G.E. Likens. 1980. Importance of organic debris dams in the structure and function of stream ecosystems. Ecology 61:1107-1113. (i)

4 References are classified according to RCW 34.05.271 (see Appendix 1) denoted by a lower case roman numeral (i – viii) in parentheses at the end of the citation.

Bilby, R.E., and J.W. Ward. 1989. Changes in characteristics and function of woody debris with increasing size of streams in western Washington. Transactions of the American Fisheries Society 118:368-378. (i)

Bilby, R.E., and J.W. Ward. 1991. Characteristics and function of large woody debris in streams draining old-growth, clear-cut, and second-growth forests in southwestern Washington. Canadian Journal of Fisheries and Aquatic Sciences 48:2499-2508. (i)

Bisson, P.A., R.E. Bilby, M.D. Bryant, C.A. Dollof, G.B. Grette, R.A. House, M.L. Murphy, K.V. Koski, and J.R. Sedell. 1987. Large woody debris in forested streams in the Pacific Northwest: past, present, and future. Pages 143-190 *in* E.O. Salo, and T.W. Cundy, editors. Streamside management: forestry and fishery interactions. Contribution No. 57. Institute of Forest Resources, University of Washington, Seattle. (viii)

Bisson, P.A., S.M. Wondzell, G.H. Reeves, and S.V. Gregory. 2003. Trends in using wood to restore aquatic habitats and fish communities in western North America. Pages 391-406 *in* S.V. Gregory, K.L. Boyer, and A.M. Gurnell, editors. The ecology and management of wood in world rivers. American Fisheries Society, Symposium 37, Bethesda, Maryland. (i)

Blersch, D.M., and P.C. Kangas. 2014. Signatures of self-assembly in size distributions of wood members in dam structures of *Castor canadensis.* Global Ecology and Conservation 2:204-213. (i)

Boyer, K.L., D.R. Berg and S.V. Gregory. 2003. Riparian management for wood in rivers. Pages 407-420 *in* S.V. Gregory, K.L. Boyer, and A.M. Gurnell, editors. The ecology and management of wood in world rivers. American Fisheries Society, Symposium 37, Bethesda, Maryland. (i)

Brookshire, E.N.J., and K.A. Dwire. 2003. Controls on patterns of coarse organic particle retention in headwater streams. Journal of the North American Benthological Society 22:17-34. (i)

Braun, D.C., and J.D. Reynolds. 2011. Relationships between habitat characteristics and breeding population densities in Sockeye Salmon. Canadian Journal of Fisheries and Aquatic Sciences 68:758-767. (i)

Bryant, M.D., T. Gomi, and J.J. Piccolo. 2007. Structures linking physical and biological processes in headwater streams of the Maybeso Watershed, southeast Alaska. Forest Science 53:371-383. (i)

Buckley, G.L. 1993. Desertification of the Camp Creek Drainage in central Oregon. Yearbook of the Association of Pacific Coast Geographers 55:91-126. (i)

Bustard, D.R., and D.W. Narver. 1975. Aspects of the winter ecology of juvenile Coho Salmon (*Oncorhynchus kisutch*) and steelhead trout (*Salmo gairdneri*). Journal of the Fisheries Research Board of Canada 32:667-680. (i)

Carah, J.K., C.C. Blencowe, D.W. Wright, and L.A. Bolton. 2014. Low-cost restoration techniques for rapidly increasing wood cover in coastal Coho Salmon streams. North American Journal of Fisheries Management 34(5):1003-1013. (i)

Case, T.L., and J.B. Kauffman. 1997. Wild ungulate influence on the recovery of willows, Black Cottonwood, and Thin-leaf Alder following cessation of cattle grazing in northeastern Oregon. Northwest Science 71:115-126. (i)

Cederholm, C.J., D.B. Houston, D.L. Cole, and W.J. Scarlett. 1989. Fate of Coho Salmon (*Oncorhynchus kisutch*) carcasses in spawning streams. Canadian Journal of Fisheries and Aquatic Sciences 46:1347-1355. (i)

Cederholm, C.J., and N.P. Peterson. 1985. The retention of Coho Salmon (*Oncorhynchus kisutch*) carcasses by organic debris in small streams. Canadian Journal of Fisheries and Aquatic Sciences 42:1222-1225. (i)

Chen, X., X. Wei, and R. Scherer. 2005. Influence of wildfire and harvest on biomass, carbon pool, and decomposition of large woody debris in forested streams of southern interior British Columbia. Forest Ecology and Management 208:101-114. (i)

Coe, H.J., P.M. Kiffney, G.R. Pess, K.K. Kloehn, and M.L. McHenry. 2009. Periphyton and invertebrate response to wood placement in large Pacific coastal rivers. River Research and Applications 25:1025-1035. (i)

Collen, P., and R.J. Gibson. 2001. The general ecology of Beavers (*Castor* spp.), as related to their influence in stream ecosystems and riparian habitats, and the subsequent effects on fish—a review. Reviews in Fish Biology and Fisheries 10:439-461. (i)

Collins, B.D., D.R. Montgomery, and A.D. Haas 2002. Historical changes in the distribution and functions of large wood in Puget lowland rivers. Canadian Journal of Fisheries and Aquatic Sciences 59:66-76. (i)

Crawford, R.C. 2003. Riparian vegetation classification of the Columbia Basin, Washington. Natural Heritage Program Report 2003-03. Washington Department Natural Resources. Olympia, Washington. (viii)

Crispin, V., R. House, and D. Roberts. 1993. Changes in instream habitat, large woody debris, and salmon habitat after the restructuring of a coastal Oregon stream. North American Journal of Fisheries Management 13:96-102. (i)

Crook, D A., and A.I. Robertson. 1999. Relationship between riverine fish and woody debris: implications for lowland rivers. Marine and Freshwater Research 50:941-953. (i)

Czarnomski, N.M., D.M. David, K.U. Snyder, J.A. Jones, and F.J. Swanson. 2008. Dynamics of wood in stream networks of the western Cascades Range, Oregon. Canadian Journal of Forest Research 38:2236-2248. (i)

Dolloff, C.A., and C.H. Reeves. 1990. Microhabitat partitioning among stream-dwelling juvenile Coho Salmon, *Oncorhynchus kisutch,* and Dolly Varden, *Salvelinus malma.* Canadian Journal of Fisheries and Aquatic Sciences 47:2297-2306. (i)

Dolloff, C.A., and M.L. Warren. 2003. Fish relationships with large wood in small streams. Pages 179-194 *in* S.V. Gregory, K.L. Boyer, and A.M. Gurnell, editors. The ecology and management of wood in world rivers. American Fisheries Society, Symposium 37, Bethesda, Maryland. (i)

Dominguez, L.G., and C.J. Cederholm. 2000. Rehabilitating stream channels using large woody debris with considerations for salmonid life history and fluvial geomorphic processes. Pages 545-563 *in* E.E. Knudsen, C.R. Steward, D.D. MacDonald, J.E. Williams, and D.W. Reiser, editors. Sustainable fisheries management: Pacific salmon. Lewis Publishers, New York. (i)

Dudley T., and N.H. Anderson. 1982. A survey of invertebrates associated with wood debris in aquatic habitats. Melanderia 39:1-21. (i)

Entrekin, S.A., J.L. Tank, E.J. Rso-Marshall, T.J. Hoellein, and G.A. Lamberti. 2009. Response of secondary production by macroinvertebrates to large wood addition in three Michigan streams. Freshwater Biology 54:1741-1758. (i)

Ehrman, T.P., and G.A. Lamberti. 1992. Hydraulic and particulate matter retention in a 3rd-order Indiana stream. Journal of the North American Benthological Society 11:341-349. (i)

Fausch, K.D., and T. G. Northcote. 1992. Large woody debris and salmonid habitat in a small coastal British Columbia stream. Canadian Journal of Fisheries and Aquatic Sciences 49:682-693. (i)

Fetherston, K.L., R.J. Naiman, and R.E. Bilby. 1995. Large woody debris, physical process, and riparian forest development in montane river networks of the Pacific Northwest. Geomorphology 13:133-144. (i)

Fox, M.J. 2001. A new look at the quantities and volumes of instream wood in forested basins within Washington State. Master's thesis. University of Washington, Seattle. (i)

Fox, M.J. 2003. Spatial organization, position, and source characteristics of large woody debris in natural systems. Doctoral dissertation. University of Washington, Seattle. (i)

Fox, M., and S. Bolton. 2007. A regional and geomorphic reference for quantities and volumes of instream wood in unmanaged forested basins of Washington State. North American Journal of Fisheries Management 27:342-359. (i)

Franklin, J.F., and C.T. Dyrness. 1988. Natural vegetation of Oregon and Washington. Oregon State University press, Corvallis, Oregon. (i)

Gregory, K.J. 2003. The limits of wood in world rivers: present, past, and future. Pages 1-19 *in* S.V. Gregory, K.L. Boyer, and A.M. Gurnell, editors. The ecology and management of wood in world rivers. American Fisheries Society, Symposium 37, Bethesda, Maryland. (i)

Gregory, S.V., K.L. Boyer, and A.M. Gurnell, editors. 2003. The ecology and management of wood in world rivers. American Fisheries Society, Symposium 37, Bethesda, Maryland. (i)

Gregory, S.V., F.J. Swanson, W.A. McKee, and K.W. Cummins. 1991. An ecosystem perspective of riparian zones: focus on links between land and water. Bioscience 41:540-551. (i)

Grizzel, J.D., and N. Wolff. 1998. Occurrence of windthrow in forest buffer strips and its effect on small streams in northwest Washington. Northwest Science 72: 214-223. (i)

Gurnell, A.M. 2003. Wood storage and mobility. Pages 75-92 *in* S.V. Gregory, K.L. Boyer, and A.M. Gurnell, editors. The ecology and management of wood in world rivers. American Fisheries Society, Symposium 37, Bethesda, Maryland. (i)

Gurnell, A.M., K.J. Gregory, and G.E. Petts. 1995. The role of coarse woody debris in forest aquatic habitats: implications for management. Aquatic Conservation: Marine and Freshwater Ecosystems 5:143-166. (i)

Gurnell, A.M., H. Piégay, F.J. Swanson, and S.V. Gregory. 2002. Large wood and fluvial processes. Freshwater Biology 47:601-619. (i)

Harmon, M.E., J.F. Franklin, F.J. Swanson, P. Sollins, S.V. Gregory, J.D. Lattin, N.H. Anderson, S.P. Cline, N.G. Aumen, J.R. Sedell, G.W. Lienkaemper, K. Cromack, and K.W. Cummins. 1986. Ecology of coarse woody debris in temperate ecosystems. Advances in Ecological Research 15:133–302. (i)

Hartman, G.F. 1965. The role of behavior in the ecology and interaction of underyearling Coho Salmon (*Oncorhynchus kisutch*) and steelhead trout (*Salmo gairdneri*). Journal of the Fisheries Board of Canada 22:1035-1081. (i)

Hassan, M.A., D.L. Hogan, S.A. Bird, C.L. May, T. Gomi, and D. Campbell. 2005. Spatial and temporal dynamics of wood in headwater streams of the Pacific Northwest. Journal of the American Water Resources Association 41:899-919. (i)

Henry, W.V., and V.C. Twitty. 1940. Contributions to the life histories of *Dicamptodon ensatus* and *Ambystoma gracile*. Copeia 1940:247-250. (i)

Heede, B.H. 1972. Influences of a forest on the hydraulic geometry of two mountain streams. Water Resources Bulletin 8:523-530. (i)

Hernandez, O., R.W. Merritt, and M.S. Wipfli. 2005. Benthic invertebrate community structure is influenced by forest succession after clearcut logging in southeastern Alaska. Hydrobiologia 533:45-59. (i)

Holland D.C. 1994. The Western Pond Turtle: habitat and history. Bonneville Power Administration, Wildlife Diversity Program, BP-62137-1, unpublished report, Portland, Oregon. (viii)

Hyatt, T.L., and R.J. Naiman. 2001. The residence time of large woody debris in the Queets River, Washington, USA. Ecological Applications 11:191-202. (i)

Hyatt, T.L., T.Z. Waldo, and T.J. Beechie. 2004. A watershed scale assessment of riparian forests, with implications for restoration. Restoration Ecology 12:175-175. (i)

Jackson, C.R., D.P. Batzer, S.S. Cross, S.M. Haggerty, and C.A. Sturm. 2007. Headwater streams and timber harvest: channel, macroinvertebrate, and amphibian response and recovery. Forest Science 53:356-370. (i)

Jamieson, B., and J. Braatne. 2001. Riparian cottonwood ecosystems and regulated flows in Kootenai and Yakima subbasins: impacts of flow regulation on riparian cottonwood forests of the Yakima River. BPA Report DOE/BP-00000005-3. Bonneville Power Administration, Portland, Oregon. (viii)

Johnson, L. B., D.H. Breneman, and C. Richards. 2003. Macroinvertebrate community structure and function associated with large wood in low gradient streams. River Research and Applications 19:199-218. (i)

Johnston, N.T., S.A. Bird, D.L. Hogan, and E.A. MacIsaac. 2011. Mechanisms and source distances for the input of large woody debris to forested streams in British Columbia, Canada. Canadian Journal of Forest Research 41:2231-2246. (i)

Jones, L.L.C., R.B. Bury, and P.S. Corn. 1990. Field observation on the development of a clutch of Pacific Giant Salamander (*Dicamptodon tenebrosus*) eggs. Northwestern Naturalist 71:93-94. (i)

Kauffman, J.B., R.L. Beschta, N. Otting, and D. Lytjen. 1997. An ecological perspective of riparian and stream restoration in the western United States. Fisheries 22:12-24. (i)

Keller, E.A., and F.J. Swanson. 1979. Effects of large organic material on channel form and fluvial processes. Earth Surface Processes 4:361-380. (i)

Latterell, J.J., and R.J. Naiman. 2007. Sources and dynamics of large logs in a temperate floodplain river. Ecological Applications 17:1127-1141. (i)

Liquori, M.K. 2006. Post-harvest riparian buffer response: implications for wood recruitment modeling and buffer design. Journal of the American Water Resources Association 42:177-189. (i)

Mack, R.N., and J.N. Thompson 1982. Evolution in steppe with few large, hooved mammals. American Naturalist 119:757-773. (i)

Martin, D.J., and L.E. Benda. 2001. Patterns of instream wood recruitment and transport at the watershed scale. Transactions of the American Fisheries Society 130:940-958. (i)

Martin, D.J., and R.A. Grotefendt. 2007. Stand mortality in buffer strips and the supply of woody debris to streams in Southeast Alaska. Canadian Journal of Forest Research 37:36-49. (i)

Maser, C.M., R.F. Tarrant, J.M. Trappe, and J.F. Franklin, editors. 1988. From the forest to the sea: a story of fallen trees. PNW-GTR-229. U.S. Forest Service, Pacific Northwest Research Station, Portland, Oregon. (viii)

May, C.L., and R.E. Gresswell. 2003. Large wood recruitment and redistribution in headwater streams in the southern Oregon Coast Range, USA. Canadian Journal of Forest Research 33:1352-1362. (i)

May, C.W., R.R. Horner, J.R. Karr, B.W. Mar, and E.B. Welch. 1997. Effects of urbanization on small streams in the Puget Sound Lowland Ecoregion. Watershed Protection Techniques 2(4):485-494. (i)

McAllister, L.S. 2008. Reconstructing historical riparian conditions for two river basins in eastern Oregon, USA. Environmental Management 42:412-425. (i)

McDade, M.H., F.J. Swanson, W.A. McKee, J.F. Franklin, and J.V. Sickle. 1990. Source distances for coarse woody debris entering small streams in western Oregon and Washington. Canadian Journal of Forest Research 20:326-330. (i)

Minckley, W.L., and J.N. Rune. 1985. Large woody debris in hot-desert streams: an historical overview. Desert Plants 7(3):142-153. (i)

Montgomery, D.R., and J.M. Buffington. 1997. Channel-reach morphology in mountain drainage basins. Geological Society of America Bulletin 109:596–611. (i)

Montgomery, D.R., J.M. Buffington, R.D. Smith, K.M. Schmidt, and G. Pess. 1995. Pool spacing in forest channels. Water Resources Research 31:1097-1105. (i)

Murphy, M.L., J. Heifetz, S.W. Johnson, K.V. Koski, and J.F. Thedinga. 1986. Effects of clear-cut logging with and without buffer strips on juvenile salmonids in Alaskan streams. Canadian Journal of Fisheries and Aquatic Sciences 43:1521-1533. (i)

Murphy, M.L., and K.V. Koski. 1989. Input and depletion of woody debris in Alaska streams and implications for streamside management. North American Journal of Fisheries Management 9:427-436. (i)

Naiman, R.J., E.V. Balian, K.K. Bartz, R.E. Bilby, and J.J. Latterell. 2002a. Dead wood dynamics in stream ecosystems. Pages 23-47 *in* W.F. Laudenslayer, P.J. Shea, B.E. Valentine, C.P Weatherspoon, and T.E. Lisle, technical coordinators. Proceedings of the symposium on the ecology and management of dead wood in western forests. PSW-GTR-181. U.S. Forest Service, Pacific Southwest Research Station, Portland, Oregon. (viii)

Naiman, R.J., R.E. Bilby, and P.A. Bisson. 2000. Riparian ecology and management in the Pacific coastal rain forest. BioScience 50:996-1011. (i)

Naiman, R.J., R.E. Bilby, D.E. Schindler, and J.M. Helfield. 2002b. Pacific salmon, nutrients, and the dynamics of freshwater and riparian ecosystems. Ecosystems 5:399–417. (i)

Naiman, R.J., C.A. Johnston, and J.C. Kelley. 1988. Alteration of North American streams by Beaver. BioScience 38:753-762. (i)

Naiman, R.J., and J.R. Sedell. 1979. Characterization of particulate organic matter transported by some Cascade Mountain streams. Journal of the Fisheries Research Board of Canada 36:17-31. (i)

Nakamura, F., and F.J. Swanson. 1993. Effects of coarse woody debris on morphology and sediment storage of a mountain stream system in western Oregon. Earth Surface Processes and Landforms 18:43-61. (i)

Nussbaum, R.A. 1969. Nests and eggs of the Pacific Giant Salamander, *Dicamptodon ensatus* (Eschsacholtz). Herpetologica 25:257–262. (i)

Olson, D.H., P.D. Anderson, C.A. Frissell, H.H. Welsh Jr., and D.F. Bradford. 2007. Biodiversity management approaches for stream–riparian areas: perspectives for Pacific Northwest headwater forests, microclimates, and amphibians. Forest Ecology and Management 246: 81-107. (i)

Parker, M.S. 1994. Feeding ecology of stream-dwelling Pacific Giant Salamander larvae (*Dicamptodon tenebrosus*). Copeia 1994:705-718. (i)

Pereira, C.R.D., and N.H. Anderson. 1982. Observations on the life history and feeding of *Cinygma integrum* (Eaton) and *Ironodes nitidus* (Eaton) (*Ephemeroptera: Heptageniidae*). Melanderia 39:35-45. (i)

Pereira, C.R.D., N.H. Anderson, and T. Dudley. 1982. Gut content analysis of aquatic insects from wood substrates. Melanderia 39:23-33. (i)

Piégay, H. 2003. Dynamics of wood in large rivers. Pages 109-134 *in* S.V. Gregory, K.L. Boyer, and A.M. Gurnell, editors. The ecology and management of wood in world rivers. American Fisheries Society, Symposium 37, Bethesda, Maryland. (i)

Pollock, M.M., T.J. Beechie, and C.E. Jordan. 2007. Geomorphic changes upstream of Beaver dams in Bridge Creek, an incised stream channel in the interior Columbia River basin, eastern Oregon. Earth Surface Processes and Landforms 32:1174-1185. (i)

Pollock, M.M., M. Heim, and D. Werner. 2003. Hydrological and geomorphic effects of Beaver dams and their influence on fishes. Pages 213-233 *in* S.V. Gregory, K.L. Boyer, and A.M. Gurnell, editors. The ecology and management of wood in world rivers. American Fisheries Society, Symposium 37, Bethesda, Maryland. (i)

Pollock, M.M., G. Lewallen, K. Woodruff, C.E. Jordan, and J.M. Castro, editors. 2015. The Beaver restoration guidebook: working with Beaver to restore streams, wetlands, and floodplains. Version 1.02. U.S. Fish and Wildlife Service, Portland, Oregon. (viii)

Powell, S.R., L.D. Daniels, and T.A. Jones. 2009. Temporal dynamics of large woody debris in small streams of the Alberta foothills, Canada. Canadian Journal of Forest Research 39:1159-1170. (i)

Ralph, S.C., G.C. Poole, L.L. Conquest, and R.J. Naiman. 1994. Stream channel morphology and woody debris in logged and unlogged basins of western Washington. Canadian Journal of Fisheries and Aquatic Sciences 51:37-51. (i)

Reeves, G.H., K.M. Burnett, and E.V. McGarry. 2003. Sources of large wood in the main stem of a fourth-order watershed in coastal Oregon. Canadian Journal of Forest Research 33:1363-1370. (i)

Reich, M., J.L. Kershner, and R.C. Wildman. 2003. Restoring streams with large wood: a synthesis. Pages 355-366 *in* S.V. Gregory, K.L. Boyer, and A.M. Gurnell, editors. The ecology and management of wood in world rivers. American Fisheries Society, Symposium 37, Bethesda, Maryland. (i)

Reimchen T.E., D. Mathewson, M.D. Hocking, J. Moran, and D. Harris. 2003. Isotopic evidence for enrichment of salmon-derived nutrients in vegetation, soil, and insects in riparian zones in coastal British Columbia. Pages 59-69 *in* J. Stockner, editor. Nutrients in salmonid ecosystems: sustaining production and

biodiversity. American Fisheries Society, Symposium 34, Bethesda, Maryland. (i)

Rhoads, B.L. 1988. Mutual adjustments between process and form in a desert mountain fluvial system. Annals of the Association of American Geographers 78:271-287. (i)

Richardson, J.S. 2008. Aquatic arthropods and forestry: effects of large-scale land use on aquatic systems in Nearctic temperate regions. The Canadian Entomologist 140:495-509. (i)

Robison, E.G., and R.L. Beschta. 1990. Identifying trees in riparian areas that can provide coarse woody debris. Forest Science 36:790-801. (i)

Roni, P., T.J. Beechie, G.R. Pess, and K.M. Hanson. 2014. Wood placement in river restoration: fact, fiction and future direction. Canadian Journal of Fisheries and Aquatic Sciences 72(3):466-478. (i)

Roni, P., and T.P. Quinn. 2001. Density and size of juvenile salmonids in response to placement of large woody debris in western Oregon and Washington streams. Canadian Journal of Fisheries and Aquatic Sciences 58:282–292. (i)

Roy, A.H., C.L. Faust, M.C. Freeman, and J.L. Meyer. 2005. Reach-scale effects of riparian forest cover on urban stream ecosystems. Canadian Journal of Fisheries and Aquatic Sciences 62:2312-2329. (i)

Schuett-Hames, D., A.E. Pleus, J. Ward, M. Fox, and J. Light. 1999. Method manual for the large woody debris survey. TFW-AM9-99-004. Forest Practices Division, Washington Department of Natural Resources, Olympia, Washington. (viii)

Sedell, J.R., P.A. Bisson, F.J. Swanson, and S.V. Gregory. 1988. What we know about large trees that fall into stream and rivers. Pages 47-80 *in* C.M. Maser, R.F. Tarrant, J.M. Trappe, and J.F. Franklin, editors. From the forest to the sea: a story of fallen trees. PNW-GTR-229. U.S. Forest Service, Pacific Northwest Research Station, Portland, Oregon. (viii)

Sedell, J.R., and K.J. Luchessa. 1981. Using the historical record as an aid to salmonid habitat enhancement. Pages 210-233 *in* N.B. Arementrout, editor. Acquisition and utilization of aquatic habitat inventory information. American Fisheries Society, Bethesda, Maryland. (i)

Sedell, J.R., F.J. Swanson, and S.V. Gregory. 1985. Evaluating fish response to woody debris. Pages 222-245 *in* T.J. Hassler, editor. Pacific Northwest stream habitat management workshop. Humboldt State University, Arcata, California. (viii)

Spence, B.C., G.A., Lomnicky, R.M. Hughes, and R.P Novitzki. 1996. An ecosystem approach to salmonid conservation. TR-4501-96-6057. ManTech Environmental Research Services Corporation, Corvallis, Oregon. (viii)

Spies, T., M. Pollock, G. Reeves, and T. Beechie. 2013. Effects of riparian thinning on wood recruitment: a scientific synthesis. Science Review Team Wood Recruitment Subgroup, Forest Science Laboratory, Corvallis, Oregon. (viii)

Steel, E.A., W.H. Richards, and K.A. Kelsay. 2003. Wood and wildlife: benefits of river wood to terrestrial and aquatic vertebrates. Pages 235-248 *in* S.V. Gregory, K.L. Boyer, and A.M. Gurnell, editors. The ecology and management of wood in world rivers. American Fisheries Society, Symposium 37, Bethesda, Maryland. (i)

Steele, C.A., and C. Brammer. 2006. Dietary overlap in giant salamanders (*Dicamptodon*): applying null models to resource partitioning. Western North American Naturalist 66:115-120. (i)

Stouder, D.J., P.A. Bisson, and R.J. Naiman, editors. 1997. Pacific salmon and their ecosystems: status and future options. Chapman & Hall, New York. (i)

Sullivan, K, T.E. Lisle, C.A. Dolloff, G.E. Grant, and L.M. Reid. 1987. Stream channels: the link between forests and fishes. Pages 30-97 *in* E.O. Salo and T.W. Cundy, editors. Streamside management: forestry and fishery interactions. Contribution No. 57. Institute of Forest Resources, University of Washington, Seattle. (viii)

Swanson, F.J., G.W. Lienkaemper, and J.R. Sedell. 1976. History, physical effects, and management implications of large organic debris in western Oregon streams. PNW-GTR-56. U.S. Forest Service, Pacific Northwest Research Station, Portland, Oregon. (viii)

Tschaplinski, P.J., and G.F. Hartman. 1983. Winter distribution of juvenile Coho Salmon (*Oncorhynchus kisutch*) before and after logging in Carnation Creek, British Columbia, and some implications for overwinter survival. Canadian Journal of Fisheries and Aquatic Sciences 40:452-461. (i)

Van Sickle, J., and S.V. Gregory. 1990. Modeling inputs of large woody debris from falling trees. Canadian Journal Forest Research 20:1593-1601. (i)

Ward, G.H., K.W. Cummins, R.W. Speaker, A.K. Ward, S.V. Gregory, and T.L. Dudley. 1982. Habitat and food resources for invertebrate communities in South Fork Hoh River, Olympic National Park. Pages 9-14 *in* E.E. Starkey, J.F. Franklin, and J.W. Matthews, editors. Ecological research in national parks of the Pacific Northwest. Forest Research Laboratory, Oregon State University, Corvallis, Oregon. (viii)

WDNR (Washington Department of Natural Resources). 2005. Forest practices habitat conservation plan. Forest Practices Division, Washington Department of Natural Resources, Olympia, Washington. (v)

Welsh, H.H., Jr., and A.J. Lind. 2002. Multiscale habitat relationships of stream amphibians in the Klamath-Siskiyou Region of California and Oregon. Journal of Wildlife Management 66:581-602. (i)

WFPB (Washington Forest Practices Board). 1987. Proposed forest practices rule and regulations: final environmental impact statement. Washington Forest Practices Board, Washington Department of Natural Resources, Olympia, Washington. (v)

WFPB (Washington Forest Practices Board). 2011. Board manual: standard methodology for conducting watershed analysis. Version 5.0. Appendix F: Fish habitat module. Washington Forest Practices Board, Washington Department of Natural Resources, Olympia, Washington. (v)

Wiggins, G.B. 1977. Larvae of North American Caddisfly Genera (Trichoptera). 1st Edition. University of Toronto Press, Ontario, Canada. (i)

Wilkins, R.P., and N.P. Peterson. 2000. Factors related to amphibian occurrence and abundance in headwater streams draining second-growth Douglas-fir forests in southwestern Washington. Forest Ecology and Management 139:79-79. (i)

Wing, M.G., and A. Skaugset. 2002. Relationships of channel characteristics, land ownership, and land use patterns to large woody debris in western Oregon streams. Canadian Journal of Fisheries and Aquatic Sciences 59:796-807. (i)

Wisseman, R.W., and N.H. Anderson. 1984. Mortality factors affecting trichoptera eggs and pupae in an Oregon coast range watershed. Pages 455-460 *in* J.C. Morse, editor. Proceedings of the 4th International Symposium on Trichoptera. Dr W. Junk Publishers, The Hague, Netherlands. (viii)

Wissmar, R.C. 2004. Riparian corridors of eastern Oregon and Washington: functions and sustainability along lowland-arid to mountain gradients. Aquatic Sciences 66:373-387. (i)

Wissmar, R.C., J.E. Smith, B.A. McIntosh, H.W. Li, and G.H. Reeves. 1994. A history of resource use and disturbance in riverine basins of eastern Oregon and Washington (early 1800s-1990s). Northwest Science 68 (special issue):1-35. (i)

Wondzell, S.M., and P.A. Bisson. 2003. Influence of wood on aquatic biodiversity. Pages 249-264 *in* S.V. Gregory, K.L. Boyer, and A.M. Gurnell, editors. The ecology and management of wood in world rivers. American Fisheries Society, Symposium 37, Bethesda, Maryland. (i)

Zalewski, M., M. Lapinska, and P.B. Bayley. 2003. Fish relationships with wood in large rivers. Pages 194-212 *in* S.V. Gregory, K.L. Boyer, and A.M. Gurnell, editors. The ecology and management of wood in world rivers. American Fisheries Society, Symposium 37, Bethesda, Maryland. (i)

Chapter 4. Stream Temperature

By: Kirk L. Krueger, Daniel J. Isaak, and Marc P. Hayes

4.1. Introduction

The great diversity of Washington's landscapes creates equally diverse stream thermal conditions (Figure 4.1). Broad ranges in elevation (0 -14,000 ft, 0 - 4,300 m), precipitation, stream size, topography, and other factors contribute to some streams having average summer temperatures as low as 39°F (4°C); whereas others only a few miles away may exceed 68°F (20°C). Much of that thermal heterogeneity is dictated by effectively immutable geomorphic attributes of landscapes (e.g., elevation, aspect, topographic slope), which affect the potential amount of solar radiation available at a given location (Boyd and Kasper 2003). However, the types of riparian vegetation and their condition also play important roles in determining the amount of solar radiation that reaches a stream's surface. Through management of riparian ecosystem conditions, especially vegetation, the spatiotemporal distribution of stream temperatures (i.e., thermal regime) (Boyd and Kasper 2003; Caissie 2006) can be affected, which in turn, directly and indirectly affect the survival and productivity of aquatic species (Beschta et al. 1987; McCullough 1999) including salmon.

Shade can substantially reduce the amount of direct (shortwave) solar radiation, usually the main cause of heating, that reaches a stream (Poole and Berman 2001). Indirect effects of riparian vegetation include, but are not limited to, maintenance of channel form and



Pink Salmon Oncorhynchus gorbuscha *moving upstream to spawn/Ned Pittman, WDFW*

hyporheic connectivity (Gregory et al. 1991; Stanford 1998; Poole and Berman 2001) that also affect stream temperatures (Boyd and Kasper 2003; Webb et al. 2008). Maintaining and restoring riparian ecosystem functions and the thermal regimes of aquatic systems is increasingly important in light of climate change and as land use intensifies. Land use can strongly influence the intensity, timing, duration, and geographic distributions (i.e., structure) of stream temperatures (NRC 2002).

In this chapter we briefly summarize the results of our literature review, and present a simple conceptual model that identifies components (environmental factors) and structures (relations of components) that affect stream temperatures, to facilitate understanding of potential effects of different management alternatives. We also briefly discuss considerations of the effects of riparian management on stream thermal regime within a watershed or stream network context, the sensitivity of some priority species to changes in stream thermal regime, and applications of current scientific information to riparian management for suitable thermal regimes for aquatic species. Much of the literature describing the effects of human activity on stream temperature has focused on summer maximum water temperatures. Increasingly, scientists are focusing on better understanding stream thermal regimes, which describe how the temperature of streams varies through time and throughout stream networks. This shift recognizes two important ideas: 1) fish and other aquatic organism use different stream habitats, defined in part by specific water temperature ranges, to complete their life cycle, and 2) heat energy inputs into streams are variable in space and time and heat energy is often carried downstream of the reach from which it was gained.

Our review of the scientific literature on the effects of riparian conditions on stream temperatures was extensive; including more than 6,000 articles relevant to riparian ecosystem research, of which more than 700 referenced stream temperatures and over 100 that referred to or reported measured effects of riparian ecosystem conditions on stream temperatures. Our work also identifies research to inform management recommendations that are applicable across a wide range of environmental conditions (e.g., various latitudes, topographies, and land uses). Further, we wanted to address the broad range of thermal conditions that are important to aquatic species (e.g., frequency, duration, intensity, and predictability of summer high temperatures and temperatures during incubation (Lytle and Poff 2004); and the geographic distribution of stream temperatures (Torgersen et al. 1999; Poole et al. 2001; Ebersole et al. 2003a). Therefore, we reference additional scientific information to provide the context that allows for better understanding and application of riparian ecosystem-specific information. Several reviews were particularly valuable in directing our efforts (e.g., Elmore and Kauffman 1994; May 2003; Moore et al. 2005; Sather and May 2007; Bowler et al. 2012; Czarnomski and Hale 2013).

Scientists are focusing on better understanding stream thermal regimes, which describe how the temperature of streams varies through time and throughout stream networks.

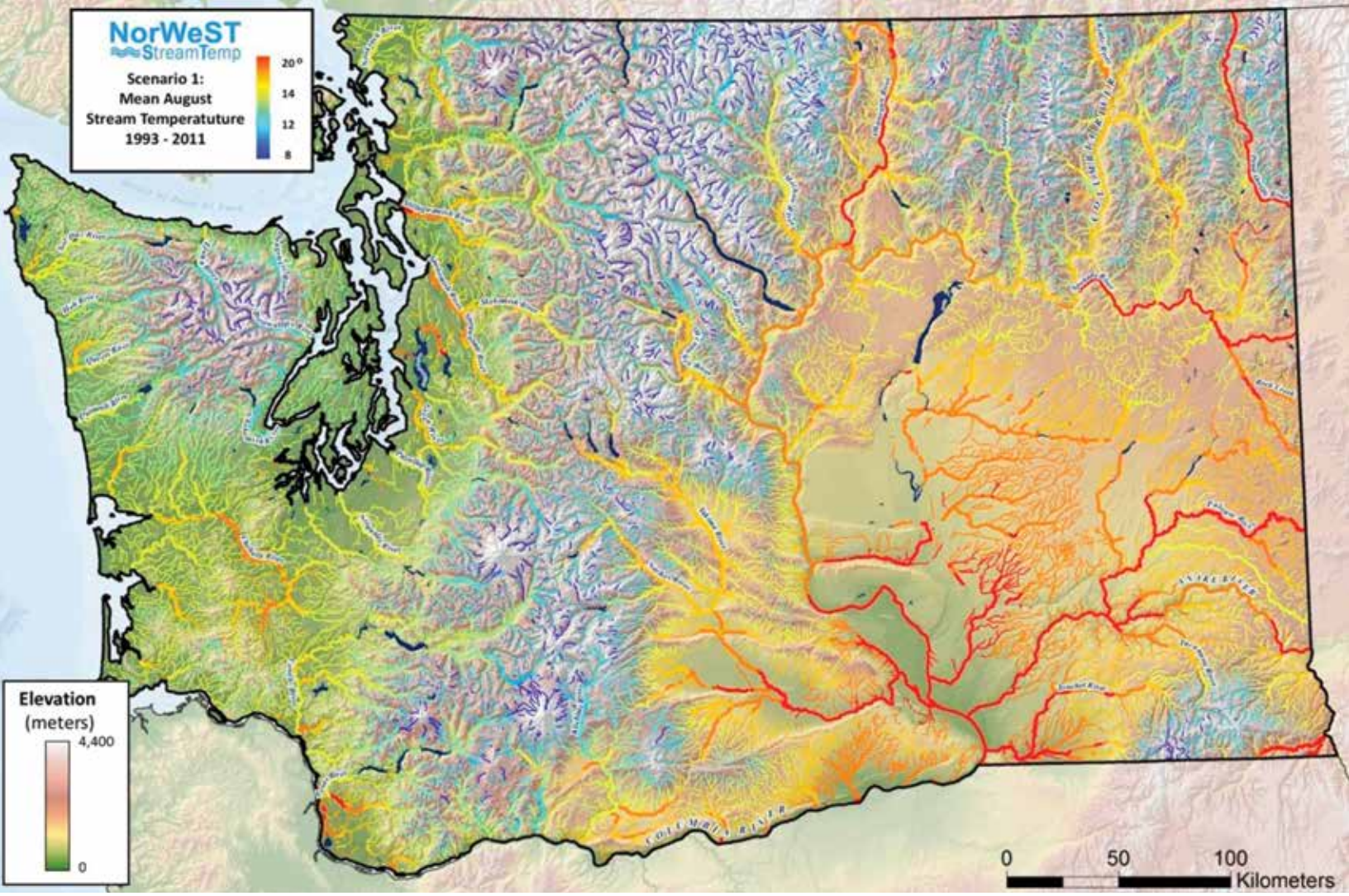


Figure 4.1. Stream thermalscape showing mean August temperatures for 66,236 kilometers (41,157 miles) of streams across Washington that was developed in the NorWeST project (poster available here: http://www.fs.fed .us/rm/boise/AWAE/projects/stream_temp/downloads/14NorWeST_WashingtonStreamTemperatureMap.pdf). Topographic and geomorphic complexity across the state creates significant thermal heterogeneity that is moderated locally by riparian conditions.

4.1.1. State of the Science

The scientific literature establishes a clear expectation that reduction of stream shade, especially due to vegetation removal, will result in warmer summer stream temperatures (e.g., Sridhar et al. 2004; Allen et al. 2007). The literature, derived primarily from descriptive (e.g., case study) and occasionally statistically predictive (e.g., generalization across many case studies) studies, demonstrates that riparian management can affect shade and in turn stream temperatures (Johnson 2004; Moore et al. 2005). The vast majority of those studies document an increase in a temperature statistic, often mean daily maximum temperature during summer, associated with a loss of shade (Johnson 2004; Moore et al. 2005; Bowler et al. 2012), but a few studies have shown mixed results (Johnson 2004; Moore et al. 2005; Janisch et al. 2012; Kibler et al. 2013).

Variability in stream temperatures among locations (Figure 4.1) and among some study results is due to both temporally constant attributes of landscapes (e.g., elevation, topographic slope, drainage area) and temporally variable attributes (e.g., stream wetted width, stream flow) that affect the potential amount of solar radiation available at a given location (Boyd and Kasper 2003) and the thermal sensitivity of the stream, respectively. The amount of solar radiation available is often referred to as thermal loading potential or

potential solar load. At a given thermal input or load, the temperature change responsiveness of a stream is often referred to as "thermal sensitivity" (Beschta et al. 1987; Moore et al. 2005). Thermal sensitivity is influenced by many physical factors. Streams with higher flows of surface and groundwater, and hyporheic exchange rates (Cristea and Burges 2010; Arismendi et al. 2012) tend to be relatively thermally insensitive. Wood loading, channel complexity and depth can also affect thermal load and sensitivity. The potential solar load in combination with thermal sensitivity (discussed in detail below) of locations across a stream network and through time largely determine a stream thermal regime.

In addition to solar radiation, other microclimate variables - such as air temperature, wind speed, and humidity - may affect instream water temperatures. Microclimate conditions interact with energy exchanges at the air-water interface (Figure 4.2) and can thereby affect stream thermal regimes (Moore et al. 2005; Benyahya et al. 2010), especially in small streams (Caissie 2016). However, we believe the effects of microclimate on the thermal regime of streams with fully functioning riparian ecosystems are minor for two reasons: 1) microclimate effects (e.g., changes in air temperature and humidity) at forest edges rarely extend farther than one tree height into mature riparian forest (Moore et al. 2005; Rykken et al. 2007; Reeves at al. 2018), and 2) sensible heat exchanges comprise only a small portion of total heat flux in streams (Johnson 2004; Moore et al. 2005). In fact, net solar radiation effects on stream temperatures are generally about an order of magnitude greater than sensible and latent heat exchanges at the air-water interface (Moore et al. 2005; D. Caissie, Fisheries and Oceans Canada, personal communication). However, we also agree with Reeves et al. (2018), who note that the range of effects measured in different studies suggests substantial uncertainties regarding riparian ecosystem management with respect to microclimate.

Riparian ecosystem-stream temperature research appears to be transitioning from largely local, descriptive (e.g., case study and generalizations of case studies) to predictive, mechanistic, and deterministic modeling across larger areas (e.g., Boyd and Kasper 2003; Allen et al. 2007). Mechanistic models attempt to include most of the factors that affect stream temperatures (Figure 4.2) in a given area and thus do not rely on statistical extrapolation from other locations. These types of models can provide relatively accurate and precise temperature predictions at various spatial and temporal scales (Leinenbach et al. 2013). Further, they can provide useful information on systems and processes that are not readily estimated through statistical approaches used in case studies. However, collecting the environmental data necessary for accurate prediction of the effects of riparian management actions on stream thermal regimes via mechanistic models is difficult and often prohibitively expensive (Allen et al. 2007). For example, studies on the effects of riparian ecosystem or land cover management on stream temperatures at large spatial extents (e.g., watersheds of large streams or rivers) and cumulative effects are very rare. Watershed-scale studies (e.g., Janisch et al. 2012; Kibler et al. 2013) are often limited to relatively small watersheds (e.g., 2 to 1,000 ha) and second order streams.

New types of statistical models for stream network data (Ver Hoef et al. 2006; Isaak et al. 2014) have been applied to large stream temperature databases (Isaak et al. 2017a) and these have enabled relatively accurate predictions (R^2 = 0.90; RMSE = 1.8°F or 1.0°C) and mapping of summer thermal conditions across all Washington streams (Figure 4.1). Those statistical approaches use predictor variables derived from broad geospatial and remotely sensed datasets (e.g., elevation, stream slope, riparian density from the National Land Cover Database) so they do not provide insights to local temperature anomalies that could be associated with alterations of riparian or channel conditions. However,

these statistical models do provide accurate thermal status maps that could be used with mechanistic models or field measurements to better ascertain the influence of riparian conditions on stream temperatures.

Scientific knowledge of the importance of stream temperatures on aquatic species has also advanced since the publication of Knutson and Naef in 1997; especially by better describing the importance of thermal regimes (rather than only extreme high temperatures) on fish survival, growth, and productivity (Ward and Stanford 1982; McCullough 1999; Caissie 2006; McCullough et al. 2009; Hinch et al. 2012). For example, the collapse of the Fraser River Sockeye Salmon *Oncorhynchus nerka* spawning run in 2009 was largely attributed to thermal exposure due to early migration, which resulted in indirect, but often fatal, effects (Hinch et al. 2012). Following Olden and Naiman (2010), we suggest that thermal regimes can be described by their rates of change, magnitude, frequency, timing, and duration, and also their spatial distribution in a stream. The timing and duration of thermal exposure, in addition to exposure to extreme temperatures, affects the survival and productivity of many aquatic species (Caissie 2006).

Importantly, studies such as those of Murphy and Hall (1981), Murphy et al. (1981), Hawkins et al. (1983), and Bilby and Bisson (1987) that demonstrated apparent beneficial effects of reduced riparian shade on an aquatic species, such as increased salmonid growth or abundance, can now be considered in a broader ecological context. It should be noted that in these studies observed temperature increases were small and apparent beneficial effects were attributed to increased solar radiation, primary production, and consequent bottom-up stimulation of the food web. These findings are consistent with the idea that oftentimes the biological effects of altered temperatures differ among locations (Li et al. 1994; Farrell et al. 2008), and that such differences in effects may be attributed to the difference between local temperature and the thermal niche of a species. For example, in reaches where temperatures are near a species' thermal maxima, additional warming will cause the habitat to become unsuitable. However, in streams that are too cold for a species, warmer temperatures may increase habitat suitability (Isaak and Hubert 2004; Isaak et al. 2017b). In addition to direct stream temperature changes on a single species, changes may affect ecological trade-offs between species. Rezende et al. (2014) showed that faster growth might also be associated with increased competition with non-native species (Lawrence et al. 2014).

Widespread alterations of upland and riparian conditions and subsequent changes in stream composition and structure have likely already impacted thermal conditions in many streams (Poole and Berman 2001) and such impacts will be further exacerbated by the ongoing effects of climate change (Isaak et al. 2012; Holsinger et al. 2014). Streams with degraded riparian conditions, however, also offer opportunities where restoration actions could mitigate future warming and improve ecological resilience by enhancing the survival and productivity of the populations and assemblages that use those systems.

4.2. Conceptual Model

We provide a conceptual model to help describe the important components, structures, and processes that affect stream temperatures and that can result in different effects of riparian management actions on stream temperatures among locations (Figure 4.2). Our conceptual model is largely a simplification of the model "Heat Source" in Boyd (1996) and Boyd and Kasper (2003) and developed based on the preponderance of scientific evidence. Heat Source is a deterministic, mechanistic model developed to predict dynamic open channel heat and mass transfer. As such, it includes parameters for all variables that are known

to significantly affect stream temperatures. Our simplified conceptual model describes components and parameters that can have a large effect on stream temperatures or that are affected by riparian ecosystem management. We provide this model in an attempt to improve basic understanding of stream thermal processes and to identify important composition, structure, and functions that are subject to management and that affect stream temperatures. Additional information based on the models of Poole and Berman (2001), Moore et al. (2005), and Leinenbach et al. (2013) are included to more clearly identify factors that affect thermal loading potential and stream thermal sensitivity via riparian management.

Scientific understanding of the environmental factors and their relations that affect stream thermal regimes is well developed, as demonstrated by the development of deterministic, mechanistic models (e.g., Boyd and Kasper 2003) that can provide accurate temperature predictions when sufficient data are available to run the model and when the stream system remains relatively stable. Such models have been applied successfully at the spatial extent of individual stream reaches (Cristea and Janisch 2007; Cole and Newton 2013) and watersheds (Coffin et al. 2011; Bisson et al. 2013; Booth et al. 2014), suggesting that our understanding of the composition, structure, and functions that affect stream temperatures are well understood and can be

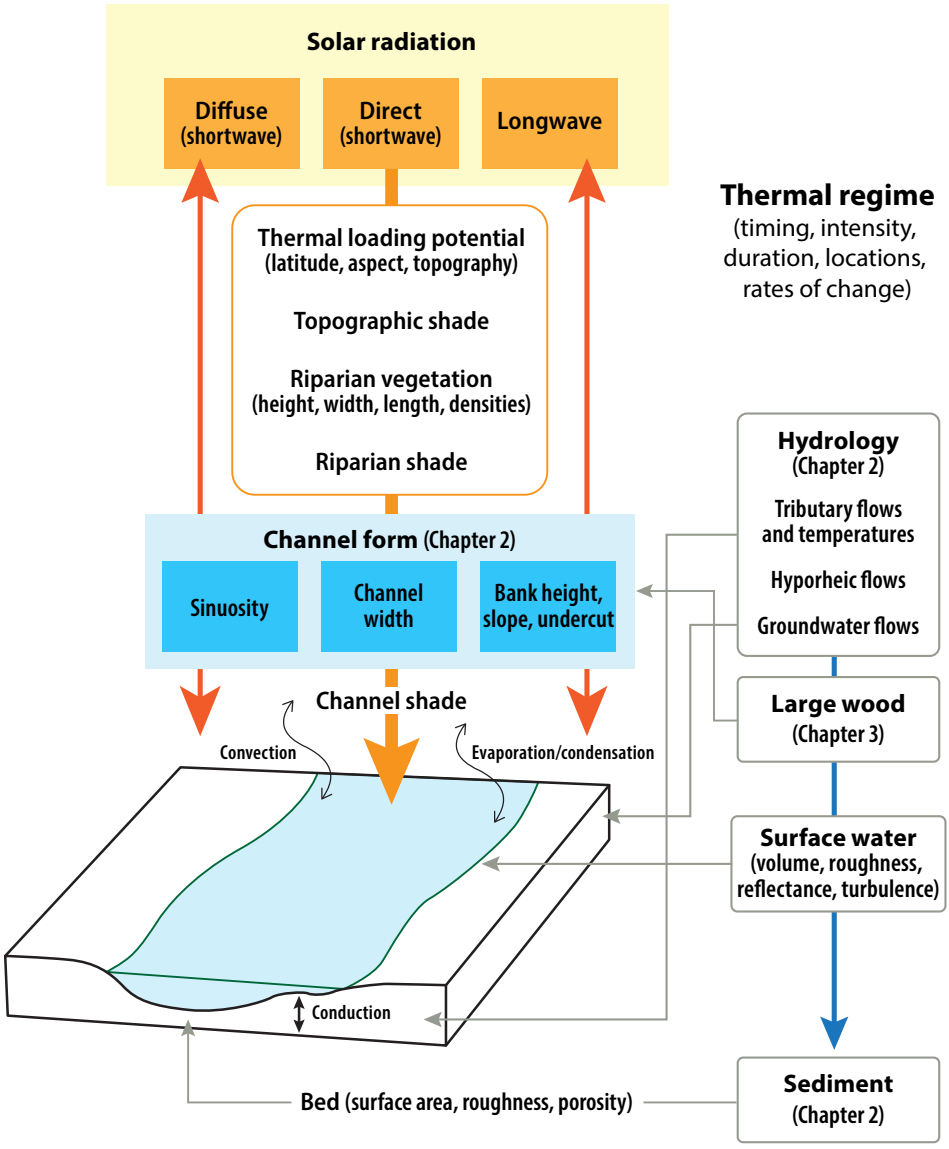


Figure 4.2. Conceptual model that identifies some factors that affect the thermal regime of stream networks. Relative importance is noted by line weight and arrows indicate directions of flows. Note that most of the elements in the model are influenced by human activities and that many components and structures are not presented here. See Boyd and Kasper (2003) for a more thorough review.



Dense tree canopies rarely provide 100% shade/Ned Pittman, WDFW

reliably applied to management problems. Rates of direct (shortwave) solar radiation reaching the stream surface and the volumes and temperatures of water are consistently identified as the dominant processes affecting the thermal regime of streams (Sinokrot and Stefan 1993; Johnson 2004). At many locations these two dominant processes are subject to management: direct solar radiation reaching a stream via vegetation management and water flows via water diversion, storage, and return (Olden and Naiman 2010).

The thermal loading potential of a stream reach is controlled in part by temporally constant and largely independent factors such as latitude, aspect, elevation, and topographic shading (Figure 4.2, Boyd and Kasper 2003; Janisch et al. 2012). Streams at high latitudes are less exposed to solar radiation, the ultimate source of heat energy to streams, than streams at low latitudes. Stream aspect affects stream temperatures because a stream's orientation relative to the path of the sun (which differs seasonally) determines the amount of direct solar radiation that a stream receives (Johnson 1971). Elevation affects the ambient air temperatures that streams are exposed to, as well as the dominant form and amount of precipitation (i.e., snow or rain). For these reasons, higher elevation streams are usually colder and commonly, although not always, less thermally sensitive than lower elevation streams (Luce et al. 2014). Topography can shade a stream from direct solar radiation and the effects of topography and aspect can interact. The effects of these four geographic factors can be difficult to detect (Isaak and Hubert 2001) and are likely responsible for some of the variability of the results of case studies that measured the effects of riparian management on stream temperatures. Note that some of these attributes (e.g., elevation) also affect the composition and structure of riparian vegetation. Stream thermal loading is not only controlled by independent factors such as latitude, aspect, elevation, and topographic shading. The scientific literature clearly identifies shade from riparian vegetation as important to stream temperatures, especially for small (narrow) streams (e.g., Beschta 1987; Poole and Berman 2001; Johnson 2004; Sridhar et al. 2004; Moore et al. 2005; Caissie 2006; Allen et al. 2007; Bowler et al. 2012; Garner et al. 2014). The effects of altered stream shading on temperatures is complex because thermal loading potential and thermal sensitivity of streams differ among locations. Some attributes, such as water volume, wetted width, and width-depth ratio can affect both thermal loading potential and thermal sensitivity (Cristea and Janisch 2007; DeWalle 2010). For a given volume of water, wider channels of the same length have a greater surface area that can intercept more direct solar radiation (Boyd and Kasper 2003) and also exchange more heat through atmospheric conduction. The width of a stream also affects the amount of shade that can be provided by topography and riparian vegetation (Cristea and Janisch 2007; DeWalle 2010). That is, riparian vegetation of given height, density, and width might shade a larger proportion of a narrow channel for a longer period than for a wide channel. Stream widths, especially wetted channel widths, are often much less temporally stable than the other factors that control thermal loading potential. Management actions that result in changes in stream width (e.g., over-grazing [Belsky et al. 1999; Chapter 2] and maintenance of wide forested riparian areas that can result in wide channels [Sweeney and Newbold 2014]) can increase thermal loading potential and thermal sensitivity.

While shortwave radiation input and water volume and temperature largely control temperature regime, longitudinal channel form (stream reach and cross section) can also affect stream temperature, for example, via high sinuosity and the presence of undercut banks (Frissell et al. 1986; Bisson et al. 2006). Channel form and features that increase stream roughness can store gravel (Buffington et al. 2004) and increase hyporheic exchange (Wondzell and Gooseff 2013) that, in turn, can affect stream temperatures by storing and releasing heat (Burkholder et al. 2008). Large wood can also store large amounts of gravel in some streams (Buffington et al. 2004) and affect channel form (Chapter 3; Keller and Swanson 1979; Abbe and Montgomery 1996; Konrad et al. 2005) which might subsequently affect stream temperatures. For example, sediment deposition due to instream large wood might increase hyporheic flow and stream width, which can subsequently effect stream temperatures. Steep or undercut banks can also provide shade (Boyd and Kasper 2003) which, in some locations (Ebersole et al. 2003b), can lower water temperatures at small spatial extents (e.g., individual pools; Ebersole et al. 2003a), even in large streams and rivers. Unfortunately, relatively few studies quantify the effects of channel form on thermal sensitivity and stream temperatures, which likely adds variability among stream temperature case studies and limits our ability to predict their relative importance at specific locations. Groundwater and tributary flows also affect stream temperatures (Malard et al. 2002) in two ways, 1) by adding volume and increasing flow velocity that can make streams less sensitive to thermal change (i.e., increasing thermal capacity), and 2) by adding water that is at a different temperature than receiving waters (Boyd and Kasper 2003; Story et al. 2003). However, the effects of groundwater flows can be difficult to detect due to spatiotemporal lags (Alvarez et al. 2004; Arrigoni et al. 2008) and difficult to apply to management due to the paucity of information describing groundwater flows. Additionally, side channels and wetlands can provide large volumes of water at different temperatures to receiving stream water (Bobba et al. 2010). Streambed attributes, such as porosity and surface area, are largely controlled by the flows of water and available sediment (see Chapter 2). Streambed attributes can affect the thermal regime of a reach by affecting heat conduction (Sinokrot and Stefan 1993), by regulating the amount and velocity of water flow through the streambed, and by controlling the rates and locations of groundwater flows (Malcolm et al. 2002). The effects of these processes on stream temperatures can be spatially and temporally discontinuous and dynamic, especially in systems where stream form is heterogeneous and dynamic (Wright et al. 2005; Wondzell 2012). Hyporheic flows often have little effect on average stream surface water temperatures except for small streams at low flows but can create discrete locations of cool water (Wondzell 2012) that may serve as important refugia for salmon. Hyporheic flows can be influenced by flow regulation (e.g., dams), which can reduce variation in both flows and temperatures that reduces the potential for hyporheic exchange to act as a thermal buffer (Ward and Stanford 1995; Poole and Berman 2001; Nyberg et al. 2008).



Juvenile salmon/Portia Leigh, WDFW

The interaction of complex in- and near-stream riparian ecosystem processes can lead to a cascade of events (i.e., a series of related events triggered by single event) and new system states (Pringle and Triska 2000; Allan 2004). These cascading events are almost impossible to predict. For example, the removal of riparian trees typically reduces shading and increases solar radiation to the stream. Even when reductions in shade have a small direct effect on stream temperatures, the loss of trees can increase bank susceptibility to erosion (Chapters 2 and 3; Micheli and Kirchner 2002; Gomi et al. 2004) resulting in a wider stream that increases thermal loading and thermally sensitivity of the stream. Similarly, channel incision resulting from riparian management, may increase local topographic shading to the stream, but lower streambed and water elevations that can shift the riparian vegetation composition and structure. This shift in riparian vegetation can result in less stable streambanks and less riparian shade that ultimately offsets any benefits of topographical shading on water temperature (Toledo and Kauffman 2001). The results of such interactions are difficult to predict because they rely on accurate predictions of changes to stream morphology, vegetation composition and structure (which interact and have non-linear responses), and water and sediment flows (which can be stochastic).

The processes that affect the timing, duration, and geographic distribution of stream temperatures are complex due to the variability of the environment in which these processes occur (Figure 4.2). The relative importance of these ecological processes differs among locations and through time (Poole and Berman 2001; Webb et al. 2008). Scientific literature is clear about the expected effect of reducing stream shading, especially during summer; water gets warmer, particularly peak temperatures. Science is less able to provide accurate and precise predictions of the effects of specific riparian management measures. For example, the studies presented in Figure 4.3 represent statistical models relating changes in riparian buffer width to changes in stream temperature. Data in Figure 4.3 are collected by measuring stream temperature before and after a reduction in the width of a forested riparian buffer which in turn decreases shade to the stream. Model output (prediction) is change in temperature related to specific buffer widths. The models tell us that reducing shade usually increases stream temperatures (following the shape of the dotted line connecting points), but they cannot predict exactly how much shade reduction will result in a specific temperature increase. A manager attempting to use the statistical model in Figure 4.3 to predict how a reduction from a fully forested site to a 30-foot wide buffer might affect summer stream temperatures is confronted with a range of possible answers. Those answers fall within the 90% credible intervals for one study representing a change between 1.25 and 2.25°C (2.25 and 4.05°F), and for another study between -0.5 to nearly 5.0°C (-0.9 to nearly 9.0°F). Uncertainty in this case describes our inability to accurately predict exact outcomes. While rarely applied due to their expense, mechanistic models and attendant data (e.g., hyporheic flows and temperatures) provide the best approach for predicting accurate site-specific outcomes from management.

Fortunately, the literature is very clear that solar radiation is often the dominant factor affecting stream heat budgets during all seasons except winter (Webb et al. 2008). Results of case studies can prove very useful by clearly describing the expected direction and shape of the relations between attributes of riparian ecosystems (e.g., width of vegetation) and stream shade and temperature. Importantly, riparian shade is often directly amenable to management and in many locations riparian vegetation height and density may be more closely associated with shade than width of riparian vegetation per se (DeWalle 2010). In any case, the literature is very clear about the importance of riparian vegetation for providing shade to streams (Figure 4.3a).

4.3. Species Sensitivity

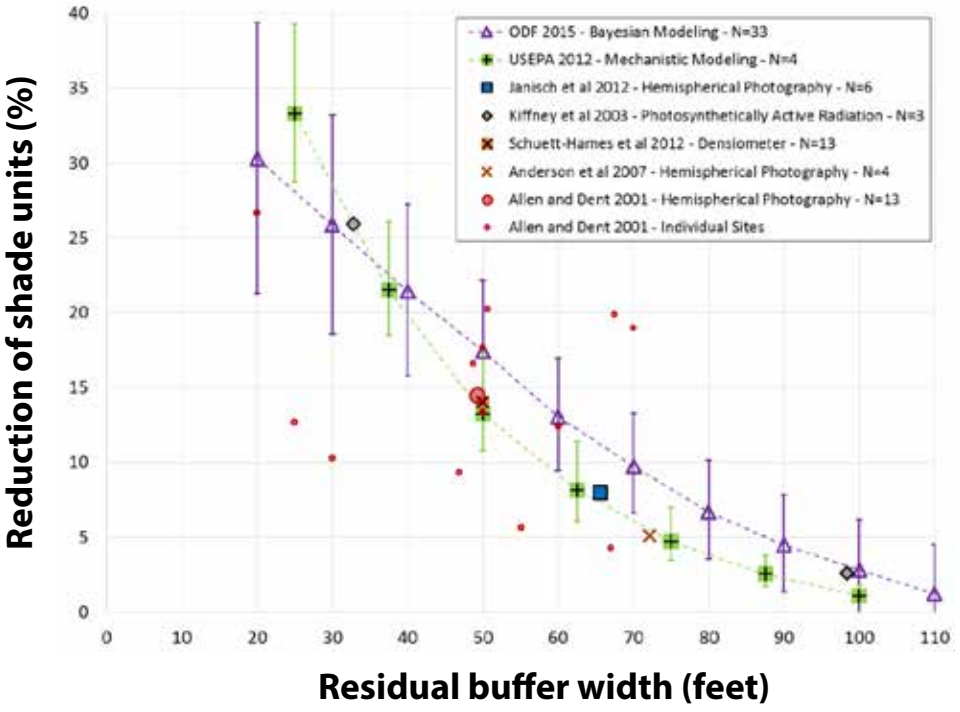
4.3.1. Fish

The scientific literature describing the importance of temperature, especially high temperatures, to fish is extensive (e.g., Brett 1952, 1971; Brett et al. 1969; Richter and Kolmes 2005). As aquatic ectotherms, the physiology of fish are strongly affected by water temperatures (McCullough et al. 2001; Welsh et al. 2001). Studies have frequently found associations between temperature and the geographic distribution (Welsh et al. 2001), spawn timing (Hodgson and Quinn 2002), growth rates, egg development and survival, competitive interactions, life stage survival, and behavior of fish (McCullough 1999; McCullough et al. 2009). Salmonids have frequently been studied because of their cultural and economic importance and their relative sensitivity to high temperatures, narrow thermal tolerance, and narrow aerobic scope (Farrell et al. 2008; Eliason et al. 2011; Ayllon et al. 2013). Summer temperature information is useful for identifying acute problems, but may be insufficient for ensuring population resilience because indirect effects and exposure to altered thermal regimes, not just extreme summer temperatures, can affect fish survival and productivity (McCullough 1999).

Recent research has increasingly focused on the effects of water temperatures and thermal regimes for fishes that have narrow thermal tolerance (i.e., range of suitable temperatures) or aerobic scope (Farrell et al. 2008; Eliason et al. 2011; Ayllon et al. 2013). This work is particularly relevant to salmonids in the Pacific Northwest that have life histories adapted to historical, location-specific thermal regimes (Brannon et al. 2004; Farrell et al. 2008; Eliason et al. 2011). Much of this research is related to the increasing threats posed by climate change, and some studies have already found evidence of existing, detrimental effects of increased stream temperatures on fish. For example, Isaak et al.



Juvenile anadromous salmon can spend up to 3 years in streams depending on the species/Ned Pittman, WDFW



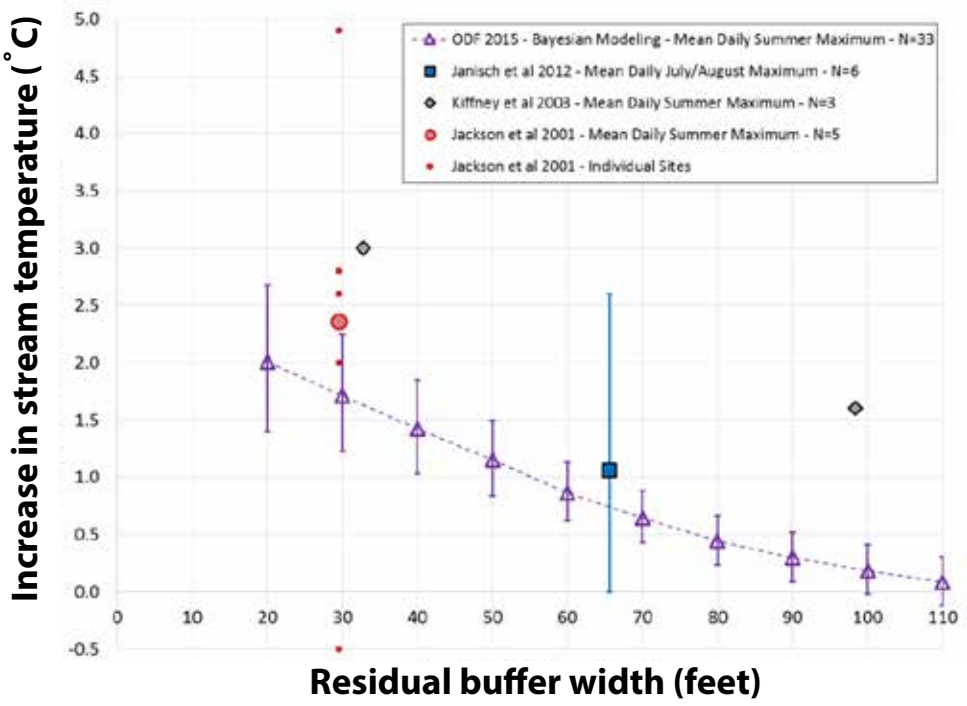


Figure 4.3. Observed shade (a: top panel) and temperature response (b: bottom panel) associated with "no-cut" riparian buffers with adjacent clearcut harvest. Only studies that employed a Before-After-Control-Impact design and conducted in Pacific Northwest forests are included. Shade unit is percent from completely shaded. Bayesian modeling results (and 90% credible intervals) were derived from data collected as part of Groom et al. (2011). Analyses provided by P. Leinenbach, USEPA Region 10.



Chum Salmon Oncorhynchus keta *in spawning colors/Ned Pittman, WDFW*

(2010, 2015) found increases in stream temperatures would result in losses of Bull Trout *Salvelinus confluentus* and Cutthroat Trout *Oncorhynchus clarkii* habitats, but also that especially cold streams could serve as climate refugia during the 21st century. Additionally, a number of recent studies have described some complex effects of altered thermal regimes to the productivity and survival of fish at different life stages and dramatic differences in thermal tolerance and aerobic scope among populations and species. For example, Hinch et al. (2012) describe complex links between the physiology, behavior, environment, disease exposure, and the effect of thermal exposure, on the population-specific survival of migrating Sockeye Salmon. Hodgson and Quinn (2002), Keefer et al. (2007), Strange (2010) and others have documented that high temperatures and previous thermal exposure can inhibit fish migration, and Marsh (1985) and Kappenman et al. (2013) have documented that high and low temperatures can impede spawning and embryo development and that optimal temperatures for embryo survival and development differ among species. Steel et al. (2012) found that thermal variability (without changing mean temperature) can affect the emergence timing and development of Chinook Salmon *Oncorhynchus tshawytscha*.

The literature is conclusive about the importance of stream thermal regimes to fish survival and productivity and also demonstrates wide variability in sensitivity to altered thermal regimes among species and among populations within species (Steel et al. 2012). More research would help us fill the sizeable gap in our understanding of the risk posed by altered thermal regimes on the survival and productivity of populations of salmonids or non-salmonid fishes, and on the ecological interactions that affect survival, productivity and population viability. For example, the time of hatching (i.e., duration of incubation) of salmonid eggs is largely determined by their thermal exposure during incubation. Relatively small changes in temperature can advance or delay maturation and subsequently hatching date (Groot and Margolis 2010) and effects of temperature can differ among closely related populations of the same species that spawn in different habitats (Hendry et al. 1998). Regardless of the ultimate cause, changes in thermal regimes can, for example, uncouple trophic interactions due to temporal mismatches, such as fry emerging when their preferred food is not available to them (Winder and Schindler 2004; Post et al. 2008). Altered thermal regimes can also affect other life stages by altering the timing of parr-smolt transformation (Zaugg and Wagner 1973), the duration of freshwater rearing (Sauter et al. 2001) which can affect ocean survival (Weitkamp et al. 2015), and the timing and success of spawning migration (Crossin et al. 2008). Altered thermal regimes can also affect ecological interactions. For example,

Wise management of riparian and aquatic systems would ideally consider the distribution and dynamics of stream temperatures in space and time and at scales that are relevant to the species in the region.

Lawrence et al. (2014) demonstrated that higher stream temperatures can expand the geographic distribution of non-native Smallmouth Bass *Micropterus dolomieu* and increase their predation on salmon. These results are complicated by the fact that effects of altered thermal regimes often differ among populations and life stages of a species, and among species (Brett 1971; Zaugg and Wagner 1973) which makes prediction of the exact effects of any riparian shade reduction and subsequent effects on stream thermal regime on fish survival and productivity uncertain. This uncertainty is compounded by fish behavioral responses, such as daily and seasonal movement among locations where thermal conditions differ (Torgersen et al. 2001).

Our understanding of the importance of altered thermal regimes on fish has improved substantially since the publication of Knutson and Naef (1997). Discussion of stream temperature by Knutson and Naef (1997) focused mostly on summer high temperatures and their effects on fish, but did not identify many components and structures of ecosystems that can affect stream temperatures or the importance of thermal regimes to fish. In particular, more recent studies are able to measure thermal exposure of fish through time, occasionally in field conditions, and estimate physiological attributes such as growth rate (Sauter and Connolly 2010).

Most studies calculate a single statistic that describes an important attribute of a stream's thermal regime (e.g., mean maximum daily summer temperature) and identify species, population, or life stage attributes that are correlated with that statistic, such as a critical thermal limit. These studies have been useful for demonstrating the importance of temperature and for setting some management objectives. However, they are insufficient for effective, long-term management of perturbed systems because changes in temperature means (i.e., chronic exposure) or extremes (i.e., acute exposure) can result in different selective pressures and evolutionary responses (Rezende et al. 2014) and because life stages, populations, and species differ widely in their sensitivity to altered thermal regimes (Farrell et al. 2008; Hinch et al. 2012). Further, we now better understand that many individual fish and especially populations use (and perhaps are dependent on) a dynamic mosaic of habitats (Fausch et al. 2002; Ward et al. 2002; Wiens 2002); that is, they move between discrete locations with different temperatures (Torgersen et al. 1999). Such movement among "patches" can be important to individual survival and population persistence because thermal conditions at discrete locations can be highly temporally variable (Dugdale et al. 2013) and spatially complex (Fullerton et al. 2015). Management of stream thermal regimes should carefully consider the spatiotemporal distribution and dynamics of thermal conditions at scales that are relevant to the species in the region (Fausch et al. 2002) at durations that are relevant to the rates of system change and recovery from disturbance.

4.3.2. Amphibians and Reptiles

Few studies address the effects of altered thermal regimes on stream-associated amphibians and reptiles, which currently limits the level of specificity to which reliable management recommendations can be made. However, some important insights are possible and these are best discussed in the context of breeding habitat: 1) amphibians that breed in the flowing portions of stream networks, and 2) amphibians and reptiles that breed in or use off-channel stillwater habitats associated with stream networks.

Instream-breeding amphibians (giant salamanders, *Dicamptodon* spp.; tailed frogs, *Ascaphus* spp.; and torrent salamanders, *Rhyacotriton* spp.) are generally described as having low thermal requirements (Bury 2008). However, those requirements are often characterized solely in terms of critical thermal maxima (Brattstrom 1963; Claussen 1973; Brown 1975; Bury



*Giant salamanders (*Dicamptodon *spp.) can be found in small western Washington streams/Eric Lund, WDFW*

2008), while stream temperatures in which these species are found are considerably lower than those maxima (invariably ≤61°F [16°C]; e.g., Brattstrom 1963; Welsh 1990; Welsh and Lind 1996; Pollett et al. 2010). Moreover, water temperatures at which these species first become stressed are entirely unknown. Several studies demonstrate higher density or relative abundances (Stoddard and Hayes 2005; Pollett et al. 2010) of amphibians at the margin of their temperature maxima although the mechanism responsible for this effect is unclear. Similar to fish, identifying critical effects of temperatures on amphibians is complicated by a host of potential variables, e.g., younger life stages frequently have cooler temperature requirements (de Vlaming and Bury 1970; Brown 1975) than older life stages. Importantly, very little research has been conducted on the effects of altered thermal regimes on the timing of life history events, such as the time of hatching, and indirect effects, such as possible ecological temporal mismatches, altered predator-prey relations, and disease frequency and effect (e.g., Hari et al. 2006), that would be useful for identifying important conservation and management actions.

Amphibians and reptiles that breed or utilize riverine off-channel stillwater habitats (e.g., oxbow lakes and permanent and seasonally flooded riverine wetlands) associated with stream networks generally have warmer thermal requirements than instream breeding amphibians. For stillwater-breeding amphibians, thermal requirements vary as a function of the thermal tolerance limits of a specific life stage (often eggs and embryos), which determine the seasonal interval in which they lay eggs. For example, Northern Red-legged Frog *Rana aurora* embryos have the lowest critical thermal maximum of any North American frog (about 68°F or 20°C) (Licht 1971), and they oviposit in late winter, at which time surface water temperatures of stillwater habitats rarely if ever put its embryos at risk. Except for our two turtle species (Western Pond Turtle *Actinemys marmorata* and Western Painted Turtle *Chryemys picta*) and selected garter snake species *Thamnophis*, especially the Common Garter Snake *T. sirtalis* and the Western Terrestrial Garter Snake *T. elegans,* few reptiles utilize aquatic habitats in the Pacific Northwest. These reptiles have



Riparian corridor/Ned Pittman, WDFW

thermal requirements that are more elevated than the temperatures generally found in stillwater habitats except during the warmest part of summer. For this reason, aerial basking (basking out of water) at daytime temperatures that are warmer than water temperature can be critical for these species for effective digestion of food or production of eggs. This pattern is especially important for turtles that need aquatic aerial basking sites isolated from predators, which in most stillwater habitats are provided by large downed wood with relatively level accessible surfaces above the water line (Holland 1994).

4.3.3. Invertebrates

Few studies have examined the effects of altered thermal regimes on stream-associated invertebrates in the Pacific Northwest. However, broad relationships between the geographic distributions of invertebrates and their thermal tolerance have been reported (Beschta et al. 1987; Moulton et al. 1993) as have changes in emergence timing and asynchronous emergence among sexes due to small increases in summer temperatures (Li et al. 2011), demonstrating the importance of temperature to invertebrates. Stream temperature can affect invertebrate density, growth, size at maturation, and sex ratios and the effects often differ among species (Hogg and Williams 1996). Altered stream thermal regimes appear to have important effects on many invertebrates and, subsequently, on stream food webs. Indirect effects such as altered predator-prey relations and disease frequency may also be important but have not been well studied. Riparian ecosystem management for aquatic invertebrates is also constrained by a general lack of information on their geographic distribution.

4.3.4. Species Sensitivity Summary

Management of vegetation in riparian ecosystems can affect stream temperatures and, subsequently, fish, amphibian, and invertebrate abundance and survival. Stream temperature influences important food web and energetic interactions between fish, amphibians, and invertebrates in multiple direct ways and likely in more subtle but relatively unstudied indirect ways (Baxter et al. 2005). The effects of thermal regime has received little study for amphibians and invertebrates. Fortunately, our understanding of the mechanisms that affect stream thermal regime can provide useful guidance in the absence of better information.

4.4. Land Use Effects

4.4.1. Urbanization

There have been very few studies specifically relating urbanization to riparian ecosystem function and subsequent effects on stream thermal regimes (Paul and Meyer 2001). Clearly, urbanization related changes to riparian areas can be similar to riparian changes associated with agriculture and forestry as far as stream temperature is concerned, e.g., removal of shade, reduction in large wood inputs. Urban areas have additional issues that can affect stream temperatures including heat island

effects, and inputs of wastewater and runoff from impervious surfaces (Kinouchi et al. 2006; Hester and Doyle 2011). Some of these complicating factors may contribute to the absence of detectable effects on stream temperatures studies in some comparative studies (Wahl et al. 2013). Nonetheless, urbanization is considered to have adverse effects on stream temperatures (LeBlanc et al. 1997; Finkenbine 1998), especially when riparian functions are affected (Booth et al. 2001). To protect stream thermal regimes in urban settings, conservation efforts should focus on maintaining riparian functions, mitigating anthropogenic changes to hydrology, and preserving watershed connectivity (e.g., movement of water, sediment, wood, nutrients, and species).

4.4.2. Agriculture

In comparison to urbanization studies, studies of the effects of agricultural practices on riparian ecosystems or subsequent effects on stream thermal regimes are fairly abundant, especially for grazing lands (e.g., Li et al. 1994; Tait et al. 1994; Maloney et al. 1999; Zoellick 2004) and crop lands (e.g., Waite and Carpenter 2000). Studies examining the effects of agriculture, particularly livestock grazing, generally find stream temperature increases associated with disturbance of the riparian ecosystem (Zoellick 2004; Webb et al. 2008). Livestock use of streamside areas can increase a stream's exposure to direct sunlight by reducing shade from streamside vegetation (Li et al. 1994). Livestock can also reduce the amount of undercut banks and increase stream channel width through trampling and vegetation removal (Belsky et al. 1999; Chapter 2). Channel widening can also result in reduced depth, which can exacerbate warming (Poole and Berman 2001). However, results of observational studies are mixed, with occasional absences of predicted detectable increases in stream temperature due to changes in riparian ecosystems as a result of agriculture (e.g., Tait et al. 1994) and wide variation in effect on riparian vegetation among locations and types of agriculture (see Maloney et al. 1999). Importantly, Zoellick (2004) found that riparian vegetation can recover after removal of the disturbance agent (e.g., livestock). For crop lands, the importance of riparian ecosystem attributes, e.g., vegetation width, height and density, on stream temperatures have been documented (Waite and Carpenter 2000) and, similar to grazed lands, effects differ widely among locations (Benedict and Shaw 2012).

Studies of the effects of land management on riparian functions and stream temperatures confirm the importance of riparian ecosystems to stream thermal regimes.

4.4.3. Forestry

Relative to urbanization and agriculture, many studies in the Pacific Northwest have examined the effects of forest management on stream temperatures. Decades of research have frequently documented increased stream temperature due to forestry practices (Olson and Rugger 2007), and our understanding of the mechanisms by which forest practices affect stream temperatures is well developed (Beschta et al. 1987; Groom et al. 2011). Most studies find that forestry, especially when riparian vegetation is disturbed, results in higher stream temperatures than in less disturbed locations (Li et al. 1994), however, exceptions to this pattern are not uncommon. For example, Liquori and Jackson (2001) found stream temperatures 3 to 7°F (1.5 to 4°C) greater in stream reaches surrounded by dense riparian forests compared to downstream reaches

adjacent to scrub-shrub riparian communities.
Many of the studies of the effects of forestry on stream temperatures include consideration of some of the components and structures that affect stream thermal regimes identified by Boyd and Kasper (2003) and Poole and Berman (2001). For example, Liquori and Jackson (2001) suggest that their results are due to lower width-to-depth ratio, higher rates of hyporheic or groundwater exchange, and greater amounts of shade in shrub-scrub associated reaches. Maloney et al. (1999) found that much of the variation in their results (in mostly agricultural settings) was explained by reach length, shade, elevation, aspect, and especially by stream gradient and air temperature. Similarly, Kiffney et al. (2003) and Janisch et al. (2012) described the influence of groundwater and hyporheic exchange on their results.

4.4.4. Land Use Summary

Studies of the effects of land management, especially the many studies of forestry, on riparian functions and stream temperatures confirm the importance of riparian ecosystems to stream thermal regimes. Additionally, they emphasize the high degree of variability among locations of the functions that affect stream thermal regimes, even among adjacent stream reaches, that so often produce variable results. Unfortunately, studies that examined the effects of land management on the complete thermal regime of a stream are lacking. Such studies could be especially valuable because the cumulative effects of riparian ecosystem or upland management on stream temperatures can dominate local effects (Chapter 8). Further, most studies use only a few statistics that describe peak or average temperatures, usually during summer. Such statistics are useful, but have limited ability to address dynamic, water quality parameters including temperature (Poole et al. 2004) related to species needs. Thus, predicting the effects of land management on other thermal attributes (e.g., duration or frequency of stressful temperatures) or during other seasons when thermal exposure can significantly affect some species (e.g., overwinter incubation) is difficult. Similarly, even cumulatively, the relatively small number of studies and their skewed geographic distribution (i.e., most are on low-order streams in maritime regions) constrain our ability to provide broad and precise generalizations or make accurate predictions to other locations. Conservation efforts for maintaining stream thermal regimes must be based on our understanding of direct and indirect mechanisms of stream heating affected by human activities, wise use of statistical models relating shade and stream temperature across the watershed until mechanistic models become available, and preserving watershed connectivity (e.g., movement of water, sediment, wood, nutrients, and species).



Light through alder tree canopy/Ned Pittman, WDFW

4.5. Conclusions

Scientific understanding of the structure and function of streams and the importance of thermal regimes has improved substantially since the publication of Knutson and Naef (1997). This understanding underscores the need to consider temperature statistics other than the daily maximum temperature during summer. We now have mechanistic,



Giant salamander (Dicamptodon *spp.*) *egg cluster/Jack Armstrong, WDFW*

deterministic models that can accurately predict changes in stream temperatures for specific locations due to specific management actions in the riparian ecosystem. We are also better able to set directional or qualitative expectations for cumulative effects on temperatures at the spatial extent of watersheds. However, quantitative information needed to run mechanistic, deterministic models to make site-scale predictions (e.g., surface water and groundwater flows and temperatures) is expensive to collect and thus are rarely used in management settings. Further, even the most capable stream temperature predictive models are limited by the assumption that the channel structure remains relatively stable (e.g., cross-section shape will not change) even though there is strong evidence that riparian and some types of upslope management affects channel stability (Chapters 2 and 3) at least in some reach types.

Scientific models and most observational studies find that shade from riparian vegetation can affect stream thermal regimes, particularly by lowering peak temperatures during summer. Recent monitoring studies have found substantial variation in the thermal sensitivity of apparently similar stream reaches. The use of improved monitoring tools (e.g., digital temperature loggers), more robust study designs e.g., Before-After-Control-Impact designs (Eberhardt 1976; Stewart-Oaten et al. 1986), more powerful statistical analyses (Gomi et al. 2006; Isaak et al. 2014), and longer study durations have improved our ability to detect effects of riparian management actions on stream temperatures. Importantly, better understanding of the structure and function of streams, especially the importance of surface, ground, and hyporheic water flows on stream temperatures, has allowed scientists to identify likely causes for failures to detect effects of riparian shade reductions on stream temperatures.

Scientific understanding of the importance of stream temperatures on aquatic species has improved substantially over the past two decades, especially for salmonids. Most studies provide useful descriptions of some direct effects of exposure to high temperatures on specific life stages. Laboratory and field studies demonstrated the importance of temperature on fish survival and allowed for comparisons among species, populations, and life stages, and thus the identification of those that are likely most sensitive to heat stress. They have also demonstrated substantial differences in sensitivity among species, populations, and life stages which make developing simple thermal standards challenging and likely inadequate for management. Several recent studies have described effects of prolonged exposure to elevated, but non-lethal, temperatures and altered thermal regimes. These studies demonstrate some of the complexity of this management challenge. Even when altered thermal regimes do not have immediate lethal effects on species, there are costs or trade-offs, such as changes in growth, survival, productivity, and energetic requirements. Detecting such effects is beyond the scope of most studies and will often require long-term, comprehensive monitoring of populations through several life cycles. Such studies will likely need to be conducted at spatial



Salmon eggs in Morse Creek/Steve Boessow, WDFW

extents and durations that account for fish behavior, such as daily and seasonal movement among locations where temperature regimes differ.

Relatively few studies that describe the effects of temperatures or thermal regimes on reptiles, amphibians or invertebrates have been completed. Most studies of these taxonomic groups have simply identified seasonal thermal preferences in the field or the effects of acute temperature in laboratory settings. Such studies are valuable for identifying thermally sensitive species, but are insufficient for management. Further, we found no study that addressed ecological interactions that might be mediated by riparian condition on a stream's thermal regime.

Studies generally show that the effects of urbanization, agriculture, and forestry on watershed and riparian ecosystems result in warmer summer stream temperatures, an expectation consistent with the conceptual model. Importantly, these land uses often include surface water routing to streams (e.g., roads and ditches) that can change the timing, intensity, duration, and temperatures of stream flows. The changes in temperature detected differed among regions, land uses, and studies. The relatively low number of studies and high variability among study results limits our ability to accurately predict outcomes in unstudied locations and precludes us from reliably calculating a mean (i.e., expected) resulting temperature change, even for a specific temperature statistic. Of the studies we reviewed, most were designed to detect an effect using a specific stream temperature statistic (e.g., mean daily maximum summer temperature) rather than changes in the stream's thermal regime. This limits the inferences that can be made, especially from studies in which anticipated temperature changes were not detected, and to make reliable, precise generalizations from study results.

Although we have sound understanding of the composition, structure, and functions that affect stream thermal regimes, substantial uncertainty remains regarding the effects of any specific riparian management action on stream thermal regimes in most locations. That uncertainty is amplified by our relative lack of understanding at large spatial and long temporal extents for which few studies have been

completed. Recovery of stream temperatures due to shade from vegetation regrowth can occur in less than a decade following disturbance (D'Souza et al. 2011), but recovery rates differ widely among locations due to differences in stream size and components that control rates of vegetation re-establishment and growth (Gecy and Wilson 1990; D'Souza et al. 2011). Although scientists are very certain that temperatures and thermal regimes are important to many aquatic species, relatively little is known about ecological interactions (e.g., predator-prey relations), behaviors (e.g., movement among locations of different temperature), and indirect effects (e.g., effects on the rates and severity of disease). These interactions may be very important. For example, Lawrence et al. (2014) suggest that riparian restoration in some locations might prevent extirpation of Chinook Salmon and restrict the expansion of non-native fish in some locations by maintaining relatively cool stream temperatures. Such uncertainties often compound and should be addressed explicitly when making management decisions, especially when the decisions can have important, lasting effects (Harwood and Stokes 2003). Management of riparian ecosystem composition (e.g., vegetation species, side channels) and structure (e.g., longitudinal and lateral connectivity) can importantly benefit aquatic species. Management for such beneficial effects might prove especially important as our climate continues to change.

The state of the science regarding stream thermal regimes is uneven. On the one hand, we have a very good understanding of the physics of stream heating and cooling. We understand the relative magnitudes of direct and indirect effects of ecosystem changes on stream thermal regimes and have the ability to quantify these effects given enough time and resources. Shade provided by riparian vegetation is generally considered the single most important, albeit not the only, process of the system that humans can directly effect. These findings are undisputed. On the other hand, because thermal regimes are affected by a variety of factors and their interactions, stream temperatures are difficult to precisely predict on the basis on any single factor alone (e.g., shade). Thus, predicting stream temperature based solely on shade removal or buffer width will likely always suffer from imprecision. In addition to this prediction challenge, and despite the fact that we know suitable water temperatures are critical to the persistence of aquatic species, we are only now beginning to understand how aquatic organisms interact with and are impacted by changes in the stream thermal regime. The combination of what we know and do not know about how changes to stream thermal regimes affect aquatic species and how human activities can affect those regimes makes conservation in the face of a changing climate particularly challenging.

4.6. Literature Cited[1]

Abbe, T.B., and D.R. Montgomery. 1996. Large woody debris jams, channel hydraulics and habitat formation in large rivers. Regulated Rivers Research & Management 12:201-221. (i)

Allan, J.D. 2004. Landscapes and riverscapes: the influence of land use on stream ecosystems. Annual Review of Ecology and Systematics 35:257-284. (i)

Allen, M., and L. Dent. 2001. Shade conditions over forested streams in the Blue Mountain and Coast Range georegions of Oregon. ODF Technical Report #13. Oregon Department of Forestry.

Allen, D., W.E. Dietrich, P.F. Baker, F. Ligon, and B. Orr. 2007. Development of a mechanistically-based, basin-scale stream temperature model: applications to cumulative effects modeling. Pages 11-24 *in* R.B. Standiford, G.A. Giusti, Y. Valachovic, W.J. Zielinski, M.J. Furniss, technical editors. Proceedings of the Redwood Region forest science symposium: what does the future hold? PSW-GTR-194. U.S. Forest Service, Pacific Southwest Research Station, Albany, California. (viii)

Alvarez, S.M., J.K. Johnson, and R. Spafford. 2004. Reclamation project allows new phase for Moon

Creek. Land and Water 48:10-15. (i)
Anderson, P.D., D.J. Larson, and S.S. Chan. 2007. Riparian buffer and density management influences on microclimate of young headwater forests of western Oregon. Forest Science 53(2): 254-269.
Arismendi, I., S.L. Johnson, J.B. Dunham, R. Haggerty, and D. Hockman-Wert. 2012. The paradox of cooling streams in a warming world: regional climate trends do not parallel variable local trends in stream temperature in the Pacific Continental United States. Geophysical Research Letters 39:L10401. (i)
Arrigoni, A.S., G.C. Poole, L.A.K. Mertes, S.J. O'Daniel, W.W. Woessner, and S.A. Thomas. 2008. Buffered, lagged, or cooled? Disentangling hyporheic influences on temperature cycles in stream channels. Water Resources Research 44:W09418.
Ayllón D., G.G. Nicola, B. Elvira, I. Parra, and A. Almodóvar. 2013. Thermal carrying capacity for a thermally-sensitive species at the warmest edge of its range. PLoS One 8:e81354. (i)
Baxter, C.V., K.D. Fausch, and W.C. Saunders. 2005. Tangled webs: reciprocal flows of invertebrate prey link streams and riparian zones. Freshwater biology 50:201-220. (i)
Belsky, A. J., A. Matzke, and S. Uselman. 1999. Survey of livestock influences on stream and riparian ecosystems in the western United States. Journal of Soil and Water Conservation 54:419–431. (i)
Benedict, C., and J. Shaw. 2012. Agricultural waterway buffer study. Washington State University Extension, Bellingham, Washington. (viii)
Benyahya L., D. Caissie, N. El-Jabi, and M.G. Satish. 2010. Comparison of microclimate vs. remote meteorological data and results applied to a water temperature model (Miramichi River, Canada). Journal of Hydrology 380:247–259. (i)
Beschta, R.L., R.E. Bilby, G.W. Brown, L.B. Holtby, and T.D. Hofstra. 1987. Stream temperature and aquatic habitat: fisheries and forestry interactions. Pages 191-232 *in* E.O. Salo and T.W. Cundy, editors. Streamside management: forestry and fishery interactions. Contribution No. 57. Institute of Forest Resources, University of Washington, Seattle. (viii)
Bilby, R.E., and P.A. Bisson. 1987. Emigration and production of hatchery Coho Salmon (*Oncorhynchus kisutch*) stocked in streams draining an old-growth and clear-cut watershed. Canadian Journal of Fisheries and Aquatic Sciences 44:1397-1407. (i)
Bisson, P.A., J.M. Buffington, and D.R. Montgomery. 2006. Valley segments, stream reaches, and channel units. Pages 23-49 *in* F.R. Hauer and G.A. Lamberti, editors. Methods in stream ecology. Elsevier, Burlington, Massachusetts. (i)
Bisson, P.A., S.M. Claeson, S.M. Wondzell, A.D. Foster, and A. Steel. 2013. Evaluating headwater stream buffers: lessons learned from watershed-scale experiments in southwest Washington. Pages 165-184 *in* P.D. Anderson and K.L. Ronnenberg, editors. Density management in the 21st Century: west side story. PNW-GTR-880. U.S. Forest Service, Pacific Northwest Research Station, Portland, Oregon. (viii)
Bobba, A.G., P.A. Chambers, and J. Spoelstra. 2010. Environmental impacts in arid and semiarid floodplains. Journal of Environmental Hydrology 18:1-15. (i)
Booth, D.B., J.R. Karr, S. Schauman, C.P. Konrad, S.A. Morley, M.G. Larson, P.C. Henshaw, E.J. Nelson, and S.J. Burges. 2001. Urban stream rehabilitation in the Pacific Northwest. Final report of EPA Grant Number R82-5284-010. University of Washington, Seattle (viii)
Booth, D.B., K.A. Kraseski, and C.R. Jackson. 2014. Local-scale and watershed-scale determinants of summertime urban stream temperatures. Hydrological Processes 28:2427-2438. (i)
Bowler, D.E., R. Mant, H. Orr, D.M. Hannah, and A.S. Pullin. 2012. What are the effects of wooded riparian zones on stream temperature? Environmental Evidence 2012:3-9. (i)
Boyd, M. 1996. Heat source: stream temperature prediction. Master's thesis. Oregon State University, Corvallis, Oregon. (i)
Boyd, M., and B. Kasper. 2003. Analytical methods for dynamic open channel heat and mass transfer:

[1] References are classified according to RCW 34.05.271 (see Appendix 1) denoted by a lower case roman numeral (i – viii) in parentheses at the end of the citation.

methodology for heat source model Version 7.0. Available: https://www.oregon.gov/deq/FilterDocs/heatsourcemanual.pdf. (January 2019). (viii)

Brannon, E.L., M.S. Powell, T.P. Quinn, and A. Talbot 2004. Population structure of Columbia River basin Chinook Salmon and steelhead trout. Reviews in Fisheries Science 12:99–232. (i)

Brattstrom, B.H. 1963. A preliminary review of the thermal requirements of amphibians. Ecology 44:238-255. (i)

Brett, J.R. 1952. Temperature tolerance in young Pacific salmon, genus *Oncorhynchus*. Journal of the Fisheries Research Board of Canada 9:265-323. (i)

Brett, J.R. 1971. Energetic responses of salmon to temperature. A study of some thermal relations in the physiology and freshwater ecology of Sockeye Salmon (*Oncorhynchus nerka*). American Zoologist 11:99–113. (i)

Brett, J.R., J.E. Shelbourn, and C.T. Shoop. 1969. Growth rate and body composition of fingerling Sockeye Salmon, *Oncorhynchus nerka,* in relation to temperature and ration size. Journal of the Fisheries Research Board of Canada 26:2363–2394. (i)

Brown, H.A. 1975. Temperature and the development of the Tailed Frog, *Ascaphus truei.* Comparative Biochemistry and Physiology 50A(2):397-405. (i)

Buffington, J.M., D.R. Montgomery, and H.M. Greenberg. 2004. Basin-scale availability of salmonid spawning gravel as influenced by channel type and hydraulic roughness in mountain catchments. Canadian Journal of Fisheries and Aquatic Sciences 61:2085-2096. (i)

Burkholder, B.K., G.E. Grant, R. Haggerty, T. Khangaonkar, and P.J. Wampler. 2008. Influence of hyporheic flow and geomorphology on temperature of a large, gravel-bed river, Clackamas River, Oregon, USA. Hydrological Processes 22:941-953. (i)

Bury, R.B. 2008. Low thermal tolerances of stream amphibians in the Pacific Northwest: implications for riparian and forest management. Applied Herpetology 5:63-74. (i)

Caissie, D. 2006. The thermal regime of rivers: a review. Freshwater Biology 51:1389–1406. (i)

Caissie, D. 2016. River evaporation, condensation and heat fluxes within a first order tributary of Catamaran Brook (New Brunswick, Canada). Hydrological Processes 30:1872–1883. (i)

Claussen, D.L. 1973. The thermal relations of the Tailed Frog, *Ascaphus truei,* and the Pacific Treefrog, *Hyla regilla*. Comparative Biochemistry and Physiology 44A(1):137-153. (i)

Coffin, C., S. Lee, and D. Garland. 2011. Bear-Evans Watershed temperature, dissolved oxygen and fecal coliform bacteria total maximum daily load: water quality implementation plan. Publication No.11-10-024. Washington Department of Ecology, Bellevue, Washington. (viii)

Cole, E., and M. Newton. 2013. Influence of streamside buffers on stream temperature response following clear-cut harvesting in western Oregon. Canadian Journal of Forest Research 43:993-1005. (i)

Cristea, N.C., and S.J. Burges. 2010. An assessment of the current and future thermal regimes of three streams located in the Wenatchee River basin, Washington State: some implications for regional river basin systems. Climatic Change 2010:493-520. (i)

Cristea, N., and J. Janisch. 2007. Modeling the effects of riparian buffer width on effective shade and stream temperature. Washington Department of Ecology, Olympia. (viii)

Crossin, G.T., S.G. Hinch, S.J. Cooke, D.W. Welch, D.A. Patterson, S.R.M. Jones, A.G. Lotto, R.A. Leggatt, M.T. Mathes, J.M. Shrimpton, G. Van Der Kraak, and A.P. Farrell. 2008. Exposure to high temperatures influences the behavior, physiology, and survival of Sockeye Salmon during spawning migration. Canadian Journal of Zoology 86:127-140. (i)

Czarnomski, N., C. Hale, W.T. Frueh, M. Allen, and J. Groom. 2013. Effectiveness of riparian buffers at protecting stream temperature and shade in Pacific Northwest forests: a systematic review. Final Report to the Forest Practices Monitoring Program. Oregon

Department of Forestry, Salem. (viii)
de Vlaming, V.L., and R.B. Bury. 1970. Thermal selection in tadpoles of the Tailed-Frog, *Ascaphus truei.* Journal of Herpetology 4:179-189. (i)
DeWalle, D.R. 2010. Modeling stream shade: riparian buffer height and density as important as buffer width. Journal of the American Water Resources Association 46:323-333. (i)
D'Souza, L.E., M. Reiter, L.J. Six, and R.E. Bilby. 2011. Response of vegetation, shade and stream temperature to debris torrents in two western Oregon watersheds. Forest Ecology and Management 261:2157-2167. (i)
Dugdale, S.J., N.E. Bergeron, and A. St-Hilaire. 2013. Temporal variability of thermal refuges and water temperature patterns in an Atlantic Salmon river. Remote Sensing of Environment 136:358-373. (i)
Eberhardt, L.L. 1976. Quantitative ecology and impact assessment. Journal of Environmental Management 4:27–70. (i)
Ebersole, J.L., W.J. Liss, and C.A. Frissell. 2003a. Thermal heterogeneity, stream channel morphology, and salmonid abundance in northeastern Oregon streams. Canadian Journal of Fisheries and Aquatic Sciences 60:1266-1280. (i)
Ebersole, J.L., W.J. Liss, and C.A. Frissell. 2003b. Cold water patches in warm streams: physicochemical characteristics and the influence of shading. Journal of the American Water Resources Association 39:355-368. (i)
Eliason, E.J., T.D. Clark, M.J. Hague, L.M. Hanson, Z.S. Gallagher, K.M. Jeffries, M.K. Gale, D.A. Patterson, S.G. Hinch, and A.P. Farrell. 2011. Differences in thermal tolerance among Sockeye Salmon populations. Science 332:109-112. (i)
Elmore, W., and J.B. Kauffman. 1994. Riparian and watershed systems: degradation and restoration. Pages 211-232 *in* M. Vavra, W.A. Laycock, and R.D. Piper, editors. Ecological implications of livestock herbivory in the West. Society of Range Management, Denver, Colorado. (viii)
Farrell, A.P., S.G. Hinch, S.J. Cooke, D.A. Patterson, G.T. Crossin, M. Lapointe, and M.T. Mathes. 2008. Pacific salmon in hot water: applying aerobic scope models and biotelemetry to predict the success of spawning migrations. Physiological and Biochemical Zoology 81:697-709. (i)
Fausch, K.D., C.E. Torgersen, C.V. Baxter, and H.W. Li. 2002. Landscapes to riverscapes: bridging the gap between research and conservation of stream fishes. BioScience 52:1-16. (i)
Finkenbine, J.K., J.W. Atwater, and D.S. Mavinic. 2000. Stream health after urbanization. Journal of the American Water Resources Association 36:1149-1160. (i)
Frissell, C.A., W.J. Liss, C.E. Warren, and M.D. Hurley. 1986. A hierarchical framework for stream habitat classification: viewing streams in a watershed context. Environmental Management 10:199-214. (i)
Fullerton, A.H., C. Torgersen, J.J. Lawler, R.N. Faux, E.A. Steel, T.J. Beechie, J.L. Ebersole, and S.J. Leibowitz. 2015. Rethinking the longitudinal stream temperature paradigm—region-wide comparison of thermal infrared imagery reveals unexpected complexity of river temperatures. Hydrological Processes 29:4719-4737. (i)
Garner, G., I.A. Malcolm, J.P. Sadler, and D.M. Hannah. 2014. What causes cooling water temperature gradients in a forested stream reach? Hydrology and Earth System Sciences 18:5361-5376. (i)
Gecy, J.L., and M.V. Wilson. 1990. Initial establishment of riparian vegetation after disturbance by debris flows in Oregon. American Midland Naturalist 123:282-291. (i)
Gomi, T., R.D. Moore, and A.S. Dhakal. 2006. Headwater stream temperature response to clear-cut harvesting with different riparian treatments, coastal British Columbia, Canada. Water Resources Research

42: W08437.
Gomi, T., R.C. Sidle, and D.N. Swanston. 2004. Hydrogeomorphic linkages of sediment transport in headwater streams, Maybeso Experimental Forest, southeast Alaska. Hydrological Processes 18:667-667. (i)
Gregory, S.V., F.J. Swanson, W.A. McKee, and K.W. Cummins. 1991. An ecosystem perspective of riparian zones. BioScience 41:540-551. (i)
Groom, J.D., L. Dent, and J. Madsen. 2011. Stream temperature change detection for state and private forests in the Oregon Coast Range. Water Resources Research 47:1-12. (i)
Groot, C., and L. Margolis. 2010. Pacific salmon life histories. University of Washington Press, Seattle. (i)
Hari, R.E., D.M. Livingston, R. Siber, P. Burkhardt-Holm, and H. Guttinger. 2006. Consequences of climate change for water temperature and brown trout populations in alpine rivers and streams. Global Change Biology 12:10-26. (i)
Harwood, J., and K. Stokes. 2003. Coping with uncertainty in ecological advice: lessons from fisheries. Trends in Ecology and Evolution 18:617–622. (i)
Hawkins, C.P., M.L. Murphy, N.H. Anderson, and M.A. Wilzbach. 1983. Density of fish and salamanders in relation to riparian canopy and physical habitat in streams of the northwestern United States. Canadian Journal of Fisheries and Aquatic Sciences 40:1173-1185. (i)
Hendry, A.P., J.E. Hensleigh, and R.R. Reisenbichler. 1998. Incubation temperature, developmental biology, and the divergence of Sockeye Salmon (*Oncorhynchus nerka*) within Lake Washington. Canadian Journal of Fisheries and Aquatic Sciences 55:1387–1394. (i)
Hester, E.T., and M.W. Doyle. 2011. Human impacts to river temperature and their effects on biological processes: a quantitative synthesis. Journal of the American Water Resources Association 47:571–587. (i)
Hinch, S.G., S.J. Cooke, A.P. Farrell, K.M. Miller, M. LaPointe, and D.A. Patterson. 2012. Dead fish swimming: a review of research on the early migration and high premature mortality in adult Fraser River Sockeye Salmon (*Oncorhynchus nerka*). Journal of Fish Biology 81:576-599. (i)
Hodgson, S., and T.P. Quinn. 2002. The timing of adult Sockeye Salmon migration into fresh water: adaptations by populations to prevailing thermal regimes. Canadian Journal of Zoology 80:542-555. (i)
Hogg, I.D., and D.D. Williams. 1996. Response of stream invertebrates to a global-warming thermal regime: an ecosystem-level manipulation. Ecology 77:395-407. (i)
Holland, D.C. 1994. The Western Pond Turtle: habitat and history. Unpublished final report, U. S. Dept. of Energy, Portland, Oregon. (viii)
Holsinger, L., R.E. Keane, D.J. Isaak, L. Eby, and M.K. Young. 2014. Relative effects of climate change and wildfires on stream temperatures: a simulation modeling approach in a Rocky Mountain watershed. Climate Change 124:191-206. (i)
Isaak, D.J., and W.A. Hubert. 2001. A hypothesis about factors that affect maximum summer stream temperatures across montane landscapes. Journal of the American Water Resources Association 37:351-366. (i)
Isaak, D.J., and W.A. Hubert. 2004. Nonlinear response of trout abundance to summer stream temperatures across a thermally diverse montane landscape. Transactions of the American Fisheries Society 133:1254-1259. (i)
Isaak, D.J., C.H. Luce, B.B. Rieman, D.E. Nagel, E.E. Peterson, D.L. Horan, S. Parkes, and G.L. Chandler. 2010. Effects of climate change and wildfire on stream temperatures and salmonid thermal habitat in a mountain river network. Ecological

Applications 20:1350-1371. (i)
Isaak, D.J., E.E. Peterson, J.M. Ver Hoef, S.J. Wenger, J.A. Falke, C. Torgersen, C. Sowder, E.A. Steel, M. Fortin, C.E. Jordan, A.S. Ruesch, N. Som, and P. Monestiez. 2014. Applications of spatial statistical network models to stream data. Wiley Interdisciplinary Reviews–Water 1:277-294. (i)
Isaak, D., S. Wenger, E. Peterson, J. Ver Hoef, D. Nagel, C. Luce, S. Hostetler, J. Dunham, B. Roper, S. Wollrab, G. Chandler, D. Horan, and S. Parkes-Payne. 2017a. The NorWeST summer stream temperature model and scenarios for the western U.S.: a crowd-sourced database and new geospatial tools foster a user community and predict broad climate warming of rivers and streams. Water Resources Research 53:9181-9205. (i)
Isaak, D.J., S.J. Wenger, and M.K. Young. 2017b. Big biology meets microclimatology: defining thermal niches of ectotherms at landscape scales for conservation planning. Ecological Applications 27:977–990. (i)
Isaak, D.J., S. Wollrab, D. Horan, and G. Chandler. 2012. Climate change effects on stream and river temperatures across the Northwest U.S. from 1980–2009 and implications for salmonid fishes. Climatic Change 113:499-524. (i)
Isaak, D.J., M.K. Young, D. Nagel, D. Horan, and M. Groce. 2015. The coldwater climate shield: delineating refugia to preserve salmonid fishes through the 21st Century. Global Change Biology 21:2540-2553. (i)
Jackson, C.R., C.A. Sturm, and J.M. Ward. 2001. Timber harvest impacts on small headwater stream channels in the coast ranges of Washington. Journal of the American Water Resources Association 37:1533–1549.
Janisch, J.E., S.M. Wondzell, and W. J. Ehinger. 2012. Headwater stream temperature: interpreting response after logging, with and without riparian buffers, Washington, USA. Forest Ecology and Management 270:302-313. (i)
Johnson, F.A. 1971. Stream temperatures in an alpine area. Journal of Hydrology 14:322-336. (i)
Johnson, S.L. 2004. Factors influencing stream temperatures in small streams: substrate effects and a shading experiment. Canadian Journal of Fisheries and Aquatic Sciences 61:913-923. (i)
Kappenman, K.M., M.A.H. Webb, and M. Greenwood. 2013. The effect of temperature on embryo survival and development in Pallid Sturgeon *Scaphirhynchus albus* (Forbes & Richardson 1905) and Shovelnose Sturgeon *S. platorynchus* (Rafinesque, 1820). Journal of Applied Ichthyology 29:1193-1203. (i)
Keefer, M.L., C.A. Peery, and M.J. Heinrich. 2008. Temperature-mediated en route migration mortality and travel rates of endangered Snake River Sockeye Salmon. Ecology of Freshwater Fish 17:136–145. (i)
Keller, E.A., and F.J. Swanson. 1979. Effects of large organic material on channel form and fluvial processes. Earth Surface Processes 4:361-380. (i)
Kibler, K.M., A. Skaugset, L.M. Ganio, and M.M. Huso. 2013. Effects of contemporary forest harvesting practices on headwater stream temperatures: initial response of the Hinkle Creek catchment, Pacific Northwest, USA. Forest Ecology and Management 310:680-691. (i)
Kiffney, P.M., J.S. Richardson, and J.P. Bull. 2003. Responses of periphyton and insect consumers to experimental manipulation of riparian buffer width along headwater streams. Journal of the American Water Resources Association 40:1060-1076. (i)
Kinouchi, T., H. Yagi, and M. Miyamoto. 2006. Increase in stream temperature related to anthropogenic heat input from urban wastewater. Journal of Hydrology 335:78–88. (i)
Knutson, K.L., and V.L. Naef. 1997. Management recommendations for Washington's priority habitats: riparian. Washington Department of Fish and Wildlife,

Olympia, Washington. (iii)
Konrad, C.P., D.B. Booth, and S.J. Burges. 2005. Effects of urban development in the Puget Lowland, Washington, on interannual streamflow patterns: consequences for channel form and streambed disturbance. Water Resources Research 41:W07009. (i)
Lawrence, D.J., B. Stewart-Koster, J.D. Olden, A.S. Ruesch, C.E. Torgersen, J.J. Lawler, D.P. Butcher, and J.K. Crown. 2014. The interactive effects of climate change, riparian management, and a nonnative predator on stream-rearing salmon. Ecological Applications 24:895-912. (i)
LeBlanc, R.T., R.D. Brown, and J.E. FitzGibbon. 1997. Modeling the effects of land use change on the water temperature in unregulated urban streams. Journal of Environmental Management 49:445–469. (i)
Leinenbach, P., G. McFadden, and C. Torgersen. 2013. Effects of riparian management strategies on stream temperature, Part II. Summary report of the Science Review Team submitted to the Interagency Coordinating Subcommittee. Bureau of Land Management, Portland, Oregon. (viii)
Li, H.W., G.A. Lamberti, T.N. Pearsons, C.K. Tait, and J.C. Buckhouse. 1994. Cumulative effects of riparian disturbances along high desert trout streams of the John Day Basin, Oregon. Transactions of the American Fisheries Society 123:627–640. (i)
Li, J.L., S.L. Johnson, and J.B. Sobota. 2011. Three responses to small changes in stream temperature by autumn-emerging aquatic insects. Journal of the North American Benthological Society 30:474-484. (i)
Licht, L.E. 1971. Breeding habits and embryonic thermal requirements of the frogs, *Rana aurora aurora* and *Rana pretiosa pretiosa*, in the Pacific Northwest. Ecology 52:116–124. (i)
Liquori, M., and C.R. Jackson. 2001. Channel response from shrub dominated riparian communities and associated effects on salmonid habitat. Journal of the American Water Resources Association 37:1639–1651. (i)
Luce, C.H., B.P. Staab, M.G. Kramer, S.J., D.J. Isaak, and C. McConnell. 2014. Sensitivity of summer stream temperatures to climate variability in the Pacific Northwest. Water Resources Research 50:1-16. (i)
Lytle, D.A., and N.L. Poff. 2004. Adaptation to natural flow regimes. Trends in Ecology and Evolution 19:94-100. (i)
Malard, F., K. Tockner, M. Dole-Olivier, and J.V. Ward. 2002. A landscape perspective of surface-subsurface hydrological exchanges in river corridors. Freshwater Biology 47:621-640. (i)
Malcolm, I.A., C. Soulsby, and A.F. Youngson. 2002. Thermal regime in the hyporheic zone of two contrasting salmonid spawning streams: ecological and hydrological implications. Fisheries Management and Ecology 9:1-10. (i)
Maloney, S.B., A.R. Tiedemann, D.A. Higgins, T.M. Quigley, and D.B. Marx. 1999. Influence of stream characteristics and grazing intensity on stream temperatures in eastern Oregon. PNW-GTR-459. U.S. Forest Service, Pacific Northwest Research Station, Portland, Oregon. (viii)
Marsh, P.C. 1985. Effect of incubation temperature on survival of embryos of native Colorado River fishes. The Southwestern Naturalist 30:129-140. (i)
May, C.W. 2003. Stream-riparian ecosystems in the Puget Sound lowland ecoregions: a review of best available science. Watershed Ecology, LLC, Poulsbo, Washington. (i)
McCullough, D.A. 1999. A review and synthesis of effects of alterations to the water temperature regime of freshwater life stages of salmonids, with special reference to Chinook Salmon. U.S. Environmental Protection Agency, Region 10, Seattle,

Washington. (viii)
McCullough, D.A., J.M. Bartholow, H.I. Jager, R.L. Beschta, E.F. Cheslak, M.L. Deas, J.L. Ebersole, J.S. Foote, S.L. Johnson, K.R. Marine, M.G. Mesa, J.H. Petersen, Y. Souchon, K.F. Tiffan, and D.A. Wurtsbaugh. 2009. Research in thermal biology: burning questions for coldwater stream fishes. Reviews in Fisheries Science 17:90-115. (i)
McCullough, D., S. Spalding, D. Sturdevant, and M. Hicks. 2001. Issue Paper 5. Summary of technical literature examining the physiological effects of temperature on salmonids. EPA-910-D-01-005. U.S. Environmental Protection Agency, Region 10, Seattle, Washington. (viii)
Micheli, E.R., and J.W. Kirchner. 2002. Effects of wet meadow riparian vegetation on streambank erosion. 2. Measurements of vegetated bank strength and consequences for failure mechanics. Earth Surface Processes and Landforms 27:687-697. (i)
Moore, R.D., D.L. Spittlehouse, and A. Story. 2005. Riparian microclimate and stream temperature response to forest harvesting: a review. Journal of the American Water Resources Association 41:813-834. (i)
Moulton, S.R., T.L. Beitinger, K.W. Stewart, and R.J. Currie. 1993. Upper temperature tolerance of four species of caddisflies (Insecta: Trichoptera). Journal of Freshwater Ecology 8:193–198. (i)
Murphy, M.L., and J.D. Hall. 1981. Varied effects of clear-cut logging on predators and their habitat in small streams in the Cascade Mountains, Oregon. Canadian Journal of Fisheries and Aquatic Sciences 38:137-145. (i)
Murphy, M.L., C.P. Hawkins, and N.H. Anderson. 1981. Effects of canopy modification and accumulated sediment on stream communities. Transactions of the American Fisheries Society 110:469-478. (i)
NRC (National Research Council). 2002. Riparian areas: functions and strategies for management. National Academy Press, Washington, D.C. (i)
Nyberg, L., O. Calles, and L. Greenberg. 2008. Impact of short-term regulation on hyporheic water quality in a boreal river. River Research and Applications 24:407-419. (i)
Olden, J.D., and R.J. Naiman. 2010. Incorporating thermal regimes into environmental flows assessments: modifying dam operations to restore freshwater ecosystem integrity. Freshwater Biology 55:86-107. (i)
Olson, D.H., and C. Rugger. 2007. Preliminary study of the effects of headwater riparian reserves with upslope thinning on stream habitats and amphibians in western Oregon. Forest Science 53:331-342. (i)
Paul, M.J., and J.L. Meyer. 2001. Streams in the urban landscape. Annual Review of Ecology and Systematics 32:333–365. (i)
Pollett, K.L., J.G. MacCracken, and J.A. MacMahon. 2010. Stream buffers ameliorate the effects of timber harvest on amphibians in the Cascade Range of southern Washington, USA. Forest Ecology and Management 260:1083-1087. (i)
Poole, G.C., and C.H. Berman. 2001. An ecological perspective on in-stream temperature: natural heat dynamics and mechanisms of human-caused thermal degradation. Environmental Management 27:787-802. (i)
Poole, G.C., J.B. Dunham, D.M. Keenan, S.T. Sauter, D.A. McCullough, C. Mebane, J.C. Lockwood, D.A. Essig, M.P. Hicks, D.J. Sturdevant, E.J. Materna, S.A. Spalding, J. Risley, and M. Deppman. 2004. The case for regime-based water quality standards. BioScience 54:155-161. (i)
Poole, G., J. Risley, and M. Hicks. 2001. Issue paper 3: spatial and temporal patterns of stream temperature (revised). EPA-910-D-01-003. U.S. Environmental Protection Agency, Region 10, Seattle, Washington. (viii)
Post, D.M., E.P. Palkovacs, E.G. Schielke, and S.I. Dodson. 2008. Interspecific variation in a predator affects community structure and cascading trophic interactions. Ecology 98:2019–2032. (i)
Pringle, C.M., and F.J. Triska. 2000. Emergent biological patterns in streams resulting from surface-subsurface water interactions at landscape scales. Pages 167-193 *in* J.B. Jones and P.J. Mulholland, editors. Streams and groundwaters. Elsevier, Burlington, Massachusetts. (i)

Reeves, G.H., D.H. Olson, S.M. Wondzell, P.A. Bisson, S. Gordon, S.A. Miller, J.W. Long, and M.J. Furniss. 2018. Chapter 7: The Aquatic Conservation Strategy of the Northwest Forest Plan–a review of the relevant science after 23 years. Pages 461-642 *in* T.A. Spies, P.A. Stine, R. Gravenmier, J.W. Long, and M.J. Reilly, technical coordinators. Synthesis of science to inform land management within the Northwest Forest Plan area. PNW-GTR-966. U.S. Forest Service, Pacific Northwest Research Station, Portland, Oregon. (viii)

Rezende E.L., L.E. Castañeda, and M. Santos. 2014. Tolerance landscapes in thermal ecology. Functional Ecology 28:799–809. (i)

Richter, A., and S.A. Kolmes. 2005. Maximum temperature limits for Chinook, Coho, and Chum Salmon, and steelhead trout in the Pacific Northwest. Reviews in Fisheries Science 13:23–49. (i)

Rykken, J.J., S.C. Chan, and A.R. Moldenke. 2007. Headwater riparian microclimate patterns under alternative forest management treatments. Forest Science 53:270-280. (i)

Sather, N.K., and C.W. May. 2007. Riparian buffer zones in the interior Columbia River Basin: a review of best available science. Battelle Memorial Institute, Marine Sciences Laboratory, Sequim, Washington. (viii)

Sauter, S.T., L.I. Cershaw, and A.G. Maule. 2001. Behavioral thermoregulation by juvenile spring and fall Chinook Salmon, *Oncorhynchus tshawytscha*, during smoltification. Environmental Biology of Fishes 61:295–304. (i)

Sauter, S.T., and P.J. Connolly. 2010. Growth, condition factor, and bioenergetics modeling link warmer stream temperatures below a small dam to reduced performance of juvenile steelhead. Northwest Science 84:369-377. (i)

Schuett-Hames, D., A. Roorbach, and R. Conrad. 2012. Results of the westside type N buffer characterization, integrity and function study final report. Cooperative Monitoring Evaluation and Research Report, CMER 12-1201. Washington Department of Natural Resources, Olympia.

Sinokrot, B.A., and H.G. Stefan. 1993. Stream temperature dynamics: measurements and modeling. Water Resources Research 29:2299-2312. (i)

Sridhar,V., A.L. Sansone, J. Lamarche, T. Dubin, and D.P. Lettenmaier. 2004. Prediction of stream temperature in forested watersheds. Journal of the American Water Resources Association 40:197-213. (i)

Stanford, J.A. 1998. Rivers in the landscape: introduction to the special issues on riparian and groundwater ecology. Freshwater Biology 40:402-406. (i)

Steel, E.A., A. Tillotson, D.A. Larsen, A. Fullerton, K.P. Denton, and B.R. Beckman. 2012. Beyond the mean: the role of variability in predicting ecological effects of stream temperatures on salmon. Ecosphere 3:104 (i)

Stewart-Oaten, A., W.W. Murdoch, and K.R. Parker. 1986. Environmental impact assessment: pseudoreplication in time? Ecology 67:929–940. (i)

Stoddard, M.A., and J.P. Hayes. 2005. The influence of forest management on headwater stream amphibians at multiple spatial scales. Ecological Applications 15:811-823. (i)

Story, A., R.D. Moore, and J.S. Macdonald. 2003. Stream temperatures in two shaded reaches below cutblocks and logging roads: downstream cooling linked to subsurface hydrology. Canadian Journal of Forest Research 33:1383-1396. (i)

Strange, J.S. 2010. Upper thermal limits to migration in adult Chinook Salmon: evidence from the Klamath River basin. Transactions of the American Fisheries Society 139:1091-1108. (i)

Sweeney, B.W., and J.D. Newbold. 2014. Streamside forest buffer width needed to protect stream water quality, habitat, and organisms: a literature review. Journal of the American Water Resources Association 50:560-584. (i)

Tait, C.K., J.L. Li, G.A. Lamberti, T.N. Pearsons, and H.W. Li. 1994. Relationships between riparian cover and the community structure of high desert streams. Journal of the North American Benthological Society 13:45–56. (i)

Toledo, Z.O., and J.B. Kauffman. 2001. Root biomass in relation to channel morphology of headwater streams. Journal of the American Water Resources Association 37:1653-1663. (i)

Torgersen, C.E., R. Faux, B.A. McIntosh, N. Poage, and D.J. Norton. 2001. Airborne thermal remote sensing for water temperature assessment in rivers and streams. Remote Sensing of Environment 76:386-398. (i)

Torgersen, C.E., D.M. Price, H.W. Li, and B.A. McIntosh. 1999. Multiscale thermal refugia and stream habitat associations of Chinook Salmon in northwestern Oregon. Ecological Applications 9:301-319. (i)

USEPA 2012. Technical memorandum to the Idaho Department of (state) Lands (IDL) Private Lands Forest Practices Act (FPA) Shade Subcommittee. Available: ftp://ftp.epa.gov/ reg10ftp/forestry/. (June 2015). (viii)

Ver Hoef, J.M., E.E. Peterson, and D. Theobald. 2006. Spatial statistical models that use flow and stream distance. Environmental and Ecological Statistics 13:449–464. (i)

Wahl, C.M., A. Neils, and D. Hooper. 2013. Impacts of land use at the catchment scale constrain the habitat benefits of stream riparian buffers. Freshwater Biology 58:2310–2324. (i)

Waite, I.R., and K.D. Carpenter. 2000. Associations among fish assemblage structure and environmental variables in Willamette Basin streams, Oregon. Transactions of the American Fisheries Society 129:754–770. (i)

Ward, J.V., F. Malard, and K. Tockner. 2002. Landscape ecology: a framework for integrating pattern and process in river corridors. Landscape Ecology 17(Supplement 1):35–45. (i)

Ward, J.V., and J.A. Stanford. 1982. Thermal responses in the evolutionary ecology of aquatic insects. Annual Review of Entomology 27:97-117. (i)

Ward, J.V., and J.A. Stanford. 1995. Ecological connectivity in alluvial river ecosystems and its disruption by flow regulation. Regulated Rivers: Research & Management 11:105-119. (i)

Webb, B.W., D.M. Hannah, R.D. Moore, L.E. Brown, and F. Nobilis. 2008. Recent advances in stream and river temperature research. Hydrological Processes 22:902–918. (i)

Weitkamp, L.A., D.J. Teel, M. Liermann, S.A. Hinton, D.M. Van Doornik, and P.J. Bentley. 2015. Stock-specific size and timing at ocean entry of Columbia River juvenile Chinook Salmon and steelhead: implications for early ocean growth. Marine and Coastal Fisheries: Dynamics, Management, and Ecosystem Science 7:370-392. (i)

Welsh, H.H. 1990. Relictual amphibians and old-growth forests. Conservation Biology 4:309-319. (i)

Welsh, H.H., Jr., G R. Hodgson, B.C. Harvey, and M.E. Roche. 2001. Distribution of juvenile Coho Salmon in relation to water temperatures in tributaries of the Mattole River, California. North American Journal of Fisheries Management 21:464-470. (i)

Welsh, H.H., Jr., and A.J. Lind. 1996. Habitat correlates of the Southern Torrent Salamander, *Rhyacotriton variegatus* (Caudata: Rhyacotritonidae), in northwestern California. Journal of Herpetology 30:385-398. (i)

Wiens, J.A. 2002. Riverine landscapes: taking landscape ecology into the water. Freshwater Biology 47:501–515. (i)

Winder, M., and D.E. Schindler. 2004. Climate change uncouples trophic interactions in an aquatic ecosystem. Ecology 85:2100–2106. (i)

Wondzell, S.M. 2012. Hyporheic zones in mountain streams: physical processes and ecosystem functions. Stream Notes (Jan. - Apr.):1-10. Stream Systems Technology Center, Rocky Mountain Research Station, Fort Collins, Colorado. (i)

Wondzell, S.M., and M.N. Gooseff. 2013. Geomorphic controls on hyporheic exchange across scales: watersheds to particles. Pages 203-218 *in* J. Shroder, editor-in-chief, and E. Wolh, editor. Treatise on Geomorphology. Academic Press, San Diego, California.

Wright, K.K., C.V. Baxter, and J.L. Li. 2005. Restricted hyporheic exchange in an alluvial river system: implications for theory and management. Journal of the North American Benthological Society 24:447-460. (i)

Zaugg, W.S., and H.H. Wagner. 1973. Gill ATPase activity related to parr-smolt transformation and migration in steelhead trout (*Salmo gairdneri*): influence of photoperiod and temperature. Comparative Biochemistry and Physiology 45:955-965. (i)

Zoellick, B.W. 2004. Density and biomass of redband trout relative to stream shading and temperature in southwestern Idaho. Western North American Naturalist 64:18–26. (i)



Long-toed salamander Ambystoma macrodactylum/*Scott Fitkin, WDFW*

Chapter 5. Pollutant Removal

By: Jeffrey L. Ullman and George F. Wilhere

5.1. Introduction

The capability of riparian areas to remove certain pollutants from runoff has been known to scientists for over 60 years (e.g., Trimble and Sartz 1957). Understanding the complex processes and associated factors that affect the pollutant removal function of riparian areas is essential for developing management strategies that will protect aquatic ecosystems. Management of riparian areas for pollutant removal differs from the other ecological functions discussed in this document in that the primary focus is on mitigating activities occurring outside the riparian area. The pollutant removal function is unique in that it only exists in the presence of human activities that generate polluted water, and it is only necessary when runoff from upland activities threaten to degrade water quality.

This chapter summarizes key information relevant to riparian pollutant removal function. First, a general background is presented on the main processes and related site-level factors affecting the transport and fate of nonpoint source pollutants in riparian areas. Next, the biological impacts, common sources, *in situ* chemistry, transport pathways, and mitigation are reviewed for five types of pollutants—sediments, excess nutrients, metals, pesticides and other organic compounds, and pathogens. Last, a summary of what is currently known about the relationships between riparian buffer width and pollutant removal is provided. Riparian buffer is not synonymous with riparian area. Riparian area is an ecological designation that is synonymous with riparian ecosystem (see Chapter 1). Riparian buffer is a management designation, and a buffer may be narrower or wider than the riparian ecosystem.



Yellowjacket Creek/George Fornes, WDFW

This chapter only addresses nonpoint-source chemical pollutants that interact with riparian areas. Hence, it does not deal with "thermal pollution" effects on water temperature (see Chapter 4), which is another important water quality parameter. Similarly, it does not deal with pollutants routed via roads, ditches, and drains into urban and suburban stormwater runoff systems, or with polluted water routed to rivers and streams via agricultural tile drainage.

While the scientific literature reviewed here includes information collected during the 1970s and 1980s, when scientists first started to rigorously investigate the removal of pollutants by riparian areas (Correll 1997), more recent findings are highlighted. Decades of research have revealed that the ecosystem structures and processes responsible for pollutant removal functions of riparian areas are complex, spatially and temporally variable, and dependent on site-level environmental conditions. This complexity and variability are the main reasons for inconsistent results found in the published research and the lack of definitive recommendations regarding the structure and size of riparian buffers required for pollutant removal. Nevertheless, general trends in research findings can guide policy makers and resource managers to management strategies that address these uncertainties and lead to adequate protection of water quality.

5.2. The Pollutant Removal Function of Riparian Areas

Water quality refers to the physical, chemical, and biological characteristics of water that indicate a waterbody's suitability to meet human needs or habitat requirements for fish and wildlife. Riparian areas exert a significant influence on water quality due to their position between terrestrial and aquatic ecosystems. Pollutants in dissolved, chemical, or suspended solid forms are transported by water from uplands to surface waterbodies, and while passing through riparian areas contaminated water undergoes a variety of physical, chemical, and biological processes that reduce pollutant concentrations. The processes in riparian areas affecting pollutant transport and fate are complex and often interrelated. Riparian areas slow surface runoff and increase infiltration of water into the soil, thereby enhancing both deposition of solids and filtration of water-borne pollutants. Riparian areas also intercept and act on contaminants in subsurface flow through dilution, sorption[1], physical transformation, chemical degradation, or volatilization by various biogeochemical processes and through uptake and assimilation by plants, fungi, and microbes.

There is overwhelming evidence in the scientific literature that riparian buffers reduce nonpoint source water pollution for a variety of pollutants—including sediments, excess nutrients, metals, organic compounds such as pesticides, and pathogens. Management activities can enhance the physical, chemical, and biological mechanisms that reduce the flow of polluted waters to river and streams.

1 Sorption or "to sorb" is a physical and chemical process by which one substance becomes attached to another. It encompasses two processes adsorption and absorption. Adsorption is the binding of molecules or particles to a substance's surface. The reverse of adsorption is desorption. Absorption is the filling of minute pores in a substance by molecules or particles.



Riparian buffer widths for pollution removal need not be one-size-fits-all/U.S. Dept. of Agriculture, National Agriculture Imagery Program

However, the science is very clear that results vary considerably depending on local conditions, and that the configuration of a riparian buffer may effectively remove one type of pollutant while having minimal effect on another. Although riparian management can reduce significantly the quantity of pollutants entering surface waters, riparian areas are not sufficient by themselves to fully mitigate pollution from nonpoint sources. Thus, it is critical to view pollution control from a holistic, watershed perspective that also manages contaminated runoff at its source, i.e., upland areas subjected to various intensive land uses: forestry, agriculture, commercial, and urban, suburban, and rural residential. Nevertheless, maintaining functional riparian areas is essential for reducing nonpoint source pollution and must be a key component in any suite of management actions focused on water quality.

5.3. Processes Influencing the Pollutant Removal Function

Riparian areas are consistently shown to remove a variety of nonpoint source pollutants, such as those originating from agricultural lands, urban areas, construction sites, and forestry operations. However, the effectiveness of riparian buffers is highly variable (Hickey and Doran 2004; Lee et al. 2004, Anbumozhi et al. 2005; Zhang et al. 2010). Inconsistencies among research results can be explained by the multi-dimensional heterogeneity of riparian ecosystems; the complex, interconnected processes that act on contaminant transport and fate; and the variety of research methods employed. Many site-specific factors contribute to this variability,

including riparian buffer width, slope, topography, surface and subsurface hydrology, soil properties, riparian vegetation, and adjacent upland characteristics. Of all these factors hydrology, soil, and vegetation play dominant roles governing pollutant transport and fate (NRC 2002). The following sections discuss the effects of these three site-level characteristics on the pollutant removal function of riparian areas.

5.3.1. Hydrology

Hydrologic regimes at the terrestrial-aquatic interface impart a particularly significant influence on the attenuation of pollutants by riparian areas. Three principal pathways govern water movement through these systems: 1) overland flow and shallow subsurface flow from adjacent uplands, 2) groundwater flow, and 3) instream water movement that includes hyporheic exchange as well as flood conditions (NRC 2002). Each of these flow paths can act as conduits for pollutant transport to aquatic ecosystems depending on site-specific conditions and pollutant type. Furthermore, seasonal stream flows, fluctuating water tables, and intermittent flooding create a dynamic environment that subjects pollutants to a range of biogeochemical processes.

Upland sources of water often originate as precipitation. During and immediately after a precipitation event, water from upland areas follows different flow paths to the stream channel, each contributing differently to pollutant transport and fate. Overland flow can be either infiltration-excess[2] (Hortonian overland flow) or saturation-excess[3] overland flow. Water that enters the soil profile can also travel downslope in shallow subsurface flow (interflow) through the unsaturated zone[4]. Depending on site-specific conditions, water in one of these flow paths may switch to another.

Collectively these flow paths are commonly termed hillslope runoff. Under certain circumstances, such as in the presence of deep, well-drained soils that facilitate percolation, portions of the shallow subsurface flow can reach the groundwater table and resume transport in the groundwater system. These pathways extend into riparian areas before reaching a surface waterbody.

As overland flow travels through the landscape it can pick up pollutants that can be in either particulate or soluble form. When water infiltrates the soil surface, suspended particulate matter and associated contaminants are entrapped at the soil surface, almost exclusively limiting the form of pollutants that are transported through the subsurface to soluble forms that remain in solution. However, recent research highlights the significance of colloid-facilitated transport as an additional means by which contaminants can move through the subsurface (Sen and Khilar 2006; Bradford and Torkzaban 2008). Colloidal forms (particles ranging from 1 to 1,000 nm) can remain dispersed in solution and exhibit characteristics resembling solutions. This behavior can consequently mobilize substances that tend to sorb to soil particles or organic matter that would otherwise not be able to move through the subsurface. While the fundamental physics and chemistry of this mechanism is understood, the contribution of colloids to pollutant migration through the soil profile is unresolved. Essentially no literature exists on the role of colloids in riparian areas, contributing to uncertainty in predicting the ultimate fate of associated pollutants.

The fundamental variables of interest regarding groundwater are flow rate and travel time, which influence natural chemical and biological processes that remove soluble pollutants, such as sorption to soils, microbial degradation, and plant uptake (Vogt et al.

2 Infiltration-excess overland flow occurs when water enters a soil system faster than the soil can absorb or transport it, such as when precipitation exceeds the infiltration capacity of the soil.

3 Saturation-excess overland flow occurs when the soil becomes saturated, and any additional precipitation results in runoff.

4 The unsaturated zone is also known as the vadose zone. It extends from the ground surface to the water table. Beneath the water table is the zone of saturation.

2012). As groundwater approaches the stream margin biogeochemical activity increases, and this gradient contributes to temporal and spatial variability in solute fluxes (Hayashi and Rosenberry 2002). It should be noted that groundwater exhibits a different geochemical composition than shallow subsurface flow that originates from precipitation events. Groundwater samples typically have a greater specific conductance (related to salinity), higher mineral content and elevated pH (Landmeyer 2011). Differences in chemical composition and biogeochemical activity are likely to manifest differences in pollutant removal from groundwater.

The hyporheic zone is the region beneath and alongside the streambed that represents the groundwater-surface water interface. While hydrologists have a solid understanding of most other hydrologic processes occurring in riparian areas, understanding of the exchanges between groundwater and in-channel surface waters is considerably less (UKEA 2009; Gu et al. 2012). Hyporheic flow patterns are multifaceted and influenced by the pressure gradient at the stream margin, (micro)morphology of the channel, the spatial distribution of hydraulic conductivity along the streambank, and the water exchange rate between the river and the riparian area (Kalbus et al. 2009; Lewandowski 2011). The complexity of the hydrologic regime is further compounded by seasonal variations, and at times intra-seasonal oscillations, in the direction of water flow (Wroblicky et al. 1998), as well as instances where ambient movement of deeper groundwater flows near the interface. Despite the confounding nature of the hyporheic zone, it is vital to consider hyporheic exchange when discussing subsurface fluxes of pollutants, as this zone is a direct link to streams through which contaminants can be transported to lotic systems (Gordon et al. 2004).

As groundwater approaches a streambank, biogeochemical activity increases. Groundwater flow rate and travel time through the riparian area influence natural chemical and biological processes that remove soluble pollutants.

Not only does the hyporheic zone play a critical role in regulating pollutant fluxes from riparian areas to the adjacent lotic environment, the heterogeneous structure at the interface, an oscillating water table, and shifting flow regimes exert a significant influence on biogeochemical cycling. The fluctuating water table alters oxygen concentrations and oxidation-reduction (redox) potential, and the flow regime provides a continuous source of reactants. This dynamic environment allows for anaerobic and aerobic processes to occur simultaneously and in close proximity (Wang et al. 2014). The strong hydraulic and biogeochemical gradients that result from mixing of the subsurface water coming from riparian areas and the surface water of the stream channel create biogeochemical hot spots that exhibit disproportionately high reaction rates compared to the surrounding matrix (McClain et al. 2003). For instance, the convergence of shallow subsurface flow and groundwater at the stream interface can generate hot spots of denitrification. Similarly, hot moments represent brief periods of elevated reaction rates relative to longer periods (e.g., during a rainfall event). Later sections of this chapter discuss this concept in more detail.

5.3.2. Soils

Soils play a critical role in influencing the transport and fate of pollutants in riparian areas. Soil texture and structure act as primary hydrologic regulators, significantly influencing the movement and distribution of contaminants. Comprised of a complex mixture of solid, liquid, and gaseous phases, riparian soils provide a heterogeneous matrix that supports plant and microbial communities. The solid phase encompasses mineral and organic particles of differing sizes and chemical composition that can sorb metals, organic chemicals, and other pollutants, thereby preventing them from migrating to the stream channel. The multiplicity and interaction of various biogeochemical processes in riparian soils contribute greatly to pollutant removal.

Unlike upland soils that are derived from terrestrial parent material, riparian soils primarily develop through the deposition of sediments that originate from various upstream sources. These alluvial deposits establish a heterogeneous patchwork of stratified sediments of different textures, which influences the movement of waterborne contaminants. Huggenberger et al. (1998) provide a good review of the geomorphology and characterization of alluvial soils, but a brief description is warranted here to provide a background related to the movement of contaminants through riparian soils. Deposits of clay, silt, sand, and gravel, and continual disturbance by seasonal high flows and occasional extreme flood events, create a complex mosaic of soil microenvironments that can vary considerably both vertically within the soil profile and along the length of the stream channel (Malanson 1993). A general trend can be observed where coarser sediments are deposited along steep-gradient streams while finer particles are washed downstream and deposited along low-gradient reaches as stream energy dissipates and wider floodplains develop (BLM 2003). Soil particle size also tends to decrease moving away from the stream edge (Huggenberger et al. 1998). This vertical, longitudinal, and lateral spatial structure results in disparate hydrologic conditions, and corresponding differences in pollutant fate, at locations in close proximity.



Rough-skinned Newt Taricha granulosa/*Renee Kinnick, WDFW*

The soil microenvironments described above influence hydrologic conditions, which consequently affect pollutant transport. Soil texture and structure dictate water storage capacity and retention, flow paths and hydraulic conductivity. Coarse textured soils enable a greater hydraulic conductivity that shortens hydraulic residence time in the riparian area, thereby reducing the period in which attenuation mechanisms can act on soluble contaminants before they reach the stream channel. Water may percolate below the root zone and limit potential interactions between vegetation and pollutants in deep, well-drained soils, such as those commonly found in forested riparian areas in humid climatic regions (NRC 2002). However, the root zone intercepts subsurface flow to a greater degree in forested riparian areas that exhibit shallow soils overlying a confining layer (e.g., shallow aquiclude). Overland flow that predominates in arid environments often undergoes limited infiltration due to a tendency for riparian soils to exhibit low permeability in these regions, which allows much of the runoff and associated waterborne contaminants to enter the stream with minimal attenuation (NRC 2002; Buffler et al. 2005).

Altered soil structure can influence pollutant attenuation (Vervoort et al. 1999). Compaction, for instance caused by over-grazing or vehicular traffic, and accompanying structural changes and surface soil instability can lead to diminished infiltration and amplified overland flow (Bohn and Buckhouse 1985; McInnis and McIver 2001). Soils with low infiltration rates typically exhibit a diminished capacity to retain pollutants in riparian areas (Johnson and Buffler 2008). Subsurface soil structure influences water movement and distribution in the unsaturated zone, affecting pollutant transport. Subsurface soil structure also impacts soil aeration and plant root growth, which have ramifications on pollutant fate. Preferential flow in soil macropores represents another facet of soil structure that affects pollutant removal (Allaire et al. 2015). Preferential flow of water through large connected void spaces in soils, which result from fractures, animal burrows and other processes, can enhance subsurface pollutant transport to river systems (Angier et al. 2002; Fuchs et al. 2009; Menichino et al. 2014). Alluvial deposits in riparian areas can further increase the connectivity of subsurface flows with stream channels, increasing lateral contaminant transport toward the stream channel. Preferential flow paths diminish the potential for contaminant sorption by both reducing interactions with soil particles and associated sorption sites and contributing to a higher flow velocity that reduces sorption kinetics. Although preferential flow paths have been a familiar concept in the field of soil science for some time, the recognized importance of these conduits has increased in recent years. This enhanced understanding is particularly important for controlling pollutants such as phosphorus that historically were not considered to undergo much, if any, subsurface transport (Angier et al. 2002; Fox et al. 2011a).

Artificial preferential flow also can be created by tile drains that are used by agricultural operations to remove excess water from the soil profile. Tile drains have been shown to enhance the movement of nutrients and herbicides from agricultural fields to streams, bypassing the natural attenuation processes that would have otherwise reduced the movement of these agrochemicals to aquatic ecosystems (Guan et al. 2011; Vidon and Cuadra 2011; Jaynes and Isenhart 2014).

In addition to playing an integral role in influencing the hydrologic linkage between upland areas and the stream channel, riparian soils provide a dynamic framework that regulates biogeochemical processes that act on contaminants. Soluble pollutants that have entered the soil profile, either from subsurface flow from upland areas or through infiltration in the riparian area, are subject to a variety of processes. Contaminants prone to sorption can be retained within the soil profile of the riparian area, reducing their potential of migrating to the stream channel. Chemicals typically have a greater affinity for clay minerals or organic matter, and thus the attenuation due to sorption will vary depending on



Riparian area along White River/Alan Bauer

the soil composition. Microbial assemblages in riparian soils can contribute to the assimilation, transformation, and degradation of a range of chemicals. Anaerobic conditions in saturated soils found in riparian areas differ considerably from the aerobic environments of adjacent uplands, altering the redox potential. The fate of numerous contaminants is influenced strongly by the redox potential of the soil and associated microbial communities. Fluctuating water tables can alter the redox state, resulting in seasonal variations in chemical species distributed within the riparian area. Although broad generalizations can be made, the literature highlights that temporal changes in soil complexities are not well understood (NRC 2002).

Vegetative communities are also impacted by soil conditions in riparian areas. Plant species exhibit habitat preferences that follow soil moisture gradients across riparian areas. The influence of vegetation on contaminant fate and transport will be discussed in the next section. However, it is salient to note here that soil compaction and other disturbances can lead to invasive plant species that can degrade riparian ecosystem function in relation to pollutant attenuation. Disturbed soils can lose their native species diversity and develop more homogenous stands of an exotic species (e.g., Himalayan Blackberry *Rubus armeniacus*) that often do not have the same vegetative density or root structure as the native population, thereby altering riparian area efficacy in pollutant removal.

5.3.3. Vegetation

Riparian vegetation also plays a critical role in attenuating pollutant transport to surface waters. Plants physically alter the movement of water and associated contaminants, provide habitat for microbial communities that assimilate and transform contaminants, and influence soil redox conditions that govern many biogeochemical cycles. Plant root systems provide bank stabilization, which reduces the direct introduction of sediments into aquatic ecosystems via streambank erosion. Soil stabilization also limits erosion and gully formation that can result from overland flow moving through a riparian area. In addition, forested riparian



Vegetated buffers reduce nonpoint source pollution to rivers and streams/U.S. Dept. of Agriculture, National Agriculture Imagery Program

areas have been shown to enhance instream processing of contaminants, including nutrients and pesticides (Sweeney et al. 2004). This section provides a brief overview of the influence vegetation has on pollutant attenuation in riparian areas and identifies critical points to consider when developing management plans. A number of focused review articles present further details on riparian vegetation-hydrology interactions and mechanisms by which plants can attenuate contaminants in riparian areas (e.g., Tabacchi et al. 2000; Williams and Scott 2009; Dosskey et al. 2010).

The high vegetation density inherent in streamside ecosystems serves a critical function in modulating overland flow and amplifying infiltration. The stems of grass and herbaceous groundcover, trunks of woody vegetation, and downed wood create resistance to overland flow, slowing it, and causing deposition onto and infiltration into the soil profile (Fisher and Binkley 2000; Schuster and Grismer 2004). Vegetation also helps maintain soil structure by increasing soil macropore formation through root growth and decay, which further enhances soil permeability. Soluble contaminants present in overland flow enter the soil column, augmenting attenuation through the various mechanisms discussed throughout this chapter. The reduced velocity of the overland flow caused by the riparian plant community causes suspended particles to settle out of the water column, reducing the transport of sediment and sediment-borne pollutants to the stream. Similarly, lower velocity flows will limit erosion within the riparian area, reducing potential contributions to stream sediment loads and avoiding gully formation, which concentrates overland flows and short circuits pollutant attenuation. A dense overstory canopy will further reduce erosion by intercepting precipitation



that would fall directly onto bare soil, and a dense plant community also reduces erosion of riparian soils by diminishing the velocity of runoff and floodwaters (Schultz et al. 2000).

Vegetation also increases soil surface roughness by producing herbaceous litter and woody debris, and by altering micro-topography, which slows surface flow and enhances infiltration of water. In contrast, sites with exposed mineral soil tend to exhibit low surface roughness that limits infiltration, and these sites are susceptible to increased transport to streams via overland flow.

Vegetation also influences the hydrologic behavior of subsurface and groundwater flow through streamside areas. Root uptake and transpiration by both herbaceous and woody plants can modify subsurface flow and soil moisture regimes in the unsaturated zone under unsaturated conditions. These alterations not only influence pollutant transport through riparian soils, but also affect redox conditions that govern biogeochemical transformations. Deeper-rooted plants can impact groundwater levels by reducing the pressure head at the water table through direct uptake or by extracting water along a water potential gradient. Hence, trees can cause daily or seasonal changes to water table levels, a phenomenon more prevalent in drier climates (Landmeyer 2011). Correspondingly, contaminant fluxes from riparian areas to surface waterbodies may exhibit similar diurnal and seasonal patterns. Water uptake by roots can similarly form a hydraulic barrier that creates an upward water flow through the soil profile that can reduce pollutant leaching and inhibit contaminant plumes from spreading horizontally (Pilon-Smits 2005).



Chinook salmon Oncorhynchus tshawytscha/*Morgan Bond*

While vegetation modulates water flow, it is vital to recognize the interconnected nature between riparian plant communities and hydrologic regimes. Riparian plant communities are determined largely by their adaptation to high moisture environments. Groundwater often represents a primary water source for riparian plants, principally trees and deeper-rooted flora. Consequently, alterations in groundwater regimes can have a detrimental impact on species diversity, density, and distribution, especially in drier regions where vegetation is typically concentrated along a narrow band of suitable soil moisture conditions (NRC 2002). Dramatic changes to plant communities can significantly limit the pollutant removal function of a riparian area. Thus, managers should consider the interrelationships between vegetation and subsurface hydrology. Kuglerová et al. (2014) expounded on this theme in a recent review examining the effects of forest management on groundwater processes and resultant water quality. The authors concluded that logging operations in riparian areas and hydrologically connected upland forests can alter groundwater regimes and affect water quality. They recommended site-specific riparian management where wider buffers would be implemented at critical groundwater discharge locations but narrower buffers would be allowed at sites lacking groundwater flow paths.

Riparian management strategies often emphasize the effectiveness of forested riparian areas for protecting water quality. However, research over the last two decades reveals that forests are not always the most effective vegetation for removing pollutants. Results can vary between sites, but research has shown that grass buffers (also called vegetative filter strips or grass filter strips) can yield similar reductions in sediments and sediment-borne pollutants (Correll 1997; Hawes and Smith 2004; Dosskey et al. 2010). Grasses and similar plants create a dense vegetative obstacle that slows overland flow, promotes deposition of sediments and attached pollutants, and provides an opportunity for the plants and associated microbes to capture soluble contaminants that enter the soil profile (Dillaha et al. 1989). Filter strips often serve as an effective alternative for protecting water quality from pollutants generated by upland activities where it is impractical to implement forested riparian areas, such as adjacent to agricultural fields, in urban settings, or along highways.

According to Lacas et al. (2005), much of the sediment removal effected by grass filter strips occurs mainly as a result of sedimentation immediately upslope of the strip in an area of still water that builds up against the strip's outer boundary. Furthermore, they note, the deposit formed upslope can expand into the filter strip, and that sediment deposition can increase to the point of forming channels that concentrate overland flow and induce the formation of water pathways with high velocities.

The primary drawback of a vegetative filter strip is that it addresses only pollutant removal and does not provide the other functions of forested riparian areas such as shading, large wood, and bank stability. Furthermore, grasses have a relatively shallow root

structure and thus vegetative filter strips are not as effective in removing pollutants from groundwater. In contrast, trees inherently have a deeper root zone that can effectively intercept subsurface flow and often reach shallow groundwater. Therefore, forested riparian areas can be more effective at removing soluble pollutants in subsurface and groundwater flow through plant uptake and by associated microbial communities that act on the pollutants in the rhizosphere. Considering both situations, structurally diverse riparian areas that contain a combination of grasses, shrubs and trees provide a more robust system for mitigating a range of pollutants (Fischer and Fischenich 2000). A similar concept was proposed by Welsch (1991), who presented a three-zone model that considered an herbaceous filter strip between uplands and the start of the riparian area, followed by a managed forest, and culminating with an undisturbed forest immediately adjacent to the streambank.

Vegetation in riparian buffers also provides a range of phytoremediation processes, wherein plants and associated microbial populations remove, contain, degrade or eliminate pollutants. Investigations on the phytoremediation potential of riparian vegetation to attenuate nutrients have been conducted for some time and results are well documented. The management of vegetation specifically as a pollutant treatment technology for organic compounds and metals has gained acceptance in general over the last couple of decades (Pilons-Smits 2005), but studies on phytoremediation specific to riparian areas remains fairly limited. However, recent research suggests that the promotion of specific plant species to attenuate organic chemicals and metals in riparian areas can be used to treat localized areas of concern (e.g., chemical spills, industrial sites, mine tailings). Design of a phytoremediation treatment system depends largely on the three primary factors identified by Susarla et al. (2002) that govern contaminant uptake and distribution in plants and the surrounding soil system: physicochemical characteristics of the pollutant (e.g., polarity, lipophilicity), environmental conditions (e.g., soil moisture, pH), and plant characteristics (e.g., available enzymes, root structure). Specifics on the phytoremediation potential of different pollutant classes in riparian areas will be discussed later in the respective sections of this chapter, while more detailed descriptions of phytoremediation are readily found in a large number of scientific reviews (e.g., Salt et al. 1998; Pulford and Watson 2003; Pilon-Smits 2005; Sarma 2011).

5.4. Specific Pollutants

For the purposes of riparian area management, we are most interested in five types of water pollutants: sediments, excess nutrients (in particular, nitrogen and phosphorus containing compounds), metals (in particular copper), toxic organic compounds (especially pesticides), and pathogens (especially those related to agricultural animal waste). The physical, chemical, and biological processes through which riparian areas remove these pollutants from water vary tremendously. Consequently, the degree to which riparian areas can remove each of these pollutants, and thereby protect aquatic ecosystems, varies significantly. The following sections describe the complicated processes and mechanisms involved in determining removal efficacy of specific pollutants by riparian areas.

Vegetation in riparian buffers provides a range of phytoremediation processes, wherein plants and associated microbial populations remove, contain, degrade or eliminate pollutants.

5.4.1. Sediments

Sediment transport in streams is a natural process, but excessive sediment loads can significantly degrade water quality. The impact of sediments on aquatic organisms has been researched extensively for many decades, and can consist of lethal, sub-lethal and behavioral effects (Newcombe and MacDonald 1991). Sediments that settle out of the water column can smother gravel and cobble streambeds that are essential for salmonid spawning and habitat for benthic macroinvertebrates and other organisms that form critical links in stream food webs. For example, the filling of interstitial spaces in coarse sediment matrices with fine sediments are thought to reduce or eliminate refuge and foraging habitat for selected life stages of stream-dwelling amphibians (Welsh and Ollivier 1998). Increased turbidity levels, indicative of suspended particles, can elicit physiological stress in fish through gill abrasion, impaired immune function and lowered growth rates (Redding et al. 1987; Au et al. 2004). High suspended sediment loads reduce visibility, which limits fish foraging ability and influences predator avoidance reactions (Redding et al. 1987). Aquatic vegetation and periphyton can be reduced due to diminished light penetration. Sediments also impart indirect effects on aquatic organisms. Elevated turbidity decreases the water albedo (reflectiveness), which increases the fraction of radiant energy absorbed by the water and increases stream temperature, leading to corresponding reductions in dissolved oxygen concentrations. Furthermore, sediments serve as a transport mechanism for other pollutants, carrying attached contaminants from upland sources to the stream channel. Soil particles that harbor legacy contaminants perpetuate water quality problems, such as those caused by DDT in some Washington streams despite this pesticide being banned in 1972 (Ecology 2007).



Restored vegetation in riparian area to capture pollutants in runoff/U.S. Dept. of Agriculture, National Agriculture Imagery Program

While the extent of these detrimental effects is largely a function of concentration and duration, and there is little agreement on the degree of ecological risk in the literature, sediments are a ubiquitous pollutant that many scientists regard as the worst form of pollution in aquatic ecosystems (Newcombe and MacDonald 1991; Waters 1995).

Erosion rates in uplands can be significantly increased by agricultural activities, construction sites, deforestation, and other land uses. Riparian areas effectively remove soil particles carried from upland areas via overland flow by slowing overland flow velocities, promoting sediment settling, and acting as sediment sinks[5]. Mass wasting (also referred to as mass movement, mass failure, or slope movement), wherein large masses of soil and geologic material move downslope into a stream, acts as another potential sediment source in hilly or steep mountainous environments. Although limited in spatial distribution, this geomorphic process can overwhelm the sediment removal capacity of riparian areas.

Our understanding of the riparian area's sediment removal function will be enhanced with a basic understanding of sediment erosion and transport processes. Briefly, the impact of falling raindrops can loosen soil particles via splash erosion. Overland flow picks up soil particles and transports them downslope through sheet erosion. Generation of concentrated flow paths results in rill erosion, which enhances sediment delivery and increases erosion rates through flow that is on the order of a few centimeters deep. Gully erosion develops when deep, narrow channels form, leading to increased erosion and more rapid sediment delivery. It is important to prevent the formation of rill and gully erosion entering riparian areas because channel formation extending into riparian areas short-circuits sediment removal and represents a direct conduit from terrestrial to aquatic systems. Merritt et al. (2003) provide an extensive review of various erosion and sediment transport models that can be employed to determine the potential sediment loads that could enter a riparian area.

While the upland hydrologic regime acts as a principal driver governing the movement of eroded soil particles, the aforementioned erosion mechanisms can be significantly tempered by intact soil cover. This can be accomplished by vegetation overlying a dense cover of herbaceous litter and woody debris. Vegetation increases surface roughness which slows surface flow and enhances water infiltration, both of which promote the settling out of sediments (Figure 5.1). Muñoz-Carpena et al. (1999) showed that spacing between vegetation is the most important parameter in sediment attenuation in riparian buffers, although soil characteristics, sediment load, and slope also play prominent roles.

Agriculturally generated nitrogen continues to present an issue, and it is becoming increasingly apparent that smaller hobby farms and lawn fertilizers used in suburban and urban areas can lead to severely degraded water quality.

[5] Streambank erosion, channel incision, and surface erosion in riparian areas present other potential sediment sources. As this chapter focuses on the removal of pollutants generated by upland activities, these geomorphological processes are outside the scope of this chapter. However, it should be noted that riparian vegetation can increase bank stability, thereby decreasing erosion along the stream channel (see Chapter 2).

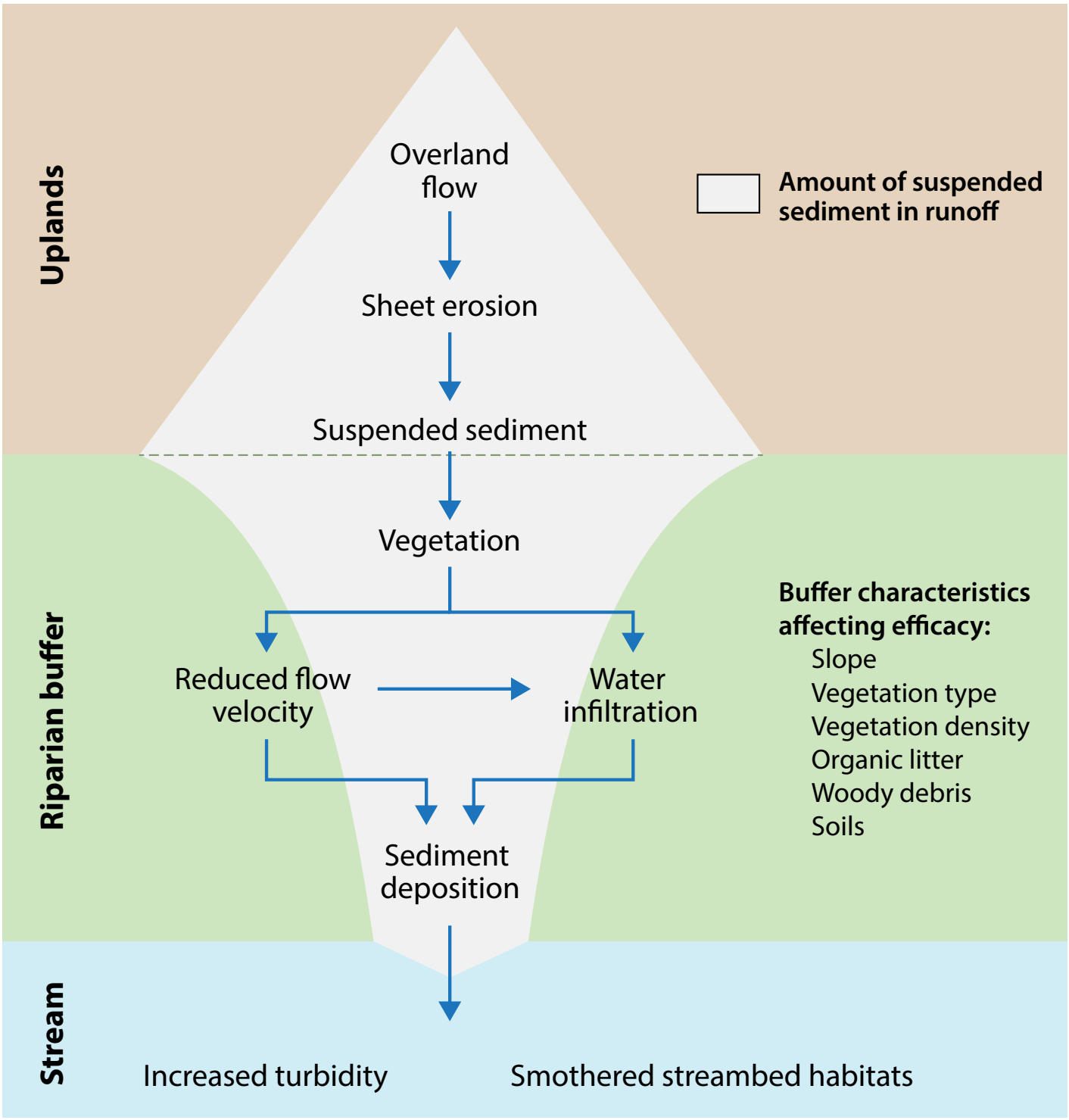


Figure 5.1 Efficacy of riparian buffer in removal of sediment from runoff. The amount of suspended sediment in runoff increases through sheet erosion of upland soils. Vegetation, woody debris, and organic litter in riparian buffer reduce flow velocity. Reduced flow velocity and increased water infiltration into soils causes deposition of suspended sediments. Sediments not removed from runoff increase turbidity and can smother gravel or cobble streambed habitats.

Riparian buffer widths required for sediment attenuation vary considerably depending on the site-specific conditions (e.g., slope, area of adjacent uplands, drainage paths, vegetation density). Sediment particle sizes are also a consideration in buffer width design – larger particles are deposited within the first 10 to 33 ft (3 to 10 m) of a buffer but smaller particles settle out at greater distances (Sheridan et al. 1999; Syversen et al. 2001; Dosskey et al. 2002; Yuan et al. 2009). The potential quantity of overland flow should also be a consideration when determining buffer widths, and hence, upland area should also factor into the determination of buffer width. Leeds et al. (1994) suggested that on agricultural lands the ratio of field drainage area to buffer area should be no greater than 50:1, and for consistently higher water quality the ratio should be on the order of 3:1 to 8:1. From research conducted on forested lands undergoing timber harvest, Clinton (2011) concluded that leaving a forested riparian buffer of 33 ft (10 m) would sufficiently reduce sediment transport to the adjacent stream, assuming responsible timber harvest practices, although greater widths have been recommended depending on the circumstance (Castelle et al. 1994). Furthermore, the relationship between buffer width and sediment attenuation is non-linear, necessitating a disproportionate increase in width to achieve an incremental increase in sediment removal. This relationship was described in a literature review of research on riparian buffers conducted by Sweeney and Newbold (2014). They concluded that a sediment removal efficiency of about 65% is typical for 30 ft (10 m) buffers but an 85% removal efficiency required more than twice that width, about 100 ft (30 m).

5.4.2. Excess Nutrients

Excess nutrients, in this context referring specifically to nitrogen and phosphorus, have long been recognized as significant water quality impairments. Eutrophication, the nutrient enrichment of aquatic systems, promotes algal blooms that shift community structure. Subsequent bloom die off leads to oxygen deficiency in the water column as oxygen is consumed by microorganisms during the decay of the excess organic matter. Hypoxia can have devastating consequences on aquatic animal communities, killing immobile organisms (e.g., clams) and mobile species (e.g., fish) that are not able to escape the deoxygenated zone. Excessive accumulation of cyanobacteria (formerly known as blue-green algae), resulting from shifts in nutrient ratios in the water, can release cyanotoxins which can cause dermal reactions, gastroenteritis, liver and kidney poisoning, and neurological impacts in humans or animals following water contact. Canine deaths due to cyanotoxin exposure have been confirmed throughout the country, with Washington reporting the highest number of cases among 27 states (Backer et al. 2013). In some cases, selected nutrients are toxic at concentrations within typical fertilizer application ranges. For example, embryos of the highly aquatic Oregon Spotted Frog *Rana pretiosa*, a federally threatened species in the Pacific Northwest, all died after 15-day exposure to nitrite (NO_2^-) concentrations lower than 2 mg/L (Marco et al. 1999).

Fertilizers and manures are major sources of excess nutrients entering riparian areas. Wastewater discharges and leaking septic tanks introduce nutrients to riverine systems, but those sources fall outside the scope of this review. Agricultural activities have long been blamed as the biggest nonpoint source for nutrients. The enormous contribution of phosphorus to the eutrophication of surface waters led to extensive promotion of various best management practices (BMPs)[6] for reducing off-field transport of phosphorus. Nevertheless, there has been a general lack of improvement in water quality of many receiving

6 In general usage "best management practice" (BMP) means one or more practices that are determined to be an effective and practicable means of preventing or reducing the amount of pollution generated by nonpoint sources to a level compatible with water quality goals. Under Washington State regulations, BMP means physical, structural, and/or managerial practices approved by the Washington Department of Ecology that, when used singularly or in combination, prevent or reduce pollutant discharges (WAC 173-201A-020).

streams. In addition to existing agricultural sources of phosphorus, it is increasingly evident that "legacy phosphorus" from past activities that accumulated in watersheds contributes to current water quality problems (Jarvie et al. 2013). Agriculturally generated nitrogen continues to present an issue, as it can leach through the soil and move with shallow groundwater flows through riparian soils and enter receiving waters. It is also becoming increasingly apparent that smaller hobby farms and lawn fertilizers used in suburban/urban areas can lead to severely degraded water quality (Cheng et al. 2014).

For a thorough discussion of nitrogen and phosphorus dynamics in natural, undisturbed riparian areas see Chapter 6. For this chapter it is salient to note the differing biogeochemical cycles exhibited by nitrogen and phosphorus: nitrogen displays complex transformations between various species including atmospheric forms whereas phosphorus undergoes relatively simple shifts between soluble, sorbed, precipitate and organic forms. Nitrogen and phosphorus are often casually grouped together as nutrients, but this discrepancy in chemical behavior leads to significantly different considerations when assessing their removal by riparian areas.

Nitrogen

Due to its soluble nature in its aqueous forms, a significant portion of the excess nitrogen entering streamside areas will enter riparian soils either through infiltration or via groundwater transport. Nitrogen then can undergo attenuation through a variety of mechanisms. It is widely accepted that denitrification acts as the primary pathway for removing nitrate (NO_3^-) from water in riparian areas (Fennessy and Cronk 1997; Cey et al. 1999; Wang et al. 2014). This process is governed by specific denitrifying bacteria that use nitrate during anaerobic respiration, reducing it to the gaseous forms of nitric oxide (NO) and nitrous oxide (N_2O) and ultimately molecular nitrogen (N_2). These gaseous species can then volatilize in harmless forms to the atmosphere and be completely eliminated as a potential pollutant. This process requires the presence of a shallow water table, anoxic conditions, denitrifying bacteria and an available carbon source—conditions commonly associated with riparian areas. Hydric soils, despite occupying a limited area within riparian areas, are important sites of anaerobic activity that promote denitrification. If groundwater bypasses riparian soils then nutrient pollution of surface waters may occur despite the presence of a riparian buffer (Burt et al. 1999). In a highly cited critical review of research on nitrate removal in riparian areas, Hill (1996) asserted that understanding denitrification requires a better understanding of groundwater interactions with riparian vegetation and soils.

Plant uptake of dissolved nitrogen in subsurface flows moving through riparian areas provides an additional mechanism that can remove considerable amounts of nitrate. A significant difference from denitrification though is that vegetative uptake is often viewed as transient storage for nitrogen because nitrogen assimilated by plants will be reintroduced to the ecosystem following leaf senescence or plant death. Both grasses and trees have been widely shown to remove nitrogen in riparian areas, but studies have yielded contradictory observations and conclusions regarding which vegetation type is more effective (Groffman et al. 1991; Osborne and Kovacic 1993; Schnaebel et al. 1997). A meta-analysis performed to assess the key riparian variables responsible for nitrogen removal concluded that forested buffers exhibited the greatest propensity for nitrogen uptake, and surpassed the efficacy of both grasses and communities composed of both trees and grass (Zhang et al. 2010). Although this study did not end the debate, many researchers believe that deeper and more expansive root structure allows trees to take up greater proportions of nitrogen. A riparian area's age may also be a variable affecting nitrogen removal. Cors and Tchon (2007) evaluated denitrification enzyme activity in two

riparian areas of different ages: 6 and 20 years old. They found the older system was significantly more effective at denitrification, which was attributed to a greater accumulation of carbon.

Research focusing on hot spots and hot moments has provided a more nuanced understanding of nitrogen dynamics in riparian areas. Hot spots and hot moments that develop in the hyporheic zone are increasingly being recognized as a contributing mechanism to nitrogen attenuation (McClain et al. 2003; Vidon et al. 2010; Gu et al. 2012). A landmark paper by Hedin et al. (1998) exemplified the concept of enhanced nitrogen removal at hot spots along the soil-stream interface in a mixed forested-agricultural watershed. A first-order stream exhibited two converging primary flow paths, one consisting of shallow subsurface flow containing high concentrations of chemical reducers (i.e., dissolved organic carbon, CH_4, and NH_4^+) and the other a near-stream upwelling of deep groundwater containing high concentrations of oxidizers (i.e., NO_3^-, N_2O, and SO_4^{2-}). A zone of high denitrification resulted that was less than 3 ft (1 m) wide and remained active for the two-year study period. Hedin et al. (1998) suggested that nitrate removal via denitrification could be sustained depending on the spatial location of high flow pathways, the propensity of the chemical environment to support rapid denitrification, and the availability of oxidizable carbon. Furthermore, they recommended that management actions enhancing natural carbon inputs could be adopted to optimize nitrate removal by denitrification.

Phosphorus

Unlike nitrogen, phosphorus possesses a binding affinity for soil particles and typically enters riparian areas adsorbed to soil particles carried by overland flow. Hence, phosphorus removal is closely connected to sediment removal by riparian areas. A comprehensive review of phosphorus dynamics in grass buffer strips surmised that that optimum phosphorus retention occurs in filter strips that are at least 16 to 33 ft (5 to 10 m) wide (Dorioz et al. 2006), but this recommendation is debatable. It is generally recognized that a positive correlation exists between buffer width and phosphorus retention in riparian areas, and hence, buffers greater than 33 ft (10 m) offer greater removal efficacy. Independent studies have consistently found 60% to 80% phosphorus removal by buffers roughly 15 to 53 ft (4.6 to 16.3 m) wide (Dillaha et al. 1989; Vought et al. 1994; Lee et al. 2003). Forested riparian ecosystems assessments have yielded less consistent results, with studies showing phosphorus removal ranging from 30% to 80% in deciduous riparian areas (Lowrance et al. 1984; Cooper and Gilliam 1987). This discrepancy corresponds with the premise that a robust stand of grass provides better attenuation of sediments and associated pollutants than forested riparian areas.



Unknown species of crayfish in the Deschutes River/Steve Boessow, WDFW

Even though these results appear convincing at first glance, a significant proportion of the body of research consists of short-term studies that fail to account for changes in riparian function over time. While it can confidently be stated that riparian areas offer effective short-term control of sediment-bound phosphorus, uncertainty exists regarding their long-term efficacy. Filter strips receiving sediment loads are well known to become less effective over time due to internal erosion and sediment accumulation. The continual incorporation of phosphorus into surface soils presumably would lead to a saturation of the system that could not only decrease removal of new phosphorus entering the

riparian area, but also lead to release and export of dissolved phosphorus to the stream that had previously been stored in riparian soils (Muscutt et al. 1993). Some studies have reported significant removal of soluble phosphorus in surface runoff (Peterjohn and Correll 1984). However, contradictory reports indicate little retention of soluble forms, with the majority moving through the area in surface runoff (Daniels and Gilliam 1996). Plants take up some of the phosphorus in the riparian soils, but this mechanism is not nearly as significant in removal as it is for nitrogen. Increased removal of soluble forms could potentially be achieved with various amendments, such as biochar (charcoal used as a soil amendment), that could enhance phosphorus sorption (Zhang et al. 2014).

A relatively new research topic related to phosphorus attenuation focuses on subsurface transport of soluble phosphorus forms. It was long accepted as dogma that phosphorus did not leach or move through the soil profile. Although scattered findings contradicted this view during the preceding decades (e.g., Peverill et al. 1977), this conviction remained recalcitrant and was still taught in university soil courses up until the last decade. This belief has now been dispelled by increasing evidence that phosphorus can move through the soil profile, particularly in coarse textured soils. A preponderance of the recent research on this topic has been conducted in upland soils, but the findings are relevant for riparian areas and are particularly true in coarse alluvial soils. This has been demonstrated by the rapid transport of soluble phosphorus forms through preferential flow paths (Fuchs et al. 2009). This movement can serve as an important transport mechanism that should be considered when determining potential phosphorus fluxes reaching the stream channel. Although extensive literature exists on phosphorus cycling in a variety of settings, relatively little information is available on phosphorus dynamics in the hyporheic zone and further research is needed to understand phosphorus flux through this interface between the stream and groundwater flowing through riparian areas (Zhang 2014).

While it can confidently be stated that riparian areas offer effective short-term control of sediment-bound phosphorus, uncertainty exists regarding their long-term efficacy. Riparian filter strips are well known to become less effective over time.

5.4.3. Metals

Metals (as well as metalloids that share similar properties, such as arsenic) are elements naturally found in geologic material. They enter the environment either through natural weathering processes or through anthropogenic activities. Localized metal deposits can result in elevated concentrations in streams that can be hazardous to biota. Metal pollution in aquatic ecosystems appeared as a serious environmental issue on a wide scale in the late 19th and early 20th century due to increasing industrial and mining activities. Contamination sources have grown over time to include a range of other activities, the most pertinent to this discussion on riparian areas being runoff from urban and agricultural lands. While mining activities present significant metal inputs into certain streams in Washington, protecting water quality from these sources requires the implementation of specific remediation techniques that are outside the scope of this chapter.

Metals present a significant environmental hazard that can lead to a variety of health issues in plants and animals. While some metals are essential elements required for normal growth and development of biota, these can also impart toxicological issues when concentrations exceed a given threshold. Among other health effects, metals can be carcinogenic, cause reproductive problems, and interfere with the normal function of the heart, bones, intestines, and kidneys. While debate continues over the specific mechanisms associated with metal toxicity in plants, it is generally recognized that oxidative stress represents a primary driver that results in cellular damage (Pinto et al. 2003). Some heavy metals bioaccumulate and biomagnify, which leads to elevated concentrations exhibited at higher trophic levels (Boening 2000). The propensity for metals to bioaccumulate can be magnified by biologically mediated transformation into organometallic complexes, such as methylmercury. Metal toxicity is often related to the chemical species formed, which often relates to their bioavailability. For instance, chromium(III) compounds are not considered a significant health risk while chromium(V) is a well-known carcinogen. Similarly, metal complexation with dissolved organic carbon often inhibits their bioavailability.

While copper's detrimental environmental impacts have been recognized for many decades (Sprague and Ramsay 1965), it has received increased attention in recent years as toxicity symptoms have become more pronounced. Copper is an essential mineral for organisms, contributing to enzymatic and metabolic function, but toxic effects have been observed at all levels of the aquatic food chain when it exceeds particular concentrations. Copper has been shown to have detrimental effects on plants, retarding growth at concentrations as low as 1.0 part per billion (ppb) and impeding photosynthesis at 5.0 ppb levels (USEPA 1980). While reductions in algal production can theoretically exert an indirect effect on zooplankton by limiting their food source, copper can impart a lethal effect on these organisms at low parts per billion levels (Ingersoll and Winner 1982). Similarly, significant mortality has been shown to occur in benthic macroinvertebrates at similar copper



Juvenile salmon need clean water/Ned Pittman, WDFW

concentrations (Clements et al. 1992). Copper presents a litany of issues to fish. Lethal concentrations vary considerably between fish species and fluctuate depending on environmental conditions. Sub-lethal effects are conveyed at lower concentrations, which include hindering osmoregulation, weakening immune response, altering enzymatic and metabolic activity, impairing olfaction (sense of smell), altering migration patterns and predator avoidance behavior, and modifying hatch rates (Lortz and McPherson 1977; Sorensen 1991; Rougier et al. 1994; Baldwin et al. 2003; Monteiro et al 2005; Sandahl et al. 2007; McIntyre et al. 2012). Synergistic impacts that occur when copper is present in combination with other pollutants highlights the current concern over this element (Hecht 2007). Effects similar to those observed in fish have been recorded in amphibians following exposure to rather low concentrations of copper ions (Cu^{2+}). For example, the concentration of copper at which half of larval Northern Leopard Frogs *Rana pipiens* would die following a seven-day exposure was estimated at 0.067 mg/L (Redick and La Point 2004). The same study revealed lethargy, loss of equilibrium, and loss of appetite at copper concentrations of 36 ppb. A widespread pattern in copper exposure studies with amphibians is a general impairment of predator evasion behaviors (Garcia-Muñoz et al. 2011).

Anthropogenic copper inputs to the environment include those of other metals, but what sets copper apart are two significant sources. The first is the agricultural use of copper-based pesticides. Copper sulfate and other copper-based pesticides are frequently used as a fungicide to protect a variety of crops, including fruits and potatoes. The second is the release of copper from vehicle brake pads. This unique source has received considerable attention as an environmental hazard worldwide, and has led to the 2010 adoption of Washington State's Brake Material Friction Act (RCW 70.285) that is phasing out copper in automobile brakes (Straffelini et al. 2015). Copper can also enter the environment through atmospheric deposition, which is a potential pathway in industrial and mining regions (USEPA 1980). These sources introduce copper into the environment as a nonpoint source pollutant, which makes copper very different from other metals. While the following discussion will continue to refer to metals in general, the reader should recognize that the nonpoint source nature of copper makes it the primary metal of concern in Washington in regards to attenuation in riparian areas.

Metals form various inorganic and organic species, the nature of which directly relates to its bioavailability and mobility through a riparian area. Metal speciation is driven through complex biogeochemical processes. Environmental conditions and the chemical nature of the surrounding constituents play a significant role in dictating the form that a metal might take. This is particularly relevant to riparian areas where fluctuating water tables alter redox conditions, and correspondingly metal dynamics in riparian soils. Daily oscillations related to the photocycle, for instance, have been shown to occur in aquatic ecosystems as a result of biogeochemical interactions involving temperature, acidity, and biofilms (Nimick et al. 2011). Consequently, zinc, manganese, and cadmium can increase several-fold between late afternoon and early morning. In contrast, arsenic undergoes the opposite diel pattern; meanwhile copper and lead do not undergo regular diel cycling.

The metal species resulting from soil acidity and redox conditions can form precipitates, exhibit an affinity to clay minerals and oxide/hydroxide compounds, and thus be more readily retained in riparian areas. Conversely, metals stay in solution as more mobile forms that leach and move toward the stream. Typically, metals more readily enter solution under acidic conditions. Meanwhile the ionic strength of the water (a measure of the concentration of all the ions in solution) presents a confounding variable in these processes. The impact of other ions manifests through enhanced metal desorption from soil particles with increasing

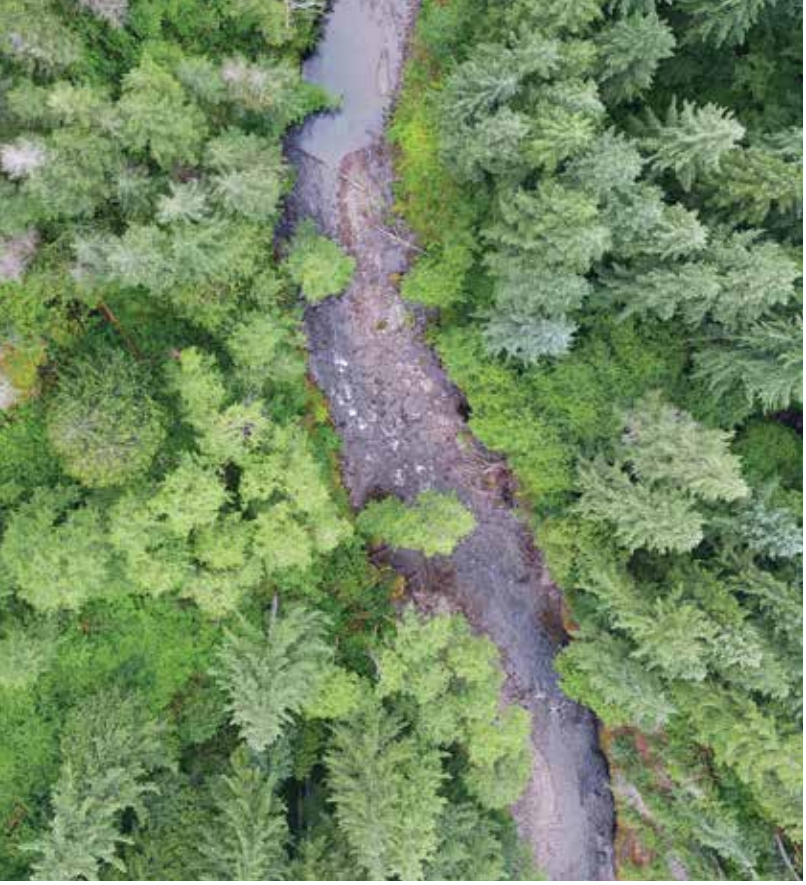
salinity. Carbonates in riparian soils promote metal retention by buffering acidity (i.e., preventing increased acidity), limiting metal solubility, and forming insoluble precipitates with metals.

Organic constituents in soil-water systems also play a major role in metal fate and transport processes. It has been clearly understood for some time that humic substances, a classification of complex and heterogeneous macromolecules that represent a substantial component of natural organic matter, have the capacity to bind significant amounts of metals (Reuter and Perdue 1977). While association of metal ions with soil organic matter can retain metals, humic substances can act as colloids and contribute to colloid-enhanced movement. The environmental factors and mechanisms involved in metal-humic interactions are multifaceted, but it is salient to recognize the impacts that organic matter in riparian soils can have on the movement of metals to the stream channel. A more detailed explanation of the inorganic and organic factors that influence metal behavior is presented in a review by Du Laing et al. (2009), which includes a specific focus on riparian areas.

Unlike organic contaminants that can degrade, metals are recalcitrant and removal in riparian areas depends largely on retention. Although the brief description of metal chemistry provided here elucidates the primary factors that affect their movement in the environment, management practices to enhance their attenuation are limited, and metal mobility will be driven overwhelmingly by environmental conditions. An exception to this statement is phytoremediation.

Phytoremediation of metals offers promise as a means to enhance metals removal in riparian areas. Although significant research on this process did not start in earnest until the late 1990s, since then hundreds of scientific papers have been published on the topic. Correspondingly, there is a plethora of review articles (e.g., Ghosh and Singh 2005; Sarma 2011; Koptsik 2014; Laghlimi et al. 2015). Four classes of phytoremediation can influence metal attenuation in soil, including phytoextraction (removal of metals from the soil-water system by plants), phytostabilzation (minimizing metal transport and sequestering them in the soil near the roots), phytovolatilization (uptake and transpiration by plants; this process is primarily limited to mercury and arsenic), and rhizofiltration (sorption, concentration and precipitation of metals in the root mass). Of these, the first two mechanisms are the most effective in attenuating metals (Laghlimi et al. 2015). In general, trees are a more effective form of vegetation due to their size, perennial nature, and the depth of root growth. Different metals will accumulate in different parts of a tree. For instance, copper tends to be immobilized and retained principally in the roots while zinc moves into the branches and leaf mass (Pulford and Watson 2003). Some plant and tree species act as hyper-accumulators that are tolerant of high metal concentrations in soils and can amass metals in their tissues through detoxification mechanisms (Sarma 2011). These species could be preferentially planted in areas where metals are a particular concern to help attenuate metal movement to the stream channel. As leaves will fall to the ground, riparian management could include the periodic removal of vegetative debris to off-site locations to avoid subsequent movement to the stream. Often there is no need to plant nonindigenous plants as a variety of common native riparian vegetative species can provide phytoremediation capabilities. For instance, willows (*Salix* spp.) have been shown to attenuate various metals in riparian areas to great effect (Bourret et al. 2009; Zhongmin et al. 2012).

Soil amendments offer another form of "green remediation" that has been increasingly used in soil systems since the turn of the century. A wide variety of amendments can be used either to mobilize metals by promoting uptake via phytoextraction or to immobilize (stabilize) metals in a solid phase. For instance, chelating agents have been applied at sites around the globe to enhance desorption, while phosphate



Tilton River/George Fornes, WDFW

fertilizers are common amendments intended to intensify metal sorption and form precipitates. Several topical reviews describing assorted soil additives have been published that provide more detail on this *in-situ* remediation technique (e.g., Bolan et al. 2014; Mahar et al. 2015). Similarly, over the last decade biochar has seen increased application in the context of attenuating metals (Ahmad et al. 2014). Although studies on the use of soil amendments to attenuate metals in riparian soils are limited, recent findings showed that additions of 11 different materials, such as biochar, bentonite, cement bypass kiln dust, and limestone to a floodplain soil could provide a potential remediation technique (Rinklebe and Shaheen 2015). An evaluation of the amendments in riparian soils heavily contaminated with copper (over 3,000 mg/kg) showed that most of the additives shifted the geochemical forms of copper through either increased sorption or by transformation to more plant available forms. Although the authors concluded that the low amendment rates that could practically be applied would inadequately immobilize copper, the increased copper concentration found in grass tissues at the same site indicates a means of enhanced phytoremediation.

Clearly, the use of soil amendments requires further field verification in riparian areas, but this approach to enhancing natural attenuation mechanisms shows promise.

5.4.4. Pesticides and Other Organic Compounds

An extensive array of organic contaminants exists in the environment that can threaten water quality in aquatic ecosystems. This category of compounds describes molecules that contain carbon covalently bonded to other elements, and includes both naturally derived and synthetic chemicals. This chapter focuses on anthropogenic compounds that exert a toxic effect on aquatic organisms.

The multitude of organic chemicals makes it impractical to touch on each class here, but common examples that present environmental health risks in aquatic habitats include polycyclic aromatic hydrocarbons (PAHs), polychlorinated biphenyls (PCBs), and pesticides. While the detrimental effects of many of these pollutants have been recognized for some time, studies continually identify emerging contaminants of concern ("emerging" does not only connote new compounds, but also chemicals that have been in use without realizing the extent of their toxicity). For instance, hazards associated with flame retardants, such as polybrominated diphenyl ethers (PBDEs), have been highlighted over the last decade (Covaci et al. 2011; Ye et al. 2015). Recent research emphasis also has been placed on a variety of trace organic compounds, including pharmaceuticals and personal-care products (PPCPs), as it is now recognized that these chemicals can exert negative impacts on fish and other aquatic organisms at both the individual and population levels even at extremely low (e.g. parts per trillions) concentrations (Mueller 2004; Kümmerer 2009a; Kümmerer 2009b; Luo et al. 2014). In addition, there is growing awareness that while individual pesticides may have little or no effect

when examined alone, that same pesticide as part of a pesticide mixture may be lethal to amphibians (Hua and Relyea 2014).

While only a brief discussion was provided above on the various organic pollutants that act as environmental contaminants, a little more information on pesticides is warranted, as they are more likely to be used in uplands and transported into riparian areas. Pesticides consist of any substance that is used to control fungal, plant, or animal pests. These chemicals represent a broad range of different chemicals that are derived from various sources such as plant extracts (nicotine, pyrethrum, neem oil), inorganics (e.g., copper sulphate; inorganic pesticides will not be discussed here), and synthetics. Synthetic pesticides are themselves a broad class that includes legacy organochlorines (chlorinated hydrocarbons such as DDT), organophosphates (e.g., Malathion), phenoxyacetic acids (e.g., MCP), carbamates (e.g., carbaryl), and neonicotinoids (e.g., imidacloprid). Pesticide pollution of streams can impact non-target organisms resulting in a wide variety of physiological and ecological problems (Mann et al. 2009), including altered growth (Alvarez and Fuiman 2005) and reproduction (Moore et al. 2007), altered community dynamics (Fleeger et al. 2003), and the loss of species (Relyea and Diecks 2008).

The ecological impacts of organic pollutants on aquatic organisms vary considerably, depending on not only the contaminant type but also the environmental conditions. Various compounds can be carcinogenic (causing cancer), mutagenic (altering genetic material and fomenting mutations), and teratogenic (stimulating abnormalities). Organic pollutants can also act as endocrine disrupting chemicals (EDCs), adversely impacting development, reproduction, neurologic, and immune system function in humans and wildlife (Colborn et al. 1993). Endocrine disruption has emerged as a key issue as studies have identified more cases of detrimental impacts, such as the discovery of atrazine-induced feminization of male Northern Leopard Frogs at very low concentrations (Hayes et al. 2003). This finding is controversial, but it has increased awareness that many organic compounds have potentially unrecognized endocrine-disrupting effects. Some organic contaminants, such as halogenated hydrocarbons, are capable of bioaccumulating in individuals and biomagnify up the food chain (Rahman et al. 2001).

To further complicate potential risk, pesticides rarely occur singly in aquatic environments. For example, a comprehensive decadal assessment of 178 streams in agricultural, urban, and mixed-land use watersheds found two or more pesticides more than 90% of the time and ten or more pesticides 20% of the time (USGS 2006). Ecological and toxicological research is increasingly recognizing the complexity of contaminant mixtures, which may have antagonistic, additive, or synergistic interactions in biota (Cedergreen 2014). For example, combining the pesticides diazinon and Malathion inhibits brain activity, and therefore swimming performance in fish at concentrations more than 50 times lower than the concentrations that cause an impact when these pesticides are used singly (Laetz et al. 2013). Although the examples given focused on pesticides, mixtures of hydrocarbons originating from roadways, parking lots and other locations can also be found in urban watersheds, including pollutants such as PAHs that originate from coal-tar-sealed parking lots (Scoggins et al. 2007). Amalgamations of these urban generated organic contaminants have been shown to impart both sub-lethal and lethal effects on aquatic organisms and disrupt stream communities (PSAT 2007; Scoggins et al. 2007; Spromberg et al. 2016).

The sheer number of different sub-classes of pesticides makes it impractical to provide information on the chemical behavior of all the potential contaminants that might be encountered in riparian areas. Pesticide pollution is extremely complex due to the multitude of types, the wide range of molecular sizes, the diversity of chemical structures, and the ability of these compounds to react and transform into new products. However,

some basic information on organic compounds will enable a better understanding of the effects riparian buffer size and structure have on pesticide pollutants. It is essential to identify the physicochemical properties of organic contaminants to adequately assess fate and transport pathways through riparian areas. Specific gravity, water solubility, vapor pressure, and partitioning coefficients such as the octanol/water partition (log K_{OW}) and organic carbon partition coefficients (K_{OC}) all serve as predictors of a substance's potential mobility and attenuation in riparian areas.

Natural organic matter has a significant impact on the degree of attenuation riparian soils impart on pesticides. The aforementioned K_{OC} represents the ratio of the amount of chemical adsorbed to the soil to the amount of chemical that remains in solution, related to the mass fraction of organic matter in the soil (Delle Site 2001). This value essentially indicates the affinity of a pollutant to soil organic matter and is a predictor of its potential mobility through the soil, where higher K_{OC} values correlate to less mobile organic contaminants and low K_{OC} values correlate to more mobile organic contaminants. Hydrophobic, nonpolar compounds, such as PAHs, are typically associated with particles in soil-water systems, whereas polar contaminants often exist in dissolved forms that exhibit a greater propensity for movement through the ecosystem.

The relationship between pesticides and their respective K_{OC} values can be confounded by humic substances, which are a heterogeneous mixture of chemically complex macromolecules that comprise a substantial component of natural organic matter. Humic substances have long been known to exert a significant impact on the movement of organic contaminants (Hayes 1970; Khan 1972). These amorphous compounds, which are classified into humic acid, fulvic acid, and humin fractions based on their molecular size and chemical behavior, can effectively bind organic pollutants and present either water-insoluble entities that are retained in the soil column or water-soluble colloids that can facilitate transport through riparian soils to the stream channel. Even when present in small quantities, these chemically reactive compounds can dramatically influence the binding, persistence, and translocation of organic pollutants. The interactions between humic substances and organic contaminants are beyond the scope of this chapter, but their potential to affect K_{OC} values by up to an order of magnitude is salient to predicting their attenuation by riparian buffers (Grathwohl 1990; Kopinke et al. 2001). Nevertheless, in general the attenuation of organic pollutants in riparian areas is positively correlated with soil organic matter.

Pesticides and other organic pollutants can also be retained in riparian areas through sorption to mineral components in the soil, although often to a lesser extent than to organic matter (Delle Site 2001). The surface area of soil particles enhances the binding of organic pollutants, which increases with finer soil textures such as those found in clays. The mineral composition of the soil particles also influences binding affinity by offering different forms of attachment sites. Those compounds that do not attach to soil material are susceptible to leaching, which can result in them entering the groundwater and being transported to the stream. Contaminants associated with inorganic particulates are usually much less bioavailable, although they can become bioavailable if particles are ingested by biota (Moermond et al. 2004).

Pesticides and other organic pollutants can undergo abiotic and biotic transformations that further compound the complexity of their chemistry. Abiotic processes include degradation due to chemical reactions such as hydrolysis (Mitchell et al. 2014; Mitchell et al. 2015). Biotic transformations include biologically mediated reactions, such as bacterial metabolism. Although the potential for biodegradation is dependent on the chemical structure of the contaminant, indigenous soil bacteria can use many organic compounds as a metabolic substrate. Repeated exposure to the same type of pesticides can foster microbial communities that

become contaminant specialists (Vidon et al. 2010). For example, soils receiving repeated applications of the pesticide 2,4-D harbor more 2,4-D-degrading microbes than similar plots receiving fewer applications (Gonod et al. 2006). Similarly, PAH-degrading bacteria were more abundant in rain gardens receiving stormwater runoff than upland control plots (LeFevre et al. 2012). The robust microbial communities found in riparian areas, resulting from conditions discussed previously, helps attenuate many organic compounds in riparian soils. Being biologically mediated, however, the degradation rates will fluctuate seasonally depending on temperature and soil moisture.

Phytoremediation by riparian vegetation provides an additional attenuation mechanism for organic contaminants. Although phytoremediation has received significant interest over the last two decades, the literature contains few papers on this method specific to pesticides in riparian areas. However, the principles are the same as those described in the vegetation section found earlier in this chapter, and presumably the results would be similarly positive. This premise was highlighted in a review article on the potential effectiveness of phytoremediation in riparian areas, where Karthikeyan et al. (2004) drew on similarities between streamside areas and other locations where phytoremediation has been effectively employed to treat pesticide-contaminated soil and water. Similarly, another review paper summarized a range of studies that investigated phytoremediation in aquatic settings, addressing plant species such as cattail (*Typha* spp.) and Cutgrass *Leersia oryzoides* which can be found along the riparian-aquatic ecosystem transition (Moore et al. 2011). A study directly examining the use of phytoremediation in riparian areas found that Tussock Sedge *Carex stricta*, Switchgrass *Panicum virgatum* and Gamagrass *Tripsacum dactyloides* led to approximately 70% reduction in total petroleum hydrocarbons under controlled riparian conditions, while there was only about 20% reduction associated with a Narrowleaf Willow *Salix exigua* and poplar (*Populus* spp.) (Euliss 2008). Following the same procedure in an uncontrolled riparian field site did not reproduce these promising results, but the authors presumed there was a continuous pollutant source re-contaminating the site during the study. A field study examining the phytoremediation potential of willows (*Salix* spp.) in riparian areas yielded a 49% decrease in PCB concentrations before contaminated groundwater reached the stream margin (Skłodowski et al. 2014). Although there is not enough information available in the literature to provide design guidelines for implementing a phytoremediation-based system, there is promise in this approach to attenuating organic contaminants in riparian areas and further research should be encouraged.

Mycoremediation, the degradation of contaminants by fungi, is a type of bioremediation that occurs in soils. This process likely takes place in riparian soils with high organic matter content where lignin-degrading fungi (more commonly known as wood-decay fungi, a class that includes brown rot, soft rot, and white rot) exist. These microorganisms possess the ability to breakdown organic contaminants, particularly PAHs, through the release of a variety of oxidizing enzymes (Haritash and Kaushik 2001). Research on promoting lignin-degrading fungi as a remediation agent started to appear in

The central problem faced by resource managers is determining the adequate riparian buffer width, composition, and structure to protect water quality with high degrees of efficacy, efficiency, and certainty.



Spawning Chum Salmon Oncorhynchus keta*/Ned Pitman, WDFW*

the literature in the 1990s, but did not receive much attention until after the turn of the century (Lamar et al. 1993; Boonchan et al. 2000; Canet et al. 2001). Results vary considerably, but it is not uncommon to observe 50% to 90% reductions in organic pollutants resulting from mycoremediation-mediated degradation (Lamar et al. 1993; Boonchan et al. 2000; Haritash and Kaushik 2001). Although this degradation process is mentioned here to highlight the mechanisms affecting organic pollutants in riparian soils, it has been suggested that mycoremediation could potentially be capitalized on as an engineered mitigation technique in riparian areas, but more research is needed (Jones 2009).

Despite the large body of knowledge that has been developed, the mechanistic understanding of pesticide transport through riparian areas is incomplete. The following summarizes our understanding of the typical transport pathways of a pesticide; this is essential information to consider when determining appropriate riparian widths for attenuation. Pesticide migration from terrestrial sources to stream channels can follow a number of different pathways. The specific transport mechanism governing pesticide movement from uplands through riparian areas and into surface waters is highly correlated to the type of pesticide in question. Surface runoff can carry pesticides off fields as either dissolved forms or attached to eroded soil particles. Leaching of compounds entails their vertical movement through the soil, after which they can either move toward the stream through the unsaturated zone or via groundwater flow. The chemicals that move in the dissolved form tend to be those that exhibit low to moderate sorption properties, as compounds that possess lower partition coefficients are prone to leach into the soil profile. Leaching is further promoted in regions with high precipitation and in soils that are coarse-textured, contain a low percentage of organic matter, or demonstrate a high degree of macropore flow. Pesticides that predominantly follow sediment-facilitated transport are generally those that display a strong affinity to soil particles (i.e., K_{OC} > 1,000 L/kg).

While the literature lacks information on the potential attenuation in riparian areas for most organic pollutants, there are a substantial number of papers on the movement of pesticides through buffer strips. A number of review papers evaluate pesticide attenuation in riparian areas, with a particular emphasis on managed vegetative filter strips (Krutz et al. 2005; Lacas et al.

2005; Reichenberger et al. 2007). Due to the complexity of the attenuation mechanisms involved, the removal rates within buffers vary considerably between disparate compounds, as well as when comparing the removal rates of the same pesticide at different locations. Depending on the conditions, mass removal rates for some pesticides can be negligible while others can reach 100%. Research has shown that herbicide type and filter strip width are primary factors affecting herbicide retention in riparian areas, while antecedent moisture conditions exert an additional effect wherein pesticide attenuation is generally negatively correlated with soil moisture. The type of vegetation appears to have negligible impact on pesticide retention, with studies showing that a grass-shrub-tree mixture exhibited comparable mitigation as grass only. Interestingly, one study found that pesticide mitigation was greater at higher incoming concentrations, which was attributed to better sorption to soil and plant material (Misra et al. 1996).

Due to confounding and often conflicting results, after 35 years of research, there remains a lack of consensus on the minimum filter strip widths needed for effective pesticide removal from surface and surface overland flow. The NRCS recommends a standard width of 49 ft (15 m) with the aim of achieving 50% effectiveness, but there is not much evidence to support this guidance (NRCS 2000). Another general recommendation for diffuse runoff suggests riparian widths of 33 and 66 ft (10 and 20 m) for hillslopes of under and over 328 ft (100 m) in length, respectively (Lacas et al. 2005). However, because this recommendation is based on only one experimental study, it may not be applicable to other locations with different hydrological, soil, and vegetative conditions.

Pesticide Spray Drift

Pesticide spray drift, the aerial transport of pesticide droplets off target areas during spray application, presents another pathway by which these chemicals can enter aquatic ecosystems. Unlike hydrological transport, pesticide physicochemical properties play a negligible role in aerial transport (although formulation does act as an influencing factor). Weather conditions (e.g., wind speed, temperature, and humidity), equipment type, application practices, and target crop all affect aerial transport. There is a better understanding of pesticide aerial drift to streams than that of hydrological pathways, either as a result of occurring in a less complex matrix, or as Reichenberger et al. (2007) asserts, due to aerial drift receiving more regulatory scrutiny.

Management of riparian areas can significantly reduce pesticide spray drift in many cases, particularly when conducted in conjunction with proper application practices. However, in their review of mitigation via windbreaks, Ucar and Hall (2001) found no general consensus on optimum riparian buffer widths to protect water quality. Their review reports that research has yielded buffer width recommendations that range from 20 to 150 ft (6 to 45 m) for ground application and 80 to over 4,000 ft (25 to over 1,200 m) for aerial application. Despite this lack of harmony in recommendations, individual cases have yielded positive results. Analysis of a forested riparian area in British Columbia found that a 25 ft (7.6 m) buffer limited the amount of herbicide reaching the stream to less than 0.1% of the aerial application (Feng et al. 1990). In an agricultural setting, a simple 10 ft (3 m) no-spray buffer reduced herbicide drift deposition to adjacent surface waters by 95%, and no measurable drift reached the stream at a width of 20 ft (6 m) as long as the wind-speed was below 15 mph (25 kph) in the direction towards the buffer (De Snoo and De Wit 1998). Many factors contribute to the effectiveness in reducing pesticide drift to acceptable levels. While wind-speed and application method exert significant impacts, vegetation height, density, orientation, and species composition all play pivotal roles. For instance, Ucar and Hall (2001) suggest that, in general, evergreen species display capture efficiencies 2 to 4 times greater than deciduous trees.

5.4.5. Pathogens

Pathogens impair more waterbodies in Washington than any other contaminant (USEPA 2015). Fecal contamination of surface waters can lead to the introduction of various pathogenic bacteria, fungi, viruses, protozoans, and worms that infect the gastrointestinal tract and present a health risk to both humans and wildlife. Common infections related to fecal pollution result from the presence of pathogenic bacteria such as *Escherichia coli* (*E. coli*), *Salmonella* spp. and *Vibrio* spp. or viruses such as Rotavirus. Primary pathogenic protozoans of concern include *Cryptosporidium parvum* and *Giardia lamblia,* which are able to form oocysts (protective spores) that allow them to survive outside of a host for long periods. Helminths represent a general class of parasitic worms, including flatworms and roundworms, which can act as intestinal parasites. The myriad pathogens that can be found in riverine systems following fecal contamination makes it impractical to list them here, but it is important to understand the four different pathogenic categories that can be conveyed to people through surface water contact or ingestion.

Pathogens comprise a diverse range of microorganisms that are typically found in low concentrations, making it impractical to test for specific pathogens when conducting water quality assessments. As an alternative, "pathogen indicator organisms" are used as a proxy to assess the potential presence of pathogens in a water sample. Commonly employed pathogen indicators include total coliforms, fecal coliforms, and *E. coli.* Total coliforms comprise a group of five genera of bacteria that easily can be analytically differentiated from other microorganisms, and while some occur naturally in soils, many are found in the gastrointestinal tract of warm-blooded animals and can serve as a general marker for fecal contamination. Fecal coliforms represent a sub-group of total coliforms that more specifically reside in the intestines of warm-blooded animals, making them a more accurate indication of the presence of fecal material in water. Washington water quality standards use fecal coliforms as indicator organisms to determine water quality impairment. *E. coli,* a species in the fecal coliform group, is a dominant inhabitant in the digestive tract and is generally considered the best indicator of fecal pollution of the three. As *E. coli* are indigenous enteric bacteria, they are not in themselves pathogenic although some strains are (e.g., *E. coli* O157:57). Although most of these indicator organisms are not pathogenic, it is common to refer to them as pathogens when discussing water quality (shortening the phrase "pathogens and pathogenic indicator organisms"), and while technically inaccurate, we will use that term in this section. We use the term in a way that should allow the reader to differentiate between whether we are referencing pathogens specifically or the broader group that includes pathogen indicator organisms.

As the pathogens in question are enteric, they are introduced into the environment through the feces of warm-blooded animals. Principal pathways for pathogens entering aquatic ecosystems are through direct defecation by livestock, wildlife, and pets in the riparian area and via overland flow carrying fecal material from upland pastures, animal feeding operations, fields that have received land-applied manures, or seepage from septic or sewage systems. Feces from domesticated dogs can be a predominant pathogen source in urban areas, as a study in Seattle attributed 30% of the fecal contamination to canines (Tobiason et al. 2002). Hobby farms also present an often-overlooked source adversely affecting water quality, and this has been shown to be an issue in Washington (Morace and McKenzie 2002).

The fate of pathogenic microorganisms in the environment is still not well understood in general and much uncertainty remains in the context of riparian areas. While many of the pathogens that can contaminate surface waters are obligate parasites,

some can persist outside of an animal's gastrointestinal tract in the environment. The length of time these microorganisms can survive under different conditions is a current topic of debate in the research community. The general assumption in the past was that these enteric organisms were not able to persist in the environment for more than a few days following excretion in feces. However, more recent research indicates that bacterial pathogens can survive for much longer periods, and it is generally recognized that persistence in the environment for two to three months is not uncommon. Longer survival rates are possible given the correct conditions, as demonstrated in a laboratory study where *E. coli* O157:H7 persisted for over 190 days in manure-amended soils (Jiang et al. 2002). General factors that influence the survival of pathogenic bacteria that enter riparian areas include soil moisture, temperature, pH, sunlight, nutrient availability, soil texture, and biological interactions. Moist, nutrient-laden, shady conditions such as those often found in riparian areas theoretically would provide an environment in which pathogens could survive longer, potentially being picked up by overland flow and introduced to adjacent stream channels.

Although considerable research has been conducted through the years on bacterial movement through environmental systems, research is in the nascent stages of examining the transport and fate of pathogens across the landscape and in riparian areas. Unc and Goss (2004) offer a concise review on the transport of bacteria from manure in relation to protecting water resources, and although the material presented does not focus on streamside areas it does provide fundamental information on the mechanisms involved in pathogen transport. The body of research that has examined pathogen attenuation in riparian areas is small although expanding, and almost all findings are related to vegetative filter strips and do not consider natural riparian ecosystems.

The capacity of vegetative filter strips to remove pathogens is not well established and research results have demonstrated that these systems exhibit great variability in their effectiveness in removing pathogens. A number of studies have shown that filter strips impart no significant influence on pathogen and pathogenic indicator organism concentrations moving toward a stream channel (Walker et al. 1990; Schellinger and Clausen 1992; Chaubey et al. 1995; Coyne at al. 1995; Entry et al. 2000). Contradictory findings have been generated by other studies that promote the idea that well maintained filter strips can serve as an effective BMP to prevent pathogens from reaching surface waterbodies (Coyne et al. 1998; Fajardo et al. 2001; Tate et al. 2006).

Inconsistent findings result from a number of factors. Soil infiltration, antecedent soil moisture conditions prior to a rain event, vegetation status, topography, and rainfall intensity and duration all have been identified as key controlling variables (Muñoz-Carpena et al. 1999; Guber et al. 2009). Each of these parameters relates to the concept that pathogens being carried in overland flow are removed by their infiltration into the soil where they typically are filtered or adsorbed to soil particles. High intensity rain events and concentrated flow can significantly reduce pathogen removal efficacy below that which would occur under low-flow conditions (Fox et al. 2011b). Vegetative filter strip width plays a significant role in pollutant removal, where a linear

Although considerable research has been conducted on bacterial movement through environmental systems, research is in the nascent stages of examining the transport and fate of pathogens across the landscape and in riparian areas.

decrease in pathogenic bacteria has been consistently observed with increasing buffer width (Young et al. 1980). However, a potential exists for trapped pathogens to later be remobilized in subsequent runoff events. Higher concentrations of pathogens have been recorded in runoff during a second runoff event, which suggests that filter strips could become indirect sources of pathogens under some conditions (Collins et al. 2004).

5.5. Effect of Riparian Buffer Width on Pollutant Removal

The pollutant removal function of riparian areas has been studied for at least 40 years (e.g., Doyle et al. 1975), and the enormous quantity of scientific research over the past four decades has motivated numerous reviews of the scientific literature (Norris 1993; Osborne and Kovacic 1993; Barling and Moore 1994; Vought et al. 1995; Fennesy and Cronk 1997; Lyons et al. 2000; Dosskey 2001; Hickey and Doran 2004; Lacas et al. 2005; Krutz et al. 2005; Polyakov et al. 2005; Hoffman et al. 2009; Dosskey et al. 2010). Despite the large quantity of research and number of literature reviews, no widely accepted recommendations have emerged on minimum buffer widths needed to protect water quality. The lack of agreement amongst scientists is due, in part, to the surprising complexity of the mechanisms that remove pollutants from surface and subsurface flows in riparian areas, to the variety of research methods used to study pollutant removal by riparian buffers, and to the many different environmental conditions at research sites.

The quantitative metric of pollutant removal by riparian areas is referred to as removal efficacy, removal efficiency, or percent removal. These measures are usually defined as:

$$E_R = \frac{m_{in} - m_{out}}{m_{in}} \times 100 \qquad (1)$$

where m_{in} and m_{out} are the mass or concentration of the pollutant entering and exiting a riparian buffer, respectively. The primary question addressed by nearly all research on the pollutant removal function of riparian areas, and by nearly all literature reviews, is how does riparian buffer width affect removal efficacy? The main answers are: 1) removal efficacy increases as buffer width increases, 2) topographic slope and vegetation type strongly affect removal efficacy, and 3) the relationship between removal efficacy and buffer width is highly variable.

In addition to the many literature reviews cited above, several statistical meta-analyses of research results (Mayer et al. 2007; Liu et al. 2008; Yuan et al. 2009; Zhang et al. 2010; Sweeney and Newbold 2014) provide synoptic perspectives on what is currently known about the relationship between buffer width and removal efficacy (Table 5.1). Research results from throughout the world were collected by all five meta-analyses, but the majority were from North America. The remainder of this section discusses the findings of those meta-analyses.

Four meta-analyses looked at the results of research on sediment removal. The meta-analyses found that buffer width alone explained 28% to 37% of the variance in sediment removal results. Models for removal efficacy versus buffer width predicted a wide range of buffer widths necessary for 90% efficacy: 33, 39, 75, and 170 ft (10, 12, 23, and 52 m) (Figure 5.2). Three of the meta-analyses found that adding slope as an independent variable significantly improved the fit of their models to the data. Two meta-analyses (Liu et al. 2008; Zhang et al. 2010) using the same studies but different modeling assumptions, found that optimum slope for sediment removal was about 10%. In other words, removal efficacy increased as slope increased from 1 to 10%, but then removal efficacy decreased as slope increased above 10%. However, extrapolating these findings to other locations should be done cautiously as this relationship may not hold under many conditions. Zhang et al. (2010) found that buffer width, slope,

and vegetation type together could explain 65% of the variance in sediment removal results. Curiously, they also found that buffers composed of grasses only or trees only were more efficacious at removing sediment than buffers composed of both grasses and trees (Figure 5.4).

Three separate meta-analyses looked at the results of research on nitrogen removal. The meta-analyses of Zhang et al. (2010) and Mayer at al. (2007) produced very different relationships for removal efficacy versus buffer width. Zhang et al. (2010) found that buffer width alone explained 44% of the variance in nitrogen removal results, but Mayer et al. (2007) found buffer width alone explained only 9%. Furthermore, Zhang et al. (2010) predicted that buffer widths of 80 ft (24 m) are necessary for 90% removal efficacy, while Mayer et al. (2007) predicted buffer widths of 436 ft (133 m) for the same efficacy (Figure 5.3). Separate models by Mayer et al. (2007) for surface and subsurface flows found a significant relationship (assuming $\alpha = 0.05$) between buffer width and removal efficacy for surface flows ($R^2 = 0.21$, $P = 0.03$) but not for subsurface flows ($R^2 = 0.02$, $P = 0.3$). Despite this result, Mayer et al. (2007) found that riparian buffers were more efficacious in removing nitrogen from subsurface waters than from surface waters. Mayer et al. (2007) found no significant relationship between nitrogen removal and buffer vegetation type but their collection of studies did show that buffers lacking trees (herbaceous cover only) were the least efficacious at removing nitrogen.

Zhang et al. (2010) found a relationship between vegetation type and nitrogen removal and that buffers composed of trees remove more nitrogen than buffers completely or partially composed of grasses. Zhang et al.'s model that included buffer width and vegetation type explained 49% of the variance in nitrogen removal results.

Comparing regression models for sediment and nitrogen removal (Figures 5.2 and 5.3) illustrates three important points regarding the pollutant removal function of riparian areas. First, the magnitude of removal efficacy for different pollutants can be very different. According to the models, 80% of sediment was removed at roughly 50 to 65 ft (15 to 20 m), but 80% removal of nitrogen may require buffer widths two to four times wider. Second, the variability of removal efficacy for various pollutants can be significantly different. The regression models for nitrogen removal show much more variation than the models for sediment removal. The wider variation is due, in part, to the greater complexity of the chemical and biological processes affecting nitrogen removal compared to the simpler physical processes affecting sediment removal. Hence, our ability to predict removal efficacy and our certainty about water quality protection can be very different for different pollutants. Third, for all pollutants the relationship between buffer width and removal efficacy follows a law of diminishing marginal returns. That is, the marginal (or incremental) amount of pollutant removal decreases as buffer width increases.

Zhang et al. (2010) also conducted meta-analysis for phosphorus and pesticides. Buffer width alone explained 35% of the variance in phosphorus removal results (Figure 5.5), and with the addition of vegetation as an independent variable, the model explained 47% of the variance. The buffer-width-only model predicts 89% phosphorus removal with a buffer 98 ft (30 m) wide.[7] Buffers with trees were found to remove more phosphorus than buffers completely or partially composed of grasses. The pesticide meta-analysis included 11 chemicals (norfluranzon, fluometuron, lindane, deisopropylatrazine, deethylatrazine, atrazine, permethrin, bromide, terbuthylazine, metolachlor, isoproturon). Buffer width alone explained 60% of the variance in pesticide removal results, and vegetation was found to be an insignificant predictor variable. The model predicts 92% pesticide removal with a buffer 65 ft (20 m) wide.

7 Because Zhang et al. (2010) assumed an asymptotic equation for their regression, the phosphorus model was invalid for efficacies greater than 89.5%.

Using data provided by Zhang et al. (2010), we calculated prediction intervals for their phosphorus model.[8] A prediction interval describes the precision of a model's predictions and the interval's width is a metric of uncertainty. For a buffer 33 ft (10 m) wide, the width of the 90% prediction interval is 64%. Therefore, while the model predicts that a 33 ft (10 m) buffer will provide an average removal efficacy of 70%, the actual removal efficacy obtained by another study on phosphorus removal (i.e., one which was not included in the meta-analysis) is likely to be somewhere between 38 and 100% (70% ± 32%). The low precision of the model's prediction interval is related to the unexplained variance that could be attributed to other variables not included in the regression, such as site slope and various soil properties.

Table 5.1. Descriptive information for functional relationships on sediment removal shown in Figure 5.2 and nitrogen removal shown in Figure 5.3. Reference numbers 1 through 4 correspond to numbers in Figures 5.2 and 5.3. In the equations, E_R is the removal efficacy, *width* is riparian buffer width, and *a*, *b*, *c*, *d*, and k_{50} are parameters determined through linear or nonlinear regression.

Pollutant	Meta-analysis	Form of equation	Model	*N****	R^2	*P* value
Sediment	(1) Liu et al. (2008)**	$E_R = a + b\ \ln(width)$	width	79	0.34	< 0.001
		$E_R = a + b \times width + c \times slope + d \times slope^2$	width & slope = 5% width & slope = 10% width & slope = 15%	79	0.43	< 0.0001
	(2) Yuan et al. (2009)	$E_R = a + b\ \ln(width)$	width	75	0.30	na*
			width & slope ≤ 5%	53	0.32	na
			width & slope > 5%	14	0.17	na
	(3) Zhang et al. (2010)**	$E_R = a\ (1 - e^{b \times width})$	width	81	0.37	< 0.0001
		$E_R = a\ (1 - e^{b \times width}) + c + d \times slope$	width & slope = 5% & grass or trees width & slope = 10% & grass or trees width & slope = 15% & grass or trees	81	0.65	< 0.001
	(4) Sweeney and Newbold (2014)	$E_R = \frac{width}{k_{50} + width}$	width	22	0.28	na
Nitrogen	(1) Mayer et al. (2007)	$E_R = a \times width^b$	width, surface water only	23	0.21	0.03
			width & herbaceous vegetation	32	0.21	0.009
			width & herbaceous/forest vegetation	11	0.39	0.04
	(2) Zhang et al. (2010)	$E_R = a\ (1 - e^{b \times width})$	width	61	0.44	< 0.0001
		$E_R = a\ (1 - e^{b \times width}) + c$	width & trees vegetation width & grass or mixed grass/trees veg.	61	0.49	< 0.001
	(3) Sweeney and Newbold (2014)†	$E_R = 100\ (1 - e^{b \times width/q})$	width & q set to 58‡ width & q set to 115	30	0.37	na*

* Signifies that *P* value was not reported in cited study.

** Nearly all the studies included by Liu et al. (2008) and Zhang et al. (2010) in their meta-analyses were the same studies.

*** *N* signifies number of studies in meta-analysis.

† Studies for subsurface nitrate removal only.

‡ q represents subsurface water flux. 58 and 115 L/m/day are median and mean subsurface water fluxes for studies collected by Sweeney and Newbold (2014).

[8] A prediction interval is a range that is likely to contain the dependent response value (Y_i) for a new observation (X_i). A prediction interval assumes that the new observation is taken from the same population used to create the regression equation.

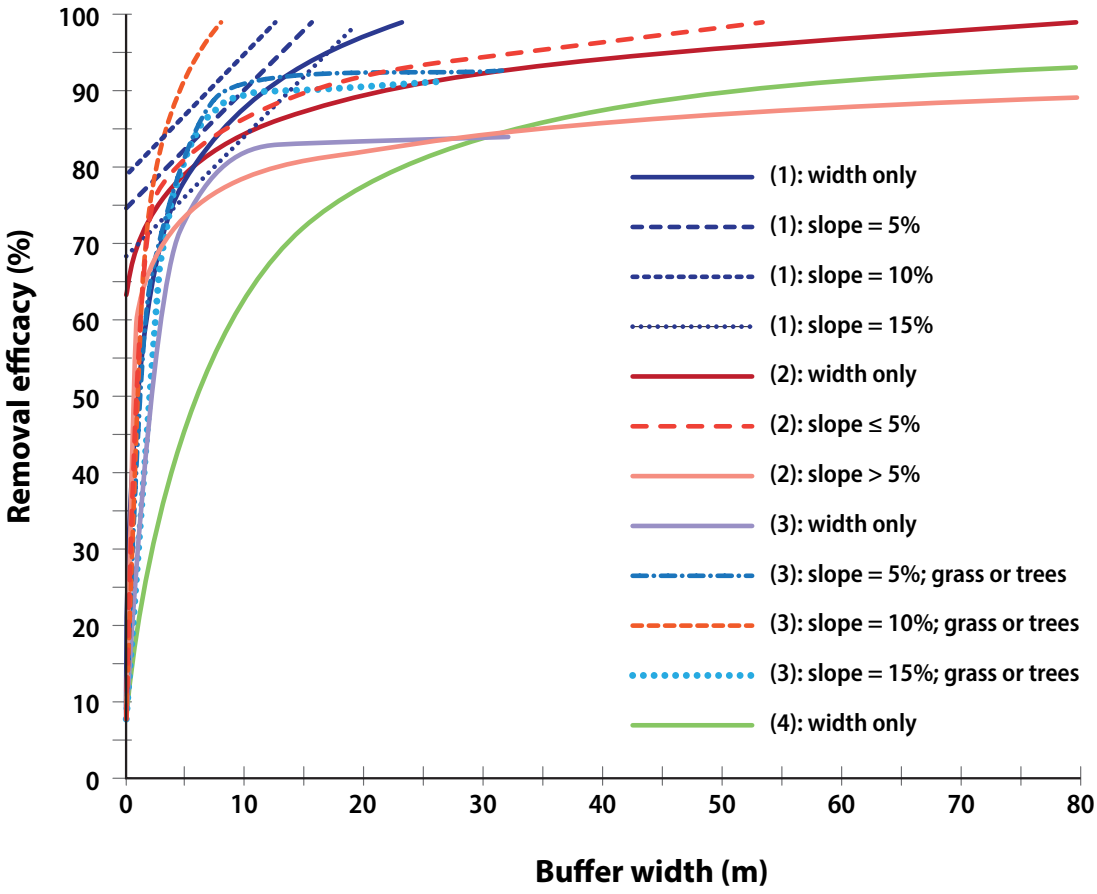


Figure 5.2. Relationships between sediment removal efficacy and riparian buffer width developed by four separate meta-analyses. Numbers in parentheses refer to different meta-analyses. See descriptive information in Table 5.1.

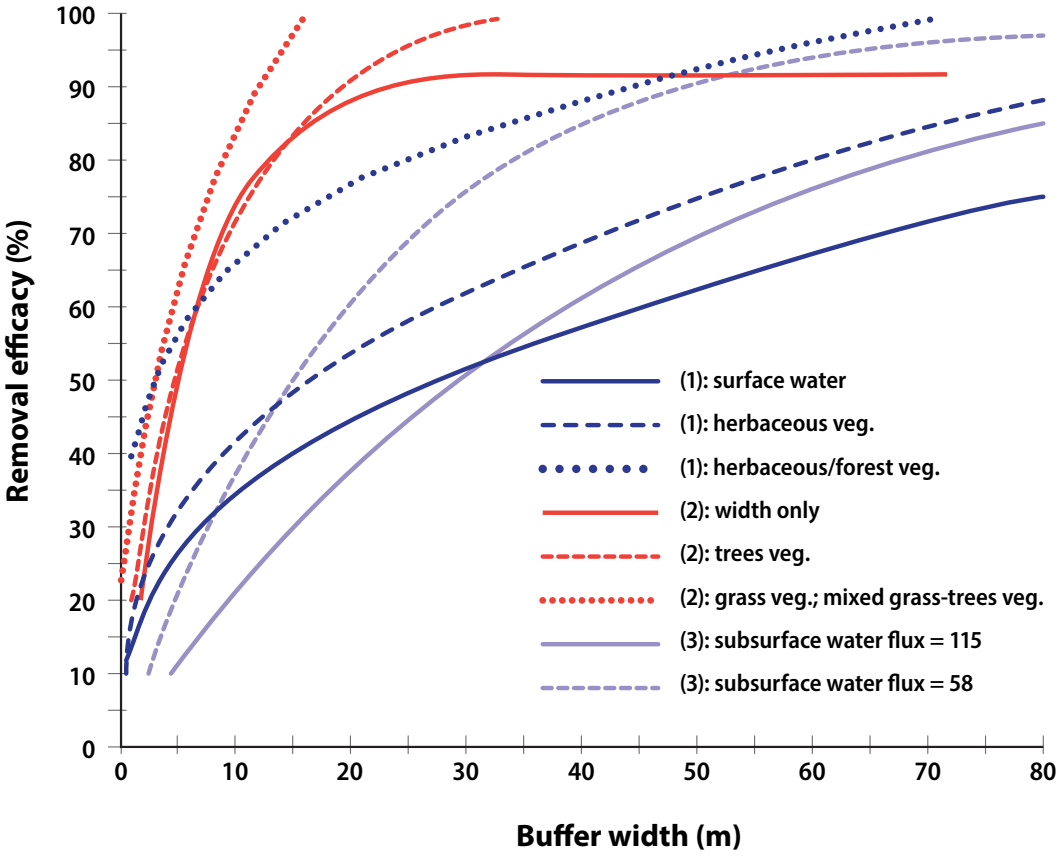


Figure 5.3. Relationships between nitrogen removal efficacy and riparian buffer width developed by three separate meta-analyses. Numbers in parentheses refer to different meta-analyses. See descriptive information in Table 5.1.

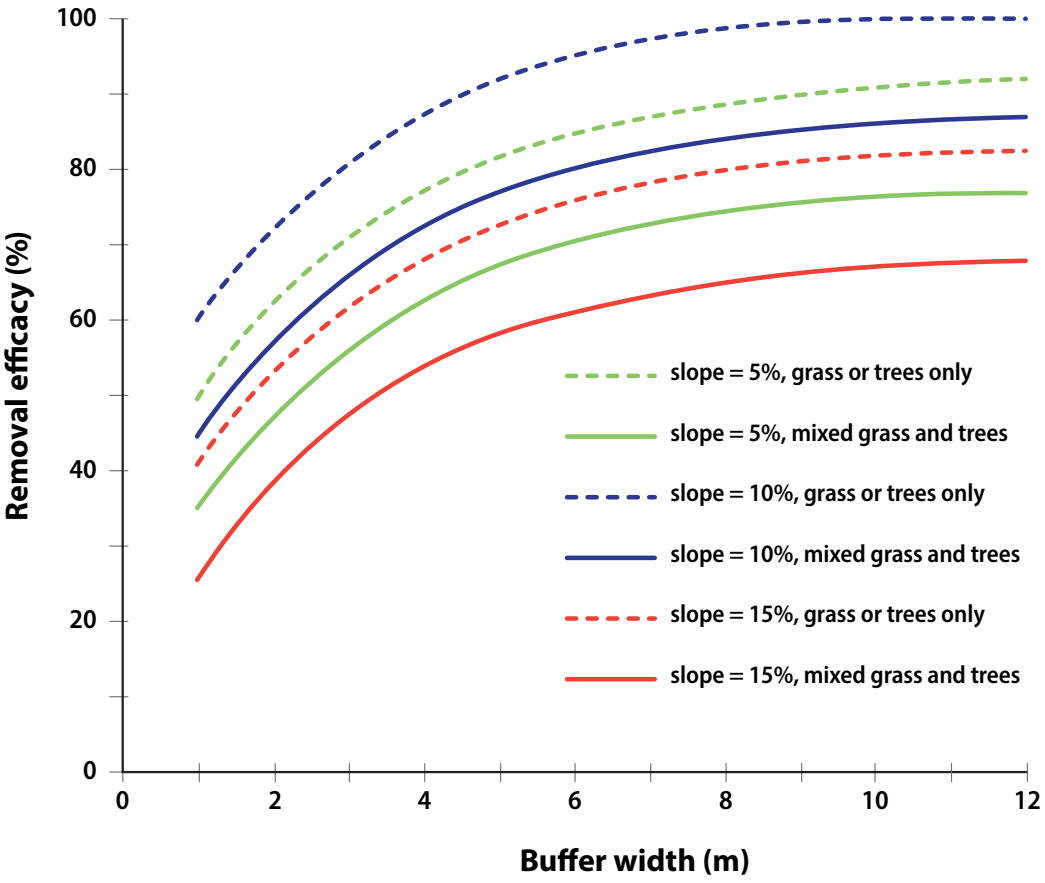


Figure 5.4. A result from meta-analysis of Zhang et al. (2010). Sediment removal efficacy as a function of buffer width, site slope, and buffer vegetation ($N = 81$, $R^2 = 0.65$, $P < 0.001$).

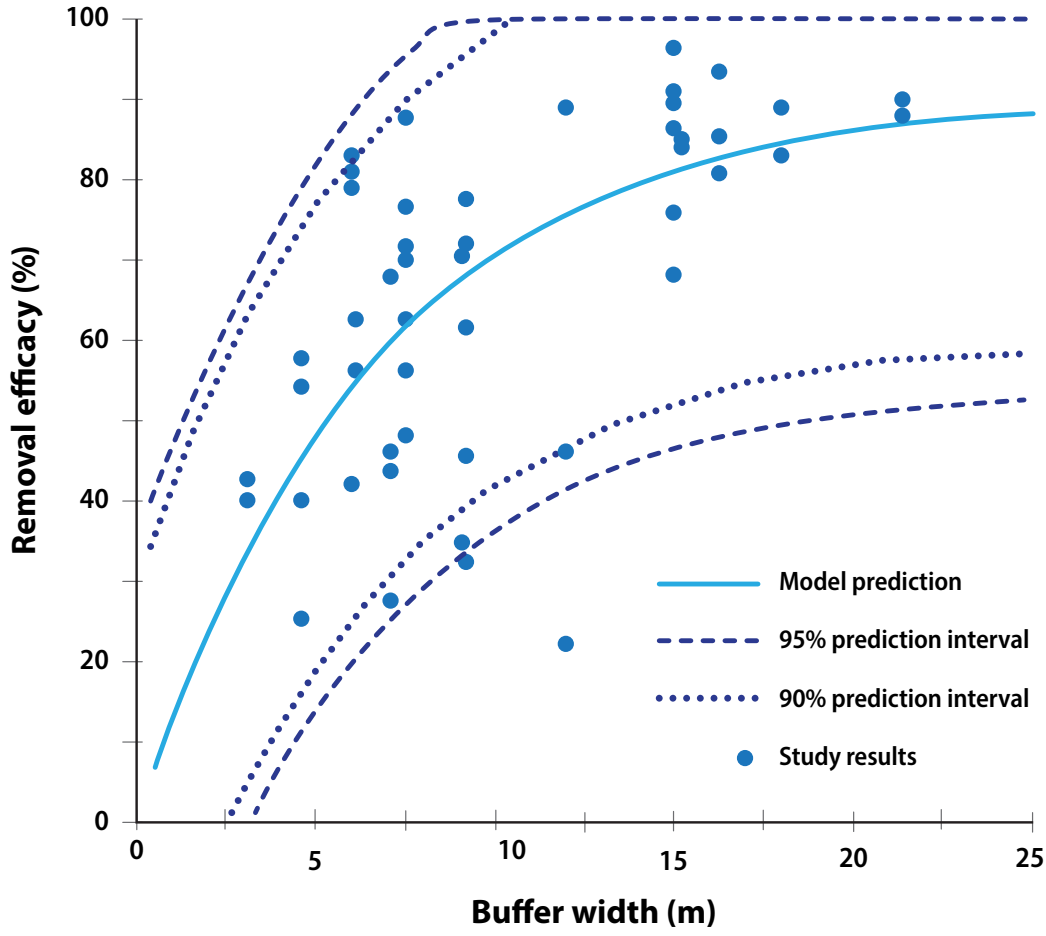


Figure 5.5. Meta-analysis of Zhang et al. (2010). Results of nonlinear regression for phosphorus removal efficacy as a function of buffer width ($N = 52$, $R^2 = 0.35$, $P < 0.0001$) with 90% and 95% prediction intervals.

5.6. Reanalysis of Meta-Analyses

A major assumption made by each of the meta-analyses was the type of equation that would result in the best fit to their data. Zhang et al. (2010), for instance, chose to use a nonlinear asymptotic equation of the form:

$$E_R = a\,(1 - e^{b \times width}) \qquad (2)$$

where E_R is removal efficacy, ***width*** refers to buffer width, and ***a*** and ***b*** are coefficients determined through nonlinear regression. In equation (2), *a* determines the maximum removal efficacy possible (i.e., it is an asymptote). Zhang et al. (2010) conducted their regression such that *a* could be less than 100%. For sediment, pesticide, nitrogen, and phosphorus pollutants, *a* equaled 91, 93, 92, and 89.5 percent, respectively. Hence, we could not determine buffer widths needed for removal efficacies greater than these values of *a* in their models. This limitation was particularly problematic for pesticides and phosphorus because Zhang et al. (2010) was the only meta-analysis for those pollutants.

To determine buffer widths needed for higher removal efficacies (90, 95, 99%), we reanalyzed Zhang et al.'s data with a nonlinear equation of the form:

$$E_R = a + b\ \ln(width) \qquad (3)$$

This form of model is the same used by Liu et al. (2008) and Yuan et al. (2009).[1] We performed linear regression in R (RCT 2013) using the lm function, but first we established that we could obtain the same regression results (same values for ***a*** and ***b***) as Zhang et al. (2010) using equation (2). This confirmed that the data we downloaded from the internet were the same data used by Zhang et al. (2010). We then redid the regression using equation (3). With the exception of sediment, the resulting models fit the data as well or better than the original models of Zhang et al. (2010) (Table 5.2). Graphical comparisons of our results and those of Zhang et al. (2010) are presented in Figure 5.6.

Table 5.2. Comparison of R^2 values for Zhang et al.'s (2010) model and our reanalysis using equation (3). *N* is the number of studies included in the meta-analysis.

Pollutant	*N*	R^2	
		Zhang et al. (2010)	Reanalysis
Sediment	81	0.37	0.31
Nitrogen	61	0.44	0.44
Phosphorus	52	0.35	0.39
Pesticides	49	0.60	0.61



Juvenile fish find shelter in a root wad/Terra Hegy, WDFW

1 Xuyang Zhang, the lead author of Zhang et al. (2010), also recommended that we use equation (3) because equation (2) cannot model 100% removal efficacy (X. Zhang, California Department of Pesticide Regulation, personal communication, May 14, 2019).

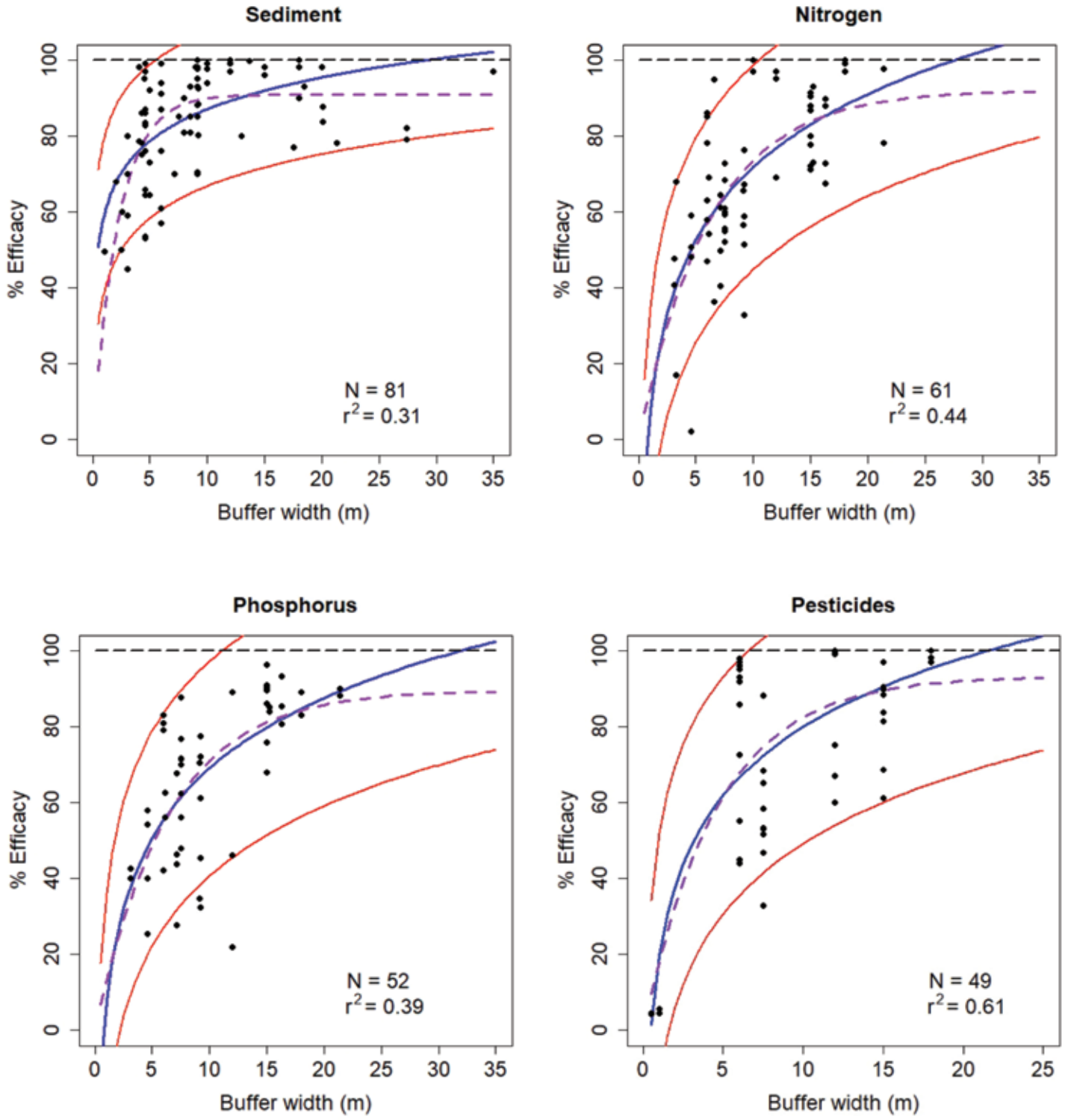


Figure 5.6. Relationship between removal efficacy and buffer width. Data from meta-analysis of Zhang et al. (2010) but reanalyzed using different form of nonlinear model. Line colors: blue: best fit model, red: 90% prediction interval, purple dashed: original model of Zhang et al. (2010), black dashed: 100% removal efficacy

We also reanalyzed two other meta-analyses – Mayer et al. (2007), and Sweeney and Newbold (2014) – for two reasons. The first reason was consistency across meta-analyses. The meta-analyses gave different answers for the relationship between removal efficacy and buffer width. For example, Zhang et al. (2010) predicted that buffer widths of 80 ft (24 m) are necessary for 90% removal efficacy of nitrogen, while Mayer et al. (2007) predicted buffer widths of 436 ft (133 m) for the same efficacy. Part of this discrepancy may be due to the type of equations adopted for their nonlinear or linear regressions, so we redid both meta-analyses using the same equation. Second, as noted earlier, a major assumption made by each of the meta-analyses was the type of equation that would result in the best fit to their data. We tested that assumption, and found that equation (3) often resulted in a better fit.

Mayer at al. (2007) chose to use a power function of the form:[2]

$$E_R = a\ width^b \qquad (4)$$

where ***a*** and ***b*** are coefficients determined through linear regression. We reanalyzed their data using equation (3). The resulting models fit the data as well or better than the original models of Mayer et al. (2007) (Table 5.3, Figure 5.7). For subsurface flow, the relationship between removal efficacy and buffer width was statistically insignificant ($P = 0.30$) and R^2 was only 0.02 for both their model and ours. We also note that both models produce somewhat absurd results – 60% of subsurface nitrogen can be removed with buffers only 2 ft wide but 90% removal requires buffers over 1200 ft wide. Hence, we will use neither model in further discussions of sub-surface nitrogen removal. For surface flow, the reanalysis resulted in a slightly better fit to the data – R^2 improved from 0.21 to 0.28.

We did not reanalyze the meta-analysis that Sweeny and Newbold (2014) did on studies of nitrogen removal from groundwater. While Sweeney and Newbold (2014)

Table 5.3. Comparison of R^2 values for Mayer et al.'s (2007) model and our reanalysis using equation (3). *N* is the number of studies included in the meta-analysis.

		Mayer et al. (2007)		Reanalysis	
Model	*N*	R^2	*P*	R^2	*P*
nitrogen, surface	23	0.21	0.03	0.28	0.009
nitrogen, subsurface	65	0.02	0.30	0.02	0.30

found a significant statistical relationship between nitrogen removal from subsurface flow and buffer width, other studies suggest the buffer width has little or no effect on nitrogen removal from subsurface flow (Hruby 2013, pp. 10-11).

For sediment removal, Sweeney and Newbold (2014) chose an equation of the form:

$$E_R = \frac{width}{k_{50} + width} \qquad (5)$$

where k_{50} equals the buffer width expected to remove 50% of sediments and it is determined through nonlinear regression. We reanalyzed their data using equation (3). The resulting model fits the data better than the original model of Sweeney and Newbold (2007). Their R^2 was 0.28 and the new R^2 is 0.33 (Figure 5.7).

Table 5.4 shows the buffer width needed to achieve desired levels of pollutant removal as predicted by meta-analyses and our reanalyses of meta-analyses. We combined predictions from multiple meta-analyses using a weighted average with the weights being the products of *N* and R^2. Note that values in Table 5.4 are predicted averages for removal efficacy. The actual efficacy realized by implementing a particular buffer width could be much better or worse. The amount of uncertainty in the realized removal efficacy is depicted by prediction intervals in Figures 5.6 and 5.7. The

2 The equation $E_R = a\ width^b$ can be transformed to the equation $\ln(E_R) = a' + b\ \ln(width)$, which is similar in structure to equation (3) and results in a similar fit to the data. Equation (3) was also the form used by Mayer et al. (2006).



Riparian areas capture pollutants/Marlin Greene, One Earth Images

reanalyzed meta-analysis of Zhang et al. (2010), for example, predicts that 90% of sediment can be removed with a 42 ft (13 m) wide buffer, however, according to the prediction interval, the buffer width needed for 90% removal could be as narrow as 8 ft (2.4 m) or as wide as 225 ft (69 m). Better models that include other independent variables, such as slope and vegetation (e.g., Zhang et al. 2010), will reduce this uncertainty, but there is a trade-off. The application of more complicated models leads to more complicated management. If, for example, managers adopted a model that includes vegetation type or vegetation structure, then, in addition to buffer width, they must also manage the condition of vegetation within the buffer.

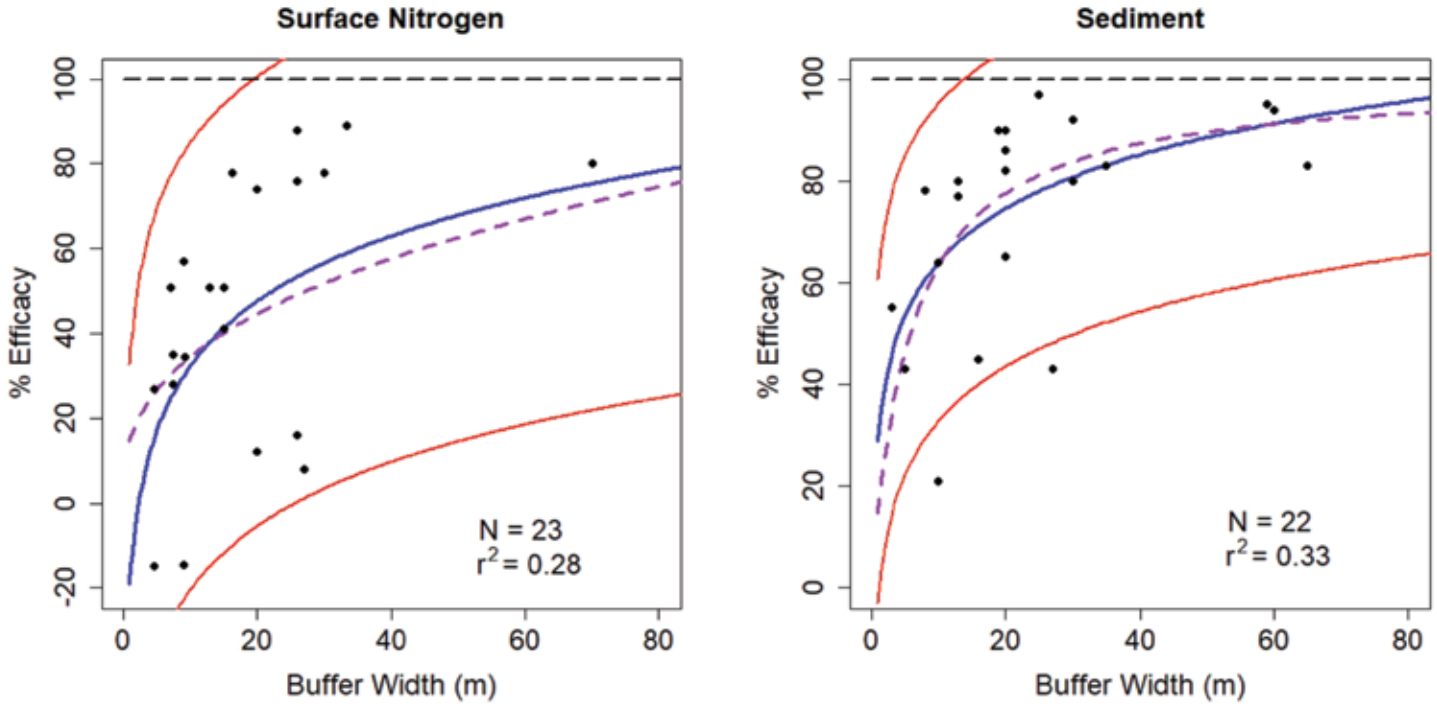


Figure 5.7. Relationship between removal efficacy and buffer width. Study results from meta-analyses reanalyzed using different form of equation in a linear regression. Left: nitrogen study results from Mayer et al. (2007). Right: sediment study results from Sweeney and Newbold (2014). Line colors: blue: best fit model, red: 90% prediction interval, purple dashed: original models from meta-analyses, black dashed: 100% removal efficacy.

Table 5.4. Buffer width in feet needed to achieve desired levels of pollutant removal from run-off. Buffer width calculated with model and/or data from the cited literature. Models had only one predictor variable, which was buffer width. Mean buffer width for sediment and nitrogen removal are weighted averages of widths determined by each meta-analysis. Weights were the product of *N* and R^2.

				Average Removal Efficacy (%)	80	90	95	99
Pollutant	**Meta-analysis**	***N***	***R^2***	**Buffer Width (ft)**				
Sediment	Liu et al. (2008)*	79	0.34		18	39	56	76
	Yuan et al. (2009)	75	0.30		18	74	149	261
	Zhang et al. (2010)*, *reanalyzed*	81	0.31		18	42	64	89
	Sweeney and Newbold (2014), *reanalyzed*	22	0.33		94	181	251	326
				Weighted mean	**25**	**62**	**101**	**153**
Nitrogen, surface	Mayer et al. (2007), *reanalyzed*	23	0.28		283	444	556	666
	Zhang et al. (2010), *reanalyzed*	61	0.44		44	63	76	88
				Weighted mean	**90**	**137**	**169**	**200**
Nitrogen, subsurface	Sweeney and Newbold (2014) ‡	30	0.37		112	161	210	322
Phosphorus	Zhang et al. (2010), *reanalyzed*	52	0.39		50	72	87	101
Pesticides	Zhang et al. (2010), *reanalyzed*	49	0.61		33	48	59	68

* Nearly all the studies included by Liu et al. (2008) and Zhang et al. (2010) were the same studies.

‡ The parameter q, which represents subsurface water flux, was set to 58, which is the median value for 30 studies analyzed by Sweeney and Newbold (2014).

5.7. Conclusions

There is a consensus in the scientific literature that riparian areas reduce the flow of pollutants to aquatic ecosystems, and that pollutant removal functions are contingent on complex interactions between hydrology, soil, and vegetation, and are influenced by many other factors as well. Because hydrology, soil, vegetation and other factors exhibit high spatial and temporal variability, the efficacy of pollutant removal functions provided by riparian areas differs substantially among sites, as well as within sites. Determining the potential for riparian areas to protect water quality is further complicated by the disparate behavior of different contaminant types in the environment. While space limitations required us to simplify this review of the scientific literature regarding pollutant removal functions of riparian areas, we provided the basic information needed for understanding these important ecological functions.

Our review of the literature presents a substantial body of scientific research with which to develop strategies, plans, or policies regarding the pollutant removal functions of riparian areas. The central problem faced by resource managers is determining the adequate riparian buffer width, composition, and structure to protect water quality with high degrees of efficacy, efficiency, and certainty. Riparian function is often simplistically characterized by buffer width and vegetation type, but these parameters only partially explain the effects that riparian areas have on pollutant removal. The current conservation paradigm remains strongly tied to the

premise that wider riparian areas are the only way to increase pollutant removal efficacy, but this is not always the case; other site-specific factors, such as conditions within the buffer, also exert a significant influence on removal efficacy. Therefore, consideration of the entire system (i.e., riparian area, uplands, vegetation, soils, ground and surface water pathways, topography, type of pollutant, etc.) is essential to developing cost-effective pollutant removal. In theory, buffer width and vegetation could be optimized for site conditions such that water quality is protected while minimizing economic costs for landowners.

Despite the many scientific uncertainties, management decisions must be made. Management decisions regarding pollutant removal by riparian buffers should be informed by science, but determining the "right" buffer width for pollutant removal cannot be purely scientific. Determining the "right" buffer width begins with choosing a desired removal efficacy, and that choice is normative. That is, the desired removal efficacy is a social choice influenced by cultural values, economic costs, and risk tolerance. Choosing a desired removal efficacy and determining the "right" buffer requires: 1) factual information regarding the anticipated impacts or outcomes of policy options (i.e., science); 2) an understanding of stakeholders' priorities and preferences (i.e., values); and 3) a process for using science and values to explore tradeoffs amongst policy options (Wilhere and Quinn 2018).

5.8. Literature Cited[3]

Ahmad, M., A.U. Rajapaksha, J.E. Lim, M. Zhang, N. Bolan, D. Mohan, M. Vithanage, S.S. Lee, and Y.S. Ok. 2014. Biochar as a sorbent for contaminant management in soil and water: a review. Chemosphere 99:19-33. (i)

Allaire, S.E., C. Sylvain, S.F. Lange, G. Thériault, and P. Lafrance. 2015. Potential efficiency of riparian vegetated buffer strips in intercepting soluble compounds in the presence of subsurface preferential flows. PLoS ONE 10: e0131840. (i)

Alvarez, M.D., and L.A. Fuiman. 2005. Environmental levels of atrazine and its degradation products impair survival skills and growth of Red Drum larvae. Aquatic Toxicology 74:229-241. (i)

Anbumozhi, V., J. Radhakrishnan, and E. Yamaji. 2005. Impact of riparian buffer zones on water quality and associated management considerations. Ecological Engineering 24:517-523. (i)

Angier, J.T., G.W. McCarty, C.P. Rice, and K. Bialek. 2002. Influence of a riparian wetland on nitrate and herbicides exported from an agricultural field. Journal of Agricultural and Food Chemistry 50:4424-4429. (i)

Au, D.W.T., C.A. Pollino, R.S.S. Wu, P.K.S. Shin, S.T.F. Lau, and J.Y.M. Tang. 2004. Chronic effects of suspended solids on gill structure, osmoregulation, growth, and triiodothyronine in juvenile Green Grouper *Epinephelus coioides.* Marine Ecology Progress Series 266:255-264. (i)

Backer, L.C., J.H. Landsberg, M. Miller, K. Keel, and T.K. Taylor. 2011. Canine cyanotoxin poisonings in the United States (1920s-2012): review of suspected and confirmed cases from three data sources. Toxins 5:1597-1628. (i)

Baldwin, D.H., J.F. Sandahl, J.S. Labenia, and N.L. Scholz. 2003. Sublethal effects of copper on Coho Salmon: impacts on non-overlapping receptor pathways in the peripheral olfactory nervous system.

[3] References are classified according to RCW 34.05.271 (see Appendix 1) denoted by a lower case roman numeral (i – viii) in parentheses at the end of the citation.

Environmental Toxicology and Chemistry 22:2266-2274. (i)

Barling, R.D., and I.D. Moore. 1994. Role of buffer strips in management of waterway pollution: a review. Environmental Management 18:543-558. (i)

BLM (Bureau of Land Management). 2003. Riparian area management: riparian-wetland soils. Technical Reference 1737-19. Denver. (viii)

Boening, D.W. 2000. Ecological effects, transport, and fate of mercury: a general review. Chemosphere 40:1335-1351. (i)

Bohn, C.C., and J.C. Buckhouse. 1985. Some responses of riparian soils to grazing management in northeastern Oregon. Journal of Range Management 38:378-381. (i)

Bolan, N., A. Kunhikrishnan, R. Thangarajan, J. Kumpiene, J. Park, T. Makino, M.B. Kirkham, and K. Scheckel. 2014. Remediation of heavy metal(loid)s contaminated soils–to mobilize or to immobilize? Journal of Hazardous Materials 266:141-166. (i)

Boonchan, S., M.L. Britz, and G.A. Stanley. 2000. Degradation and mineralization of high-molecular-weight polycyclic aromatic hydrocarbons by defined fungal-bacterial cocultures. Applied and Environmental Microbiology 66:1007-1019. (i)

Bourret, M.M., J.E. Brummer, and W.C. Leininger. 2009. Establishment and growth of two willow species in a riparian zone impacted by mine tailings. Journal of Environmental Quality 38:693-701. (i)

Bradford, S.A., and S. Torkzaban. 2008. Colloid transport and retention in unsaturated porous media: a review of interface-, collector-, and pore-scale processes and models. Vadose Zone Journal 7:667-681. (i)

Buffler, S., C. Johnson, J. Nicholson, and N. Mesner. 2005. Synthesis of design guidelines and experimental data for water quality function in agricultural landscapes in the Intermountain West. National Agroforestry Center, Lincoln, Nebraska. (viii)

Burt, T.P., L.S. Matchett, W.T. Goulding, C.P. Webster, and N.E. Haycock. 1999. Denitrification in riparian buffer zones: the role of floodplain hydrology. Hydrologic Processes 13:1451-1463. (i)

Canet, R., J.G. Brinsting, D.G. Malcolm, J.M. Lopez-Real, and A.J. Beck. 2001. Biodegradation of polycyclic aromatic hydrocarbons (PAHs) by native microflora and combinations of white-rot fungi in a coal-tar contaminated soil. Bioresource Technology 76:113-117. (i)

Castelle, A.J., A.W. Johnson, and C. Conolly. 1994. Wetland and stream buffer size requirements–a review. Journal of Environmental Quality 23:878-882. (i)

Cedergreen, N. 2014. Quantifying synergy: a systematic review of mixture toxicity studies within environmental toxicology. PLoS ONE 9:e96580. (i)

Cey E.E., D.L. Rudolph, R. Aravena, and G. Parkin. 1999. Role of the riparian zone in controlling the distribution and fate of agricultural nitrogen near a small stream in southern Ontario. Journal of Contaminant Hydrology 37:45–67. (i)

Chaubey, I., D.R. Edwards, T.C. Daniel, P.A. Moore, and D.J. Nichols. 1995. Effectiveness of vegetative filter strips in controlling losses of surface-applied poultry litter constituents. Transactions of the American Society of Agricultural Engineers 38:1687-1692. (i)

Cheng, Z.Q., E.L. McCoy, and P.S. Grewal. 2014. Water, sediment, and nutrient runoff from urban lawns established on disturbed subsoil or topsoil and managed with inorganic or organic fertilizers. Urban Ecosystems 17:277-289. (i)

Clements, W.H., D.S. Cherry, and J. Cairns, Jr. 1990. Macroinvertebrate community responses to copper in laboratory and field experimental streams. Archives of Environmental Contaminants and Toxicology 19:361-365. (i)

Clinton, B.D. 2011. Stream water responses to timber harvest: riparian buffer width effectiveness. Forest Ecology and Management 261:979-988. (i)

Colborn, T., F.S.V. Saal, and A.M. Soto. 1993. Developmental effects of endocrine-disrupting chemicals in wildlife and humans. Environmental Health Perspectives 101:378-384. (i)

Collins, R., A. Donnison, C. Ross, and M. McLeod. 2004. Attenuation of effluent-derived faecal microbes in grass buffer strips. New Zealand Journal of Agricultural Research 47:565-574. (i)

Cooper, J.R., and J.W. Gilliam. 1987. Phosphorus redistribution from cultivated fields into riparian areas. Soil Science Society of American Journal 51:1600-1604. (i)

Cors, M., and B. Tychon. 2007. Grassed buffer strips as nitrate diffuse pollution remediation tools: management impact on the denitrification enzyme activity. Water Science and Technology 55:25-30. (i)

Correll, D.L. 1997. Buffer zones and water quality protection: general principles. Pages 7-20 *in* N. Hancock, T. Burt, K. Goulding, and G. Pinay, editors. Buffer zones: their processes and potential in water protection. Quest Environmental, Hertfordshire, United Kingdom. (viii)

Covaci, A., S. Harrad, M.A.E. Abdallah, N. Ali, R.J. Law, D. Herzke, and C.A. de Wit. 2011. Novel brominated flame retardants: a review of their analysis, environmental fate and behavior. Environment International 37:532-556. (i)

Coyne, M.S., R.A. Gilfillen, R.W. Rhodes, and R.L. Blevins. 1995. Soil and fecal-coliform trapping by grass filter strips during simulated rain. Journal of Soil and Water Conservation 50:405-408. (i)

Coyne, M.S., R.A. Gilfillen, A. Villalba, Z. Zhang, R. Rhodes, L. Dunn, and R.L. Blevins. 1998. Fecal bacteria trapping by grass filter strips during simulated rain. Journal of Soil and Water Conservation 53:140-145. (i)

Daniels, R.B., and J.W. Gilliam. 1996. Sediment and chemical load reduction by grass and riparian filters. Soil Science Society of America Journal 60:246-251. (i)

De Snoo, G.R., and P.J. De Witt. 1998. Buffer zones for reducing pesticide drift to ditches and risks to aquatic organisms. Ecotoxicology and Environmental Safety 41:112-118. (i)

Delle Site, A. 2001. Factors affecting sorption of organic compounds in natural sorbent/water systems and sorption coefficients for selected pollutants—a review. Journal of Physical and Chemical Reference Data 30:187-439. (i)

Dillaha, T.A., R.B. Reneau, S. Mostaghimi, and D. Lee. 1989. Vegetative filter strips for agricultural nonpoint source pollution control. Transactions of American Society of Agricultural Engineers 32:513-519. (i)

Dorioz, J.M., D. Wang, J. Poulenard, and D. Trévisan. 2006. The effect of grass buffer strips on phosphorus dynamics—a critical review and synthesis as a basis for application in agricultural landscapes in France. Agriculture, Ecosystems and Environment 117:4-21 (i)

Dosskey, M.G. 2001. Toward quantifying water pollution abatement in response to installing buffers on crop land. Environmental Management 28:577-598. (i)

Dosskey, M.G., M.J. Helmers, D.E. Eisenhauer, T.G. Franti, and K.D. Hoagland. 2002. Assessment of concentrated flow through riparian buffers. Journal of Soil and Water Resources Association 57:336-343. (i)

Dosskey, M.G., P. Vidon, N.P. Gurwick, C.J. Allan, T.P. Duval, and R. Lowrance. 2010. The role of riparian vegetation in protecting and improving chemical water quality in streams. Journal of the American Water Resources Association 46:261-277. (i)

Doyle, R.C., D.C. Wolf, and D.F. Bezdicek. 1975. Effectiveness of forest buffer strips in improving the water quality of manure polluted runoff. Pages 299-302 *in* Managing livestock wastes. Proceedings of 3rd international symposium on livestock wastes. Food and Agricultural Organization of the United Nations, Rome. (viii)

Du Laing, G., J. Rinklebe, B. Vandecasteele, E. Meers, and F.M.G. Tack. 2009. Trace metal behavior in estuarine and riverine floodplain soils and sediments: a review. Science of the Total Environment 407:3972-3985. (i)

Ecology (Washington State Department of Ecology). 2007. Mission Creek watershed DDT total maximum daily load: water quality improvement report. Publication number 07-10-046. Olympia, Washington. (viii)

Entry, J.A., R.K. Hubbard, J.E. Thies, and J.J. Fuhrmann. 2000. The influence of vegetation in riparian filterstrips on coliform bacteria: II. Survival in soils. Journal of Environmental Quality 29:1215-1224. (i)

Euliss, K., C. Ho, A.P. Schwab, S. Rock, and M.K. Banks. 2008. Greenhouse and field assessment of phytoremediation for petroleum contaminants in a riparian zone. Bioresource Technology 99:1961-1971. (i)

Fajardo, J.J., J.W. Bauder, and S.D. Cash. 2001. Managing nitrate and bacteria in runoff from livestock confinement areas with vegetative filter strips. Journal of Soil and Water Conservation 56:185-191. (i)

Feng, J.C., D.G. Thompson, and P.E. Reynolds. 1990. Fate of glyphosate in a Canadian Forest Watershed. 1. Aquatic residues and off-target deposit assessment. Journal of Agricultural and Food Chemistry 38:1110-1118. (i)

Fennesy, M.S., and J.K. Cronk. 1997. The effectiveness and restoration potential of riparian ecotones for the management of nonpoint source pollution, particularly nitrate. Critical Reviews in Environmental Science and Technology 27:285-317. (i)

Fisher, R.F., and D. Binkley. 2000. Ecology and management of forest soils. Wiley, New York. (i)

Fischer, R.A., and J.C. Fischenich. 2000. Design recommendations for riparian corridors and vegetative buffer strips. U.S. Army Engineer Research and Development Center, Vicksburg, Mississippi. (viii)

Fleeger, J.W., K.R. Carman, and R.M. Nisbet. 2003. Indirect effects of contaminants in aquatic ecosystems. Science of the Total Environment 317:207-233. (i)

Fox, G.A., D.M. Heeren, R.B. Miller, A.R. Mittelstet, and D.E. Storm. 2011a. Flow and transport experiments for a streambank seep originating from a preferential flow pathway. Journal of Hydrology 403:360-366. (i)

Fox, G.A., E.M. Matlock, J.A. Guzman, D. Sahoo, and K.B. Stunkel. 2011b. *Escherichia coli* load reduction from runoff by vegetative filter strips: a laboratory-scale study. Journal of Environmental Quality 40:980-988. (i)

Fuchs, J.W., G.A. Fox, D.E. Storm, C.J. Penn, and G.O. Brown. 2009. Subsurface transport of phosphorus in riparian floodplains: influence of preferential flow paths. Journal of Environmental Quality 38:473-484. (i)

Garcia-Muñoz, E., F. Guerrero, and G. Parra. 2011. Larval escape behavior in anuran amphibians as a wetland rapid pollution biomarker. Marine and Freshwater Behaviour and Physiology 44:109-123. (i)

Ghosh, M., and S.P. Singh. 2005. A review of phytoremediation of heavy metals and utilization of its byproducts. Applied Ecology and Environmental Research 3:1-18. (i)

Gonod, L.V., F. Martin-Laurent, and C. Chenu. 2006. 2,4-D impact on bacterial communities, and the activity and genetic potential of 2,4-D degrading communities in soil. FEMS Microbiology Ecology 58:529-537. (i)

Gordon, N.D., T.A. McMahon, B.L. Finlayson, C.J. Gippel, and R.J. Nathan. 2004. Stream hydrology: an introduction for ecologists. Wiley, West Sussex, England. (i)

Grathwohl, P. 1990. Influence of organic matter from soils and sediments from various origins on the sorption of some chlorinated aliphatic hydrocarbons: Implications on K_{OC} correlations. Environmental Science & Technology 24:1687-1693. (i)

Groffman, P.M., E.A. Axelrod, J.L. Lemonyon, and W.M. Sullivan. 1991. Dentrification in grass and forest vegetated filter strips. Journal of Environmental Quality 20:671-674. (i)

Gu, C., W. Anderson, and F. Maggi. 2012. Riparian biogeochemical hot moments induced by stream fluctuation. Water Resources Research 48:W09546. (i)

Guan, K., S.E. Thompson, C.J. Harman, N.B. Basu, P.S.C. Rao, M. Sivapalan, A.I. Packman, and P.K. Kalita. 2011. Spatiotemporal scaling of hydrological and agrochemical export dynamics in a tile-drained midwestern watershed. Water Resources Research 47:W00J02. (i)

Guber, A.K., A.M. Yakirevich, A.M. Sadeghi, Y.A. Pachepsky, and D.R. Shelton. 2009. Uncertainty evaluation of coliform bacteria removal from vegetative filter strip under overland flow condition. Journal of Environmental Quality 38:1636-1644. (i)

Haritash, A.K., and C.P. Kaushik. 2001. Biodegradation aspects of polycyclic aromatic hydrocarbons (PAHs): a review. Journal of Hazardous Materials 169:1-15. (i)

Hawes, E., and M. Smith. 2004. Riparian buffer zones: functions and recommended widths. Yale School of Forestry and Environmental Studies, New Haven, Connecticut. (viii)

Hayashi, M., and D.O. Rosenberry. 2002. Effects of ground water exchange on the hydrology and ecology of surface water. Ground Water 40:309–316. (i)

Hayes, M.H.B. 1970. Adsorption of triazine herbicides on soil organic matter, including a short review on soil organic matter chemistry. Residue Reviews 32:137-174. (i)

Hayes, T., K. Haston, M. Tsui, A. Hoang, C. Haeffele, and A. Vonk. 2003. Atrazine-induced hermaphroditism at 0.1 ppb in American Leopard Frogs *Rana pipiens*: laboratory and field evidence. Environmental Health Perspectives 111:568-575. (i)

Hecht, S.A., D.H. Baldwin, C.A. Mebane, T. Hawkes, S.J. Gross, and N.L. Scholz. 2007. An overview of sensory effects on juvenile salmonids exposed to dissolved copper: applying a benchmark concentration approach to evaluate sublethal neurobehavioral toxicity. Tech Memo NMFS-NWFSC-83. National Marine Fisheries Service, Seattle. (viii)

Hedin, L.O., J.C. von Fischer, N.E. Ostrom, B.P. Kennedy, M.G. Brown, and G.P. Robertson. 1998. Thermodynamic constraints on nitrogen transformations and other biogeochemical processes at soil-stream interfaces. Ecology 79:684-703. (i)

Hickey, M.B., and B. Doran. 2004. A review of efficiency of buffer strips for the maintenance and enhancement of riparian ecosystems. Water Quality Research Journal of Canada 39:311-317. (i)

Hoffmann, C.C., C. Kjaergaard, J. Uusi-Kämppä, H.C.B. Hansen, and B. Kronvang. 2009. Phosphorus retention in riparian buffers: review of their efficiency. Journal of Environmental Quality 38:1942-1955. (i)

Hill, A.R. 1996. Nitrate removal in stream riparian zones. Journal of Environmental Quality 25:743-755. (i)

Hruby, T. 2013. Update on wetland buffers: the state of the science, final report. Washington State Department of Ecolgy, Olympia, Washington. (viii)

Hua, J., and R. Relyea. 2014. Chemical cocktails in aquatic systems: pesticide effects on the response and recovery of >20 animal taxa. Environmental Pollution 189(June):18-26. (i)

Huggenberger, P., E. Hoehn, R. Beschta, and W. Woessner. 1998. Abiotic aspects of channels and floodplains in riparian ecology. Freshwater Biology 40:407-425. (i)

Ingersoll, C.G., and R.W. Winner. 1982. Effect on *Daphnia pulex* (De Geer) of daily pulse exposures to copper or cadmium. Environmental Toxicology and Chemistry 1:321-327. (i)

Jarvie, H.P., A.N. Sharpley, B. Spears, A.R. Buda, L. May, and P.J.A. Kleinman. 2013. Water quality remediation faces unprecedented challenges from "legacy phosphorus". Environmental Science & Technology 47:8997–8998. (i)

Jaynes, D.B., and T.M. Isenhart. 2014. Reconnecting tile drainage to riparian buffer hydrology for enhanced nitrate removal. Journal of Environmental Quality 43:631-638. (i)

Jiang, X., J. Morgan, and M.P. Doyle. 2002. Fate of *Escherichia coli* O157:H7 in manure-amended soil. Applied and Environmental Microbiology 68:2605-2609. (i)

Johnson, C.W., and S. Buffler. 2008. Riparian buffer design guidelines for water quality and wildlife habitat functions on agricultural landscapes in the Intermountain West. RMRS-GTR-203. U.S. Forest Service, Rocky Mountain Research Station, Fort Collins, Colorado. (viii)

Jones, G.K. 2009. Bioremediation of contaminated riparian zones using mycorrhizal fungi–an exploration of the feasibility of restoration through mycoremediation. Master's thesis. The Evergreen State College, Olympia, Washington. (i)

Kalbus, E., C. Schmidt, J.W. Molson, F. Reinstorf, and M. Schirmer. 2009. Influence of aquifer and streambed heterogeneity on the distribution of groundwater discharge. Hydrology and Earth System Sciences 13:69-77. (i)

Karthikeyan, R., L.C. Davis, L.E. Erickson, K. Al-Khatib, P.A. Kulakow, P.L. Barnes, S.L. Hutchinson, and A.A. Nurzhanova. 2004. Potential for plant-based remediation of pesticide-contaminated soil and water using nontarget plants such as trees, shrubs, and grasses. Critical Reviews in Plant Sciences 23:91-101. (i)

Khan, S.U. 1972. Adsorption of pesticide by humic substances—a review. Environmental Letters 3:1-12. (i)

Kopinke, F.D., A. Georgi, and K. Mackenzie. 2001. Sorption of pyrene to dissolved humic substances and related model polymers. 1. Structure-property correlation. Environmental Science & Technology 35:2536-2542. (i)

Koptsik, G.N. 2014. Problems and prospects concerning the phytoremediation of heavy metal polluted soils: a review. Eurasian Soil Science 47:923-939. (i)

Krutz, L.J., S.A. Senseman, R.M. Zablotowicz, and M.A. Matocha. 2005. Reducing herbicide runoff from agricultural fields with vegetative filter strips: a review. Weed Science 53:353-367. (i)

Kuglerová, L., A. Ågren., R. Jansson, and H. Laudon. 2014. Towards optimizing riparian buffer zones: ecological and biogeochemical implications for forest management. Forest Ecology and Management 334:74-84. (i)

Kümmerer, K. 2009a. Antibiotics in the aquatic environment—a review—Part I. Chemosphere 75:417-434. (i)

Kümmerer, K. 2009b. Antibiotics in the aquatic environment—a review—Part II. Chemosphere 75:435-441. (i)

Lacas, J., M. Voltz, V. Gouy, N. Carluer, and J. Gril. 2005. Using grassed strips to limit pesticide transfer to surface water: a review. Agronomy for Sustainable Development 25:253-266. (i)

Laetz, C.A., D.H. Baldwin, V. Hebert, J.D. Stark, and N.L. Scholz. 2013. Interactive neurobehavioral toxicity of diazinon, malathion, and ethopop to juvenile Coho Salmon. Environmental Science & Technology 47:2925-2931. (i)

Laghlimi, M., B. Baghdad, H. El Hadi, and A. Bouabdli. 2015. Phytoremediation mechanisms of heavy metal contaminated soils: a review. Open Journal of Ecology 5:375-388. (i)

Lamar, R.T., J.W. Evans, and J.A. Glaser. 1993. Solid-phase treatment of a pentachlorophenol-contaminated soil using lignin-degrading fungi. Environmental Science & Technology 27:2566-2571. (i)

Landmeyer, J.E. 2011. Introduction to phytoremediation of contaminated groundwater: historical foundation, hydrologic control, and contaminant remediation. Springer Science& Business Media, New York. (i)

Lee, K.H., T.M. Isenhart, and R.C. Schultz. 2003. Sediment and nutrient removal in an established multi-species riparian buffer. Journal of Soil and Water Conservation 58:1-8. (i)

Lee, P., C. Smith, and S. Boutin. 2004. Quantitative review of riparian buffer width guidelines from Canada and the United States. Journal of Environmental Management 70:165-180. (i)

Leeds, R., L.C. Brown, M.R. Sulc, and L. VanLieshout. 1994. Vegetative filter strips: application, installation and maintenance. Publication number AEX-467-94. Ohio State University Extension, Columbus, Ohio. (viii)

LeFevre, G.H., R.M. Hozalski, and P.J. Novak. 2012. The role of biodegradation in limiting the accumulation of petroleum hydrocarbons in raingarden soils. Water Research 46:6753-6762. (i)

Lewandowski, J., L. Angermann, G., Nutzmann, and J.H. Fleckenstein. 2011. A heat pulse technique for the determination of small-scale flow directions and flow velocities in the streambed of sand-bed streams, Hydrological Processes 25:3244-3255. (i)

Liu, X., X. Zhang, and M. Zhang. 2008. Majors factors influencing the efficacy of vegetated buffers on sediment trapping: a review and analysis. Journal of Environmental Quality 37:1667-1674. (i)

Lortz, H.W., and B.P. McPherson. 1977. Effects of copper and zinc on smoltification of Coho Salmon. EPA-600/3-77-032. U.S. Environmental Protection Agency, Corvallis, Oregon. (i)

Lowrance, R., R. Todd, J. Fail, Jr., O. Hendrickson, Jr., R. Leonard, and L. Asmussen. 1984. Riparian forests as nutrient filters in agricultural watersheds. Bioscience 34:374-377. (i)

Luo, Y.L., W.S. Guo, H.H. Ngo, L.D. Nghiem, F.I. Hai, J. Zhang, S. Liang, and X.C.C. Wang. 2014. A review on the occurrence of micropollutants in the aquatic environment and their fate and removal during wastewater treatment. Science of the Total Environment 473:619-641. (i)

Lyons, J., S.W. Trimble, and L.K. Paine. 2000. Grass versus trees: managing riparian areas to benefit streams of central North America. Journal of the American Water Resources Association 36:919-930. (i)

Mahar, A., W. Ping, L.I. Ronghua, and Z. Zengqiang. 2015. Immobilization of lead and cadmium in contaminated soil using amendments: a review. Pedosphere 25:555-568. (i)

Malanson, G.P. 1993. Riparian landscapes. Cambridge studies in ecology. Cambridge University Press, Cambridge, United Kingdom. (i)

Mann, R.M., R.V. Hyne, C.B. Choung, and S.P. Wilson. 2009. Amphibians and agricultural chemicals: review of the risks in a complex environment. Environmental Pollution 157:2903–2927. (i)

Marco, A., C. Quilchano, and A. Blaustein. 1999. Sensitivity to nitrate and nitrite in pond-breeding amphibians from the Pacific Northwest, USA. Environmental Toxicology and Chemistry 18:2836-2839. (i)

Mayer, P.M., S.K. Reynolds, M.D. McCutchen, and T.J. Canfield. 2006. Riparian buffer width, vegetative cover, and nitrogen removal effectiveness: a review of current science and regulations. EPA/600/R-05/118. U.S. Environmental Protection Agency, Cincinnati, Ohio. (viii)

Mayer, P.M., S.K. Reynolds, M.D. Marshall, D. McCutchen, and T.J. Canfield. 2007. Meta-analysis of nitrogen removal in riparian buffers. Journal of Environmental Quality 36:1172-1180. (i)

McClain, M.E., E.W. Boyer, C.L. Dent, S.E. Gergel, N.B. Grimm, P.M. Groffman, S.C. Hart, J.W. Harvey, C.A. Johnston, and E. Mayorga. 2003. Biogeochemical hot spots and hot moments at the interface of terrestrial and aquatic ecosystems. Ecosystems 6:301-312. (i)

McInnis, M.L., and J. McIver. 2001. Influence of off-stream supplements on stream banks of riparian pastures. Journal of Range Management 54:648-652. (i)

McIntyre, J.K., D.H. Baldwin, D.A. Beauchamp, and N.L. Scholz. 2012. Low level copper exposure increases visibility and vulnerability of juvenile Coho Salmon to Cutthroat Trout predators. Ecological Applications 22:1460-1471. (i)

Menichino, G.T., A.S. Ward, and E.T. Hester. 2014. Macropores as preferential flow paths in meander bends. Hydrological Processes 28:482-495. (i)

Merritt, W.S., R.A. Letcher, and A.J. Jakeman. 2003. A review of erosion and sediment transport models. Environmental Modelling & Software 18:761-799. (i)

Misra, A.K., J.L. Baker, S.K. Mickelson, and H. Shang. 1996. Contributing area and concentration effects on herbicide removal by vegetative buffer strips. Transactions of the American Society of Agricultural Engineers 39:2105-2111. (i)

Mitchell, S.M., J.L. Ullman, A.L. Teel, and R.J. Watts. 2014. pH and temperature effects on the hydrolysis of three - lactam antibiotics: ampicillin, cefalotin and cefoxitin. Science of the Total Environment 466-467:547-555. (i)

Mitchell, S.M., J.L. Ullman, A.L. Teel, and R.J. Watts. 2015. Hydrolysis of amphenicol and macrolide antibiotics: chloramphenicol, florfenicol, spiramycin, and tylosin. Chemosphere 134:504-511. (i)

Moermond, C.T.A., F. Roozen, J.J.G. Zwolsman, and A.A. Koelmans. 2004. Uptake of sediment-bound bioavailable polychlorobiphenyls by Benthivorous Carp (*Cyprinus carpio*). Environmental Science & Technology 38:4503-4509. (i)

Monteiro, S.M., J.M. Mancera, A. Fontainhas-Fernandes, and M. Sousa. 2005. Copper induced alterations of biochemical parameters in the gill and plasma of

Oreochromis niloticus. Comparative Biochemistry and Physiology C—Toxicology & Pharmacology 141:375-383. (i)

Moore, M.T., R. Kröger, and C.R. Jackson. 2011. The role of aquatic ecosystems in the elimination of pollutants. Pages 288-304 ***in*** F. Sánchez-Bayo, P.J. van den Brink, and R.M. Mann, editors. Ecological impacts of toxic chemicals. Bentham Science, Oxford, Mississippi.

Moore, A., N. Lower, I. Mayer, and L. Greenwood. 2007. The impact of a pesticide on migratory activity and olfactory function in Atlantic Salmon (*Salmo salar L.*) smolts. Aquaculture 273:350-359. (i)

Morace, J.L., and S.W. McKenzie. 2002. Fecal-indicator bacteria in the Yakima River Basin, Washington—an examination of 1999 and 2000 synoptic-sampling data and their relation to historic data. Water Resources Investigations Report 02-4054. U.S. Geological Survey, Portland, Oregon. (viii)

Mueller, S.O. 2004. Xenoestrogens: mechanisms of action and detection methods. Analytical and Bioanalytical Chemistry 378:582-597. (i)

Muñoz-Carpena, R., J.E. Parsons, and J.W. Gilliam. 1999. Modeling hydrology ad sediment transport in vegetative filter strips. Journal of Hydrology 214:111-129. (i)

Muscutt, A.D., G.L. Harris, S.W. Bailey, and D.B. Davies. 1993. Buffer zones to improve water-quality—a review of their potential use in UK agriculture. Agriculture Ecosystems & Environment 45:59-77. (i)

Newcombe, C.P., and D.D. MacDonald. 1991. Effects of suspended sediments on aquatic ecosystems. North American Journal of Fisheries Management 11:72-82. (i)

Nimick, D.D., C.H. Gammons, and S.R. Parker. 2011. Diel biogeochemical processes and their effect on the aqueous chemistry of streams: a review. Chemical Geology 283:3-17. (i)

Norris, V. 1993. The use of buffer zones to protect water quality: a review. Water Resources Management 7:257-272. (i)

NRC (National Research Council). 2002. Riparian areas: functions and strategies for management. National Academy Press, Washington, D.C. (i)

Osborne, L.L., and D.A. Kovacic. 1993. Riparian vegetated buffer strips in water-quality restoration and stream management. Freshwater Biology 29:243-258. (i)

Peterjohn, W.T., and D.L. Correll. 1984. Nutrient dynamics in an agricultural watershed: observations on the role of a riparian forest. Ecology 65:1466-1475. (i)

Peverill, K.I., L.A. Douglas, and N.B. Greenhill. 1977. Leaching losses of applied P and S from undisturbed cores of some Australian surface soils. Geoderma 19:91-96. (i)

Pilon-Smits, E. 2005. Phytoremediation. Annual Review of Plant Biology 56:15-39. (i)

Pinto, E., T.C.S. Sigaud-Kutner, M.A.S. Leitão, O.O. Okamoto, D. Morse, and P. Colepicolo. 2003. Heavy metal-induced oxidative stress in algae. Journal of Phycology 39:1008-1018. (i)

Polyakov, V., A. Fares, and M.H. Ryder. 2005. Precision riparian buffers for the control of nonpoint source pollutant loading into surface water: a review. Environmental Reviews 13:129-144. (i)

PSAT (Puget Sound Action Team). 2007. 2007 Puget Sound update: ninth report of the Puget Sound Ambient Monitoring Program. Puget Sound Action Team, Olympia, Washington. (viii)

Pulford, I.D., and C. Watson. 2003. Phytoremediation of heavy metal-contaminated land by trees—a review. Environment International 29:529-540. (i)

Rahman, F., K.H. Langford, M.D. Scrimshaw, and J.N. Lester. 2001. Polybrominated diphenyl ether (PBDE) flame retardants. Science of the Total Environment 275:1-17. (i)

RCT (R Core Team). 2013. R: a language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. (viii)

Redding, J.M., C.B. Schreck, and F.H. Everest. 1987. Physiological effects on Coho Salmon and steelhead

of exposure to suspended solids. Transactions of the American Fisheries Society 116:737-744. (i)

Redick, M.S., and T.W. La Point. 2004. Effects of sublethal copper exposure on behavior and growth of *Rana pipiens* tadpoles. Bulletin of Environmental Contamination and Toxicology 72:706-710. (i)

Reichenberger, S., M. Bach, A. Skitschak, and H. Frede. 2007. Mitigation strategies to reduce pesticide inputs into ground- and surface water and their effectiveness; a review. Science of the Total Environment 384:1-35. (i)

Relyea, R.A., and N. Diecks. 2008. An unforeseen chain of events: lethal effects of pesticides on frogs at sublethal concentrations. Ecological Applications 18:1728-1742. (i)

Reuter, J.H., and E.M. Perdue. 1977. Importance of heavy metal-organic matter interactions in natural waters. Geochimica et Cosmochimica Acta 41:325-334. (i)

Rinklebe, J., and S.M. Shaheen. 2015. Miscellaneous additives can enhance plant uptake and affect geochemical fractions of copper in a heavily polluted riparian grassland soil. Ecotoxicology and Environmental Safety 119:58-65. (i)

Rougier, F., D. Troutaud, A. Ndoye, and P. Deschaux. 1994. Nonspecific immune-response of Zebrafish, *Brachydanio rerio* (Hamilton-Buchanan) following copper and zinc exposure. Fish & Shellfish Immunology 4:115-127. (i)

Salt, D.E., R.D. Smith, and I. Raskin. 1998. Phytoremediation. Annual Review of Plant Physiology and Plant Molecular Biology 49:643-668. (i)

Sandahl J.F., D.H. Baldwin, J.J. Jenkins, and N.L. Scholz. 2007. A sensory system at the interface between urban stormwater runoff and salmon survival. Environmental Science & Technology 41:2998-3004. (i)

Sarma, H. 2011. Metal hyperaccumulation in plants: a review focusing on phytoremediation technology. Journal of Environmental Science and Technology 4:118-138. (i)

Schellinger, G.R., and J.C. Clausen. 1992. Vegetative filter treatment of dairy barnyard runoff in cold regions. Journal of Environmental Quality 21:40-45. (i)

Schnaebel, R.R., J.A. Shaffer, W.L. Stout, and L.F. Cornish. 1997. Denitrification distributions in four valley and ridge riparian ecosystems. Environmental Management 21:283-290. (i)

Schultz, R.C., J.P. Colletti, T.M. Isenhart, C.O. Marquez, W.W. Simpkins, and C.J. Ball. 2000. Riparian forest buffer practices. Pages 189-281 *in* H.E. Garett, W.J. Rietveld, and R.F. Fisher, editors. North American agroforestry: an integrated science and practice. American Society of Agronomy, Madison, Wisconsin. (viii)

Schuster, S., and M.E. Grismer. 2004. Evaluation of water quality projects in the Lake Tahoe Basin. Environmental Monitoring and Assessment 90:225-242. (i)

Scoggins, M., N.L. McClintock, L. Gosselink, and P. Bryer. 2007. Occurrence of polycyclic aromatic hydrocarbons below coat-tar-sealed parking lots and effects on stream benthic macroinvertebrate communities. Journal of the North American Benthological Society 26:694-707. (i)

Sen, T.K., and K.C. Khilar. 2006. Review on subsurface colloids and colloid-associated contaminant transport in saturated porous media. Advances in Colloid and Interface Science 119:71-96. (i)

Sheridan, J.M., R. Lowrance, and D.D. Bosch. 1999. Management effects on runoff and sediment transport in riparian forest buffers. Transactions of the American Society of Agricultural Engineers 42:55-64. (i)

Skłodowski, M., E. Kiedrzynska, M. Kiedrzynski, M. Urbaniak, K.M. Zielinska, J.K. Kurowski, and M. Zalewski. 2014. The role of riparian willows in phosphorus accumulation and PCB control for lotic water quality improvement. Ecological Engineering 70:1-10. (i)

Sorensen, E.M. 1991. Metal poisoning in fish. CRC Press, Boca Raton, Florida. (i)

Sprague, J.B., and A. Ramsay. 1965. Lethal levels of mixed copper-zinc solutions for juvenile salmon. Journal of the Fisheries Research Board of Canada 22:425-432. (i)

Spromberg, J.A., D.H. Baldwin, S.E. Damm, J.K. McIntyre, M. Huff, C.A. Sloan, B.F. Anulacion, J.W. Davis, and N.L. Scholz. 2016. Coho Salmon spawner mortality in western US urban watersheds: bioinfiltration prevents lethal storm water impacts. Journal of Applied Ecology 53:398–407. (i)

Straffelini, G., R. Ciudin, A. Ciotti, and S. Gialanella. 2015. Present knowledge and perspectives on the role of copper in brake materials and related environmental issues: a critical assessment. Environmental Pollution 207:211-219. (i)

Susarla, S., V.F. Medina, and S.C. McCutcheon. 2002. Phytoremediation: an ecological solution to organic chemical contamination. Ecological Engineering 18:647-658. (i)

Sweeney B.W., T.L. Bott, J.K. Jackson, L.A. Kaplan, J.D. Newbold, L.J. Standley, W.C. Hession, and R.J. Horwitz. 2004. Riparian deforestation, stream narrowing, and loss of stream ecosystem services. Proceedings of the National Academy of Science 101:14132-14137. (i)

Sweeney, B.W., and J.D. Newbold. 2014. Streamside buffer width needed to protect stream water quality, habitat, and organisms: a literature review. Journal of the American Water Resources Association 50:560-584. (i)

Syversen, N., L. Oygarden, and B. Salbu. 2001. Cesium-134 as a tracer to study particle transport processes within a small catchment with a buffer zone. Journal of Environmental Quality 30:1771-1783. (i)

Tabacchi, E., L. Lambs, H. Guilloy, A. Planty-Tabacchi, E. Muller, and H. Décamps. 2000. Impacts of riparian vegetation on hydrological processes. Hydrological Processes 14:2959-2976. (i)

Tate, K.W., E.R. Atwill, J.W. Bartolome and G. Nader. 2006. Significant *Escherichia coli* attenuation by vegetative buffers on annual grasslands. Journal of Environmental Quality 35:795-805. (i)

Tobiason, S.A., C. Nickerson, R. Zisette, and M. Samadpour. 2002. Stormwater bacteria source tracing at Seattle-Tacoma International Airport. Proceedings of the Water Environment Federation's technical exhibition and conference. Water Environment Federation, Alexandria, Virginia. (viii)

Trimble, G.R., and R.S. Sartz. 1957. How far from a stream should a logging road be located? Journal of Forestry 55:339-341. (i)

Ucar, T., and F.R. Hall. 2001. Windbreaks as a pesticide drift mitigation strategy: a review. Pest Management Science 57:663-675. (i)

UKEA (United Kingdom Environmental Agency). 2009. The hyporheic handbook: a handbook on the groundwater–surface water interface and hyporheic zone for environment managers. Science report SC050070. Integrated Catchment Science Programme, Bristol, United Kingdom. (viii)

Unc, A., and M.J. Goss. 2004. Transport of bacteria from manure and protection of water resources. Applied Soil Ecology 25:1-18. (i)

NRCS (National Resources Conservation Service). 2000. Conservation buffers to reduce pesticide losses. Washington, D.C. (i)

USEPA (U.S. Environmental Protection Agency). 1980. Ambient water quality criteria for copper. EPA 440/5-80-036. Washington D.C. (viii)

USEPA (U.S. Environmental Protection Agency). 2003. Evaluation of sediment transport models and comparative application of two watershed models. EPA/600/R-03/139. Cincinnati, Ohio. (viii)

USEPA (U.S. Environmental Protection Agency). 2015. Washington causes of impairment for 303(d) listed waters. Available: http://iaspub.epa.gov/tmdl_waters10/attains_state.control?p_state=WA#causes/. (January 2019). (viii)

USGS (U.S. Geological Survey). 2006. Pesticides in the nation's streams and ground water 1992-2001 – a summary. Fact Sheet 2006-3028. Sacramento, California . (i)

Vervoort, R.W., D.E. Radcliffe, and L.T. West. 1999. Soil structure development and preferential solute flow. Water Resources Research 35:913-928. (i)

Vidon, P., C. Allan, D. Burns, T.P. Duval, N. Gurwick, S. Inamdar, R. Lowrance, J. Okay, D. Scott, and S. Sebestven. 2010. Hot spots and hot moments in riparian zones: potential for improved water quality management. Journal of the American Water Resources Association 46:278-298. (i)

Vidon, P., and P.E. Cuadra. 2011. Phosphorus dynamics in tile-drain flow during storms in the US Midwest. Agricultural Water Management 98:532-540. (i)

Vogt, T., M. Schirmer, and O.A. Cirpka. 2012. Investigating riparian groundwater flow close to a losing river using diurnal temperature oscillations at high vertical resolution. Hydrology and Earth System Sciences 16:473-487. (i)

Vought, L.B.-M., J. Dahl, C.L. Pedersen, and J.O. Lacoursière. 1994. Nutrient retention in riparian ecotones. Ambio 23:343-348. (i)

Vought. L.B.-M., G. Pinay, A. Fuglsang, and C. Ruffinoni. 1995. Structure and function of buffer strips from a water quality perspective in agricultural landscapes. Landscape and Urban Planning 31:323-331. (i)

Walker, S.E., S. Mostaghimi, T.A. Dillaha, and F.E. Woeste. 1990. Modeling animal waste management practices–impacts on bacteria levels in runoff from agricultural lands. Transactions of the American Society of Agricultural Engineers 33:807-817. (i)

Wang, Z., Z. Wang, and Y. Pei. 2014. Nitrogen removal and microbial communities in a three-stage system simulating a riparian environment. Bioprocess and Biosystem Engineering 37:1105-1114. (i)

Waters, T.F. 1995. Sediment in streams: sources, biological effects and control. American Fisheries Society Monograph 7. American Fisheries Society, Bethesda, Maryland. (i)

Welsch, D.J. 1991. Riparian forest buffers: function and design for protection and enhancement of water resources. NA-PR-07-91. U.S. Forest Service, Radnor, Pennsylvania. (viii)

Welsh, H.H., and L.M. Ollivier. 1998. Stream amphibians as indicators of ecosystem stress: A case study from California's Redwoods. Ecological Applications 8:1118-1132. (i)

Wilhere, G.F., and T. Quinn. 2018. How wide is wide enough?: values, science, and law in riparian habitat conservation. Natural Resources Journal 58:279-318. (i)

Williams, D.G., and R. Scott. 2009. Vegetation-hydrology interactions: dynamics of riparian plant water use. Pages 37-56 *in* J. Stromberg and B. Tellman, editors. Ecology and conservation of the San Pedro River. University of Arizona Press, Tucson, Arizona. (i)

Wroblicky, G.J., M.E. Campana, H.M. Valett, and C.N. Dahm. 1998. Seasonal variation in surface-subsurface water exchange and lateral hyporheic area of two stream-aquifer systems. Water Resources Research 34:317-328. (i)

Young, R.A., T. Huntrods, and W. Anderson. 1980. Effectiveness of vegetated buffer strips in controlling pollution from feedlot runoff. Journal of Environmental Quality 9:483-487. (i)

Yuan, Y., R.L. Bingner, and M.A. Locke. 2009. A review of effectiveness of vegetative buffers on sediment trapping in agricultural areas. Ecohydrology 2:321-336. (i)

Zhang, Z. 2014. Nonpoint source and water quality monitoring. Pages 261-299 *in* S. Eslamian, editor. Handbook of engineering hydrology: environmental hydrology and water management. CRC Press, Boca Raton, Florida. (i)

Zhang, M., B. Gao, J. Fang, A.E. Creamer, and J.L. Ullman. 2014. Self-assembly of needle-like layered double hydroxide (LDH) nanocrystals on hydrochar: characterization and phosphate removal ability. RSC Advances 4:28171-28175. (i)

Zhang, X., X. Liu, M. Zhang, and R.A. Dahlgren. 2010. A review of vegetated buffers and a meta-analysis of their mitigation efficacy in reducing nonpoint source pollution. Journal of Environmental Quality 39:76-84. (i)

Zhongmin, J., C. Hua, W. Hong, and L. Changxiao. 2012. Photosynthetic responses of the riparian Salix variegate to cadmium stress in Three Gorges Reservoir region. Scientia Silvae Sinicae 48:152-158. (i)



Okanogan National Forest/Scott Fitkin, WDFW

Chapter 6. Nutrient Dynamics in Riparian Ecosystems

By: Paul M. Mayer, Jana E. Compton, and George F. Wilhere

6.1. Introduction

Riparian ecosystems play a vital role in the dynamics of nutrients within watersheds, especially for the three primary macronutrients carbon (C), nitrogen (N), and phosphorus (P). Because they are positioned at the interface between the stream and upland areas, riparian ecosystems mediate the movement of materials and energy between land and water. Riparian areas can be sources or sinks of energy, water, nutrients, organic matter, and organisms within a watershed. Organic matter from riparian areas, an important source of energy and nutrients, makes its way into streams via plant litterfall, or through transport by water, wind, or animals. Organic matter in streams provides habitat and food for microbes, insects, fish, amphibians, birds, and other organisms, and decomposes to release plant-available inorganic nutrients like ammonium, nitrate, and phosphate. Riparian areas also store energy and nutrients from organic matter coming from upland and instream sources through biotic uptake, sorption and exchange, and slowing or trapping particles. Riparian areas also are sites with high rates of nutrient transformation, including conversion of inorganic nitrogen into the gases N_2 or N_20 via denitrification. Riparian ecosystems are influenced by upland activities that supply nutrients that follow flow paths through these ecosystems, eventually reaching streams via surface and subsurface flows. Age, vegetation composition, topography, soil type, and condition of the riparian ecosystem all factor into the fate and transport of nutrients. In addition, the position in the drainage network and connectivity of the riparian area, along with disturbance and management history, affect nutrient processing rates.

Nutrients and the hydrological and biogeochemical processes that dictate their transport and fate are the subject of much current research in riparian ecology (Mayer et al. 2010a, 2014) because of their critical importance for growth and maintenance of life in the riparian ecosystem and the subsequent effects on stream biota and water quality. Although many micro- and macro-nutrients cycle through riparian areas, this chapter addresses only the three primary macronutrients C, N, and P.

Streams in the Pacific Coastal Ecoregion of Washington State are generally oligotrophic, well shaded, and sensitive to nutrient enrichment (Welch et al. 1998). When more N and P enters a riparian ecosystem than can be immediately utilized or stored, degradation of aquatic habitat conditions can occur and negative consequences within or beyond the riparian ecosystem may result. Excess N and P input to streams and estuaries may lead to harmful algal blooms, hypoxia, fish kills, and contamination of drinking water supplies. Although stream nutrient concerns have a somewhat lower profile in the Pacific Northwest (PNW) relative to other areas of the US, such as the Chesapeake Bay or Great Lakes watersheds, approximately 20% of assessed rivers and 8% of assessed lakes in Washington are regarded by the state as having impaired conditions related to an overabundance of nutrients (USEPA ATTAINS database).

Here, we describe nutrient cycles in riparian areas in the PNW, focusing on C, N, and P from natural and anthropogenic sources. Other nutrients, such as calcium, sulfur, or molybdenum, are not as widely studied but have been shown to be important in areas of the PNW for forest growth or other ecosystem processes (Silvester 1989; Chappell et al. 1991; Perakis et al. 2006). When possible, we discuss implications of common land management activities on nutrient dynamics by contrasting disturbed versus undisturbed riparian ecosystems. We also discuss new information gained from recent stable isotope studies and meta-analyses of riparian nutrient removal that have greatly improved our understanding of the permanence and effectiveness of nutrient removal processes in PNW riparian ecosystems.

6.1.1. Nutrient Dynamics in the Pacific Northwest

Figure 6.1 illustrates processes occurring in a largely undisturbed PNW forested riparian ecosystem and associated stream and upland. Water traveling through the riparian area (surface and subsurface flow) is the main transport mechanism for dissolved C, N, and P. These nutrients can be taken up directly by primary producers and decomposers, passively transported to groundwater or the hyporheic zone, or carried to surface waters via subsurface, overland, or channelized flow. The hydrologic regime dictates the timing and magnitude of nutrient movement into aquatic systems, and can create instream pulses of C, N, and P both in particulate and dissolved form (Kaushal et al. 2010).

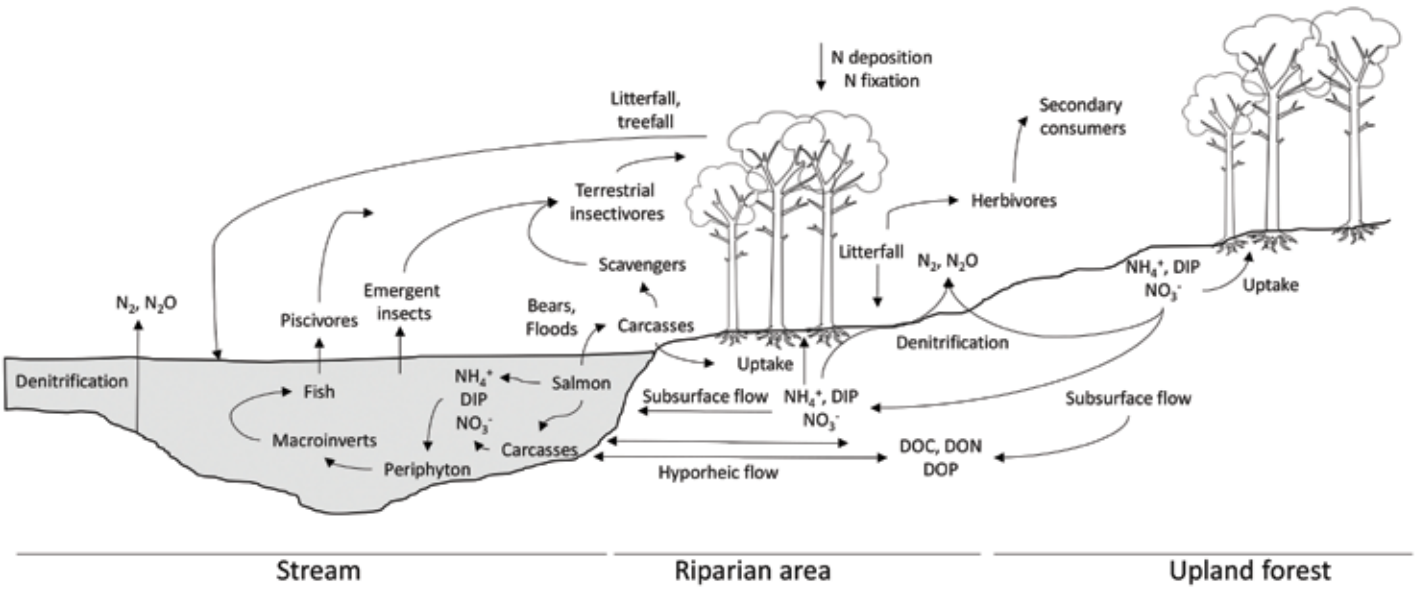


Figure 6.1. Nutrient cycle of an undisturbed PNW forested riparian ecosystem and connected stream and upland forest. Modified from Moyle et al. (2009). DIP = dissolved inorganic phosphorus; DOC, DON, DOP = dissolved organic carbon, nitrogen and phosphorus, respectively.



Most streams in the Pacific Northwest are nutrient-poor ecosystems/Ned Pittman, WDFW

Soil compaction and impervious surfaces typically reduce retention capacity of nutrients in space and time by preventing infiltration and thereby limit the interaction of nutrients with soils, roots, and soil biota. Riparian ecosystems exhibit a continuum of physical characteristics which have implications for nutrient dynamics. Riparian ecosystems along low-order streams, for example, are often narrower and steeper than those along mainstem rivers with wide, level floodplains. Consequently, surface and subsurface hydrological regimes controlling biogeochemical processes in riparian areas also differ along a continuum. Along small, steep forested streams, the water table is usually low and aerobic processes dominate, whereas level areas adjacent to larger rivers may provide water table conditions favoring anaerobic processes that reduce N via denitrification, a microbial transformation of dissolved nitrate N to gaseous molecular N (Burt et al. 2002; Hefting et al. 2004). The hyporheic zone is an area beneath the stream and riparian area where surface water and ground water continually interact. This zone can have a large influence on chemical characteristics of the surface water and, therefore, plays a role in determining biological attributes of streams (Wondzell et al. 2011).

As nutrient molecules move downstream, they may be taken up by algae and microbes living on rocks and wood in the channel in slick mats called biofilms (Cardinale et al. 2002). The polysaccharide layers of biofilms are sites of active nutrient turnover where microscopic algae, fungi, and bacteria consume N and P, die and release nutrients that then move further downstream. Microbial communities may be consumed by grazers such as larval aquatic insects or snails, which in turn may be consumed by larger predators such as fishes or birds. As prey and predators are consumed or die, they release nutrients to the aquatic and terrestrial environments through decay and in this way C, N, and P cycle in a process of uptake and release called nutrient spiraling (Newbold et al. 1982). The distance a molecule moves downstream during a complete cycle is its spiraling length, a metric that explicitly relates nutrient utilization to nutrient supply (Newbold et al. 1982). Long spiraling lengths indicate that: 1) nutrient uptake is inefficient because the system is saturated with nutrients and organisms

can no longer fully exploit the incoming nutrient loads, 2) conditions are not optimal for uptake, such as when water flow is too fast, or 3) the stream does not support a community of organisms that effectively processes the nutrients.

In anthropogenically undisturbed Pacific Northwest watersheds, nutrients are ultimately derived from atmospheric and geologic sources, while plants play an important role in the initial uptake of N and P from these sources (McClain et al. 1998). Spatial variation in vegetation, geologic substrates, and human activities drive the variation in stream N and P concentrations and fluxes across the PNW (Wigington et al. 1998; Wise and Johnson 2011). The geology and geomorphology of a watershed and stream channel set the conditions for mineral composition of the groundwater reaching the stream because the shape and slope of the channel and banks affect water movement and velocity. Some bedrock types yield high stream P (Ice and Binkley 2003), leading to high regional P variability in riparian ecosystems and streams. Some types of vegetation can fix atmospheric gaseous N via symbiotic relationships with bacteria in their root systems, and in turn produce more biologically available N than they consume, thereby contributing to N loads in watersheds. A prime example is N_2-fixing Red Alder *Alnus rubra*, an important source of dissolved N in streams in western Oregon and Washington (Compton et al. 2003; Wise and Johnson 2011; Greathouse et al. 2014).

Nitrogen may occur in organic forms as microbial, plant, or animal tissue and in dissolved organic forms, or, if inorganic, primarily as nitrate ($N0_3^-$) and ammonium (NH_3^+), which are forms that can be assimilated by organisms into organic molecules. Forests in the PNW generally have fairly tight N and P cycles with little N or P lost or leached from the system. Rather, there are low rates of N and P inputs and outputs, but high rates of internal cycling (Sollins et al. 1980; Compton and Cole 1998). Triska et al. (1984) showed that N inputs to a stream reach in an old-growth forest watershed in Oregon's Cascade Mountains were dominated by dissolved organic N from groundwater (69% of inputs), with litterfall and precipitation playing smaller roles.

Human activities like timber harvest, farming, or urban development alter nutrient cycles (Figure 6.2), producing higher fluxes, shorter storage durations, and higher concentrations of nutrients in subsurface flow, some of which will enter streams. Disturbances through forestry, grazing, agriculture or urbanization can alter the timing and routing of water through a landscape (Tague and Grant 2004), which can influence nutrient uptake and delivery to streams. Agriculture can contribute to excess nutrients in riparian and aquatic ecosystems through increased runoff of N and P from fertilizer and livestock manure (Wise and Johnson 2011). Point sources and urban stormwater runoff are the dominant sources of N within urban areas. For P, geologic materials dominate natural sources, with point sources such as urban runoff, farm manure, and fertilizer important in areas under anthropogenic land uses. Timber harvest increases stream nitrate and to a lesser extent phosphate concentration (Fredricksen et al. 1975; Scrivener 1975; Martin and Harr 1989). These increases generally persist for a short time, although Brown et al. (1973) saw increases in nitrate persist for six years post-timber harvest and burning.

Historically, a major source of allochthonous[1] nutrients and energy-rich carbon compounds was anadromous salmon (Cederholm et al. 1999; Gende et al. 2002). Anadromous, semelparous fish return from the ocean to spawn and die in their natal streams. The mass of every salmon carcass, of which 95% is accumulated in the marine environment (Naiman et al. 2002), is deposited in oligotrophic freshwater environments. The magnitude of nutrient and chemical energy losses to freshwater ecosystems caused by declines in salmon populations can best be appreciated by comparing current and historical salmon run sizes. Gresh et al. (2000)

1 Allochthonous means originating or formed in a place other than where found. Hence, in the context of aquatic ecosystems, allochthonous nutrients found in a stream originated in terrestrial ecosystems. In contrast, autochthonous means originating or formed in the place where found.



Historically, carcasses of adult salmon delivered approximately 100,000 tons of nutrients to rivers and streams of Washington/Ned Pittman, WDFW

estimated that the current biomass of salmon runs for all Pacific salmon species (Chinook *Oncorhynchus tshawytscha,* Coho *Oncorhynchus kisutch,* Sockeye *Oncorhynchus nerka,* Chum *Oncorhynchus keta,* and Pink *Oncorhynchus gorbuscha*) in Puget Sound, the Washington Coast, and the Columbia River Basin are 25, 5, and 1% of historical biomass (circa early 1900s), respectively. This represents a loss of 122,470 US tons per year (111,104 metric tons) of marine-derived nutrients and chemical-energy in these watersheds. Naiman et al. (2002) estimated that in the Willapa Bay Watershed the biomass of Chinook, Coho, and Chum Salmon carcasses in streams decreased from 2,920 to 226 US tons (2,649 to 205 metric tons per year), and that marine derived N and P decreased by more than 90%.

Figure 6.2 represents nutrient cycling in a watershed with more human-associated disturbance, including an

absence of salmon returns; by comparing Figures 6.1 and 6.2, changes in the cycling loop and intra-system transfers are evident when salmon are missing. Much of the cycling of marine-derived nutrients is mediated by predators and scavengers that move large amounts of marine-derived nutrients substantial distances into the terrestrial environment either as salmon carcasses or as metabolic waste products, i.e., urine and feces (Naiman et al. 2002). In several small streams on the Olympic Peninsula, Cederholm et al. (1989) observed that Coho Salmon carcasses were consumed by 22 species of mammals and fish (e.g., American Black Bear *Ursus americanus,* Northern River Otter *Lontra canadensis,* Mink *Mustela vison,* Bald Eagles *Haliaeetus leucocephalus,* and Ravens *Corvus corax*), and that 40% of salmon carcasses were moved by scavengers from the water to riparian areas. Flooding also can deposit salmon carcasses in riparian areas (Ben-David et al. 1998). Salmon carcasses provide N and P nutrients for microbes, plants, and animals, and influence all trophic levels in riparian ecosystems (Willson and Halupka 1995; Compton et al. 2006). Trees and shrubs in riparian areas along spawning sites in the Kadashan and Indian rivers of southeast Alaska derived approximately 23% of their foliar nitrogen from decayed salmon carcasses, and growth rates of Sitka Spruce *Picea sitchensis* were significantly increased (Helfield and Naiman 2001). On average, 17% of the nitrogen incorporated into the riparian vegetation of a stream in western Washington was derived from carcasses of spawning salmon, and significant percentages of marine-derived N (up to 30%) and C (up to 39%) were found in aquatic insects, Cutthroat Trout *Oncorhynchus clarkii*, and juvenile salmon (Bilby et al. 1996).

Other animals subsidize riverine food webs by transporting nutrients across watersheds or by altering the hydrology (Chapter 8 in this document; Naiman and Rogers 1997; Masese et al. 2015). As ecosystem engineers, American Beaver *Castor canadensis* have a significant influence on stream nutrients. Beaver can influence biogeochemical cycles by impounding streams and changing hydrologic regimes and organic matter and sediment transport (Pollock et al. 2007).

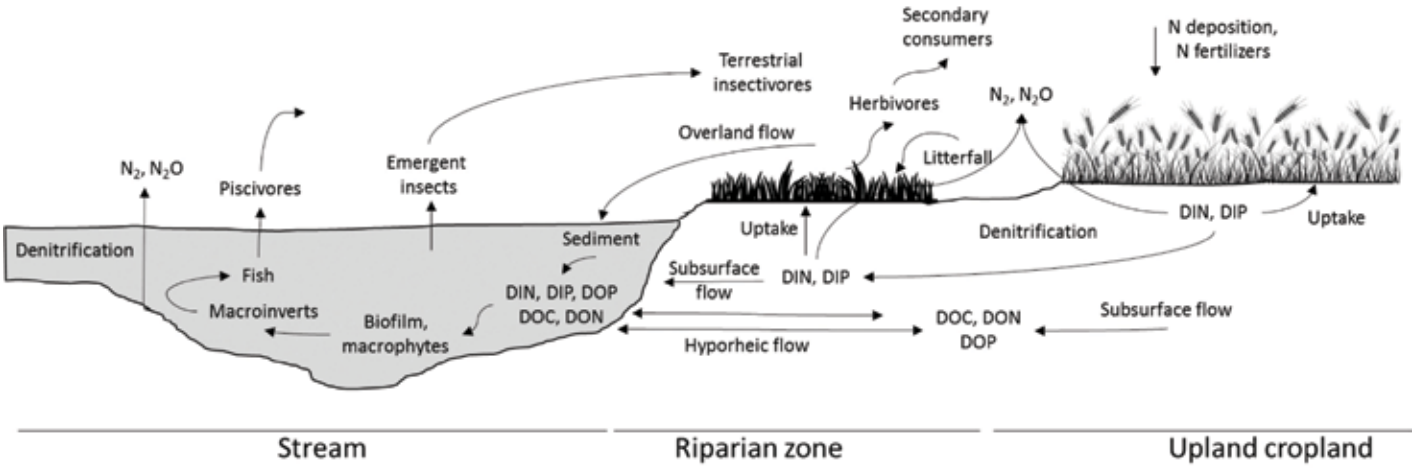


Figure 6.2. Nutrient cycle of a disturbed PNW riparian ecosystem and connected stream and upland cropland. Much of the cycling of marine-derived nutrients is facilitated by predators and scavengers that move nutrients into the terrestrial environment either as salmon carcasses or as urine and feces. Modified from Moyle et al. (2009). DIP = dissolved inorganic phosphorus; DIN = dissolved inorganic nitrogen (nitrate and ammonium); DOC, DON, DOP = dissolved organic carbon, nitrogen and phosphorus, respectively.

Retention of total N and P increased 72% and 43%, respectively after Beaver populations recovered in a Minnesota watershed (Naiman et al. 1994) and organic matter (carbon) retention increased three-fold after a stream was impounded by Beaver (Naiman et al. 1988). However, Beaver impoundments also influence N dynamics by flooding riparian forests, creating anoxic conditions in forest soils leading to an increase in denitrification and subsequent reduction in N (Naiman et al. 1988). Elk *Cervus canadensis*, deer (*Odocoileus* spp.), and livestock can also be important sources of N and P when found in close proximity to streams.

Riparian vegetation can affect uptake and delivery of nutrients to streams. Riparian plant roots can slow water movement and stabilize soils as well as take up dissolved nutrients. The types of vegetation and growth patterns in riparian areas determine the amount and timing of litterfall and woody material delivery to a stream. The height and density of vegetation dictate shading and solar input to the stream, thus affecting conditions for plant growth and N and P uptake. The key limiting nutrients for primary production in PNW streams are N and P (Welch et al. 1998), but there has not been enough experimental work conducted across the region to determine precisely when and where this occurs.

Shallow groundwater adjacent to stream channels often is a hot spot for N removal processes and a storage zone for other solutes.

6.1.2. Carbon

The cycling of C in riparian and aquatic ecosystems is complex and can differ among locations and through time because C can be available in different forms and is produced by different sources, thereby affecting its transport and fate. Carbon is tightly linked to N and P, driving biological transformations of these nutrients. Organic C regulates ecosystem functions in streams and rivers because dissolved organic carbon (DOC) is a primary energy source for microorganisms. Riparian vegetation in forests influences DOC composition and contributes a substantial proportion of stream organic C budgets (McDowell and Likens 1988). DOC in streams is a mixture of recalcitrant, (i.e., difficult to process components) and more easily metabolized labile fractions that drive biogeochemical processes involving nitrogen (Kaushal and Lewis 2005). For example, availability of dissolved and particulate organic C can limit denitrification, a microbial process critical to maintaining water quality, which has important implications for managing N in streams (Newcomer et al. 2012). Denitrification occurs only under anaerobic conditions where microbes shift from respiring oxygen to respiring nitrate, releasing nitrous oxide, and inert N_2 gas. These conditions may be ephemeral, fluctuating in response to water tables and associated changes in redox potential (Mayer et al. 2010b).

Anoxic conditions also promote the production of methane. Production of methane and nitrous oxides, increase in riparian areas with increased organic C supply (Kaushal et al. 2014). Dissolved organic carbon also can increase biological oxygen demand, thereby reducing oxygen for fish (Stanley et al. 2012).

Various organic C types from biofilm, leaves, and soil organic matter may have differential effects on ecosystem functions in forested streams (McDowell and Likens 1988), agricultural streams (Royer and David 2005), and urban streams. For example, C derived from

grasses supports more denitrification than C from tree leaves (Newcomer et al. 2012). Because the microbes that influence the transport and fate of N in riparian ecosystems require C as an energy source, C and N are inextricably linked in a biogeochemical sense.

Shading of small headwater streams in forested watersheds can obscure 95% of sunlight (Murphy 1998); hence, in-stream productivity is typically light-limited. Consequently, the main energy source for such streams is allochthonous chemical energy contained in litter from riparian areas (Conners and Naiman 1984; Bisson and Bilby 1998). In headwater streams, litter directly supports an animal community compromised predominantly of invertebrate detrivores which, in turn, support a community of invertebrate predators (Wallace et al. 1997). Detrivores, microbes, and physical breakup convert the coarse particulate organic material (CPOM) of litter to fine particulate organic material (FPOM) which is utilized by invertebrate communities downstream (Bisson and Bilby 1998; Richardson and Danehy 2007). Headwaters comprise 60 to 80% of the cumulative length of a watershed's drainage network (Benda et al. 2005); hence, headwaters contribute a substantial amount of chemical energy to mainstem rivers and associated biota. For example, Wipfli (2005) estimated that every kilometer of fish-bearing stream received enough energy from headwaters to support 100 to 2,000 young-of the-year salmonids.

Carbon cycles through riparian ecosystems via CO_2 uptake from the atmosphere through photosynthesis, litterfall, decomposition and/or consumption. Riparian litter is a critically important source of C for streams as energy for invertebrates and microbes that form the basis of food webs. Deciduous-dominated riparian forests grow quickly and initially deliver more litter to streams and have a more pronounced seasonal litter contribution than coniferous-dominated forests (Hart et al. 2013). Conifers, however, play an important structural role as large wood in streams. Deciduous species like Red Alder can increase fine litter flux and



The main energy source for small headwater streams is allochthonous chemical energy provided by leaf litter/Marc Hayes, WDFW

nutrient delivery to terrestrial and aquatic food webs, thus complementing the year-round shade and wood provided by conifers (Hart et al. 2013).

Chemical energy, required by heterotrophic organisms (those that do not produce their own food from sunlight), is contained within the various C compounds of organic matter. The fundamental effects of organic matter on ecosystem composition, structure, and functions have motivated conceptual theories to describe riverine ecosystems (Pingram et al. 2012). The River Continuum Concept (RCC; Vannote et al. 1980) describes the balance of allochthonous C (produced externally to the stream) to autochthonous C (produced in-stream) in riverine ecosystems from headwaters to mainstem rivers. This balance plays a key role in structuring the invertebrate community. According

to RCC, in narrow headwater streams (first to third order), nearly all C is allochthonous produced by litter from riparian vegetation because shade severely limits the production of autochthonous C produced through in-stream photosynthesis. Because medium-sized streams (fourth to sixth order) are wider, shading decreases, in-stream photosynthesis increases, and the density of litter inputs decreases. Hence, the quantities of allochthonous and autochthonous C may be about equal. In large rivers (≥ seventh order), shading effects only a small portion of surface water, however, turbidity and water depth limit photosynthetic production. Consequently, according to RCC, the main source of energy in large rivers is allochthonous C from upstream. The RCC also posits that the quantity and quality of organic matter, which changes along the river continuum, affects the composition of the aquatic invertebrate community.

Litter from riparian areas is clearly an important source of limiting nutrients and organic matter for aquatic ecosystems. Consequently, providing adequate amounts of litter to streams is an important issue for riparian area management and addressing this issue requires an understanding of litter delivery into streams. FEMAT (1993:V-26) developed a conceptual model, known as the FEMAT curves, that depicts relationships between riparian ecological functions, including litterfall, and distance from a stream channel. Bilby and Heffner (2016) studied factors influencing litter delivery into streams in young and mature conifer forests of the western Washington Cascades and found that litter travel increased with increasing tree height, topographic slope, and wind speed. They estimated that riparian buffer widths needed to capture 95% of annual litter input from mature conifer forests to streams are between 60 to 83 ft (18 to 25 m) depending on a site's slope and wind exposure. The mean tree height of their three mature forest sites was 154 ft (47 m). Hence, riparian buffer widths needed to meet the 95% capture objective range from 39 to 54% of mean tree height. Bilby and Heffner (2016) warn that they may have underestimated litter travel distances because they released litter from only the bottom of the tree canopy, but litter travels farther with increasing height, and therefore, litter produced within the tree canopy is likely to travel farther.

While stream flows carry organic matter, insects, and other invertebrates downstream to subsidize food webs in higher order streams, there may also be upstream movement of aquatic organisms that subsidizes food webs in lower order streams. In a Welsh mountain stream, for example, amphipods *Gammarus pulex* showed net upstream movement whereas stonefly (*Trichoptera* spp.) females showed no upstream flight preference, but females moving upstream contained twice as many eggs (Dudley-Williams and Williams 1993). In many cases, however, such as with mayflies (family Baetida), seasonal upstream movements of adults via an aerial pathway are pronounced (Hershey et al. 1993). Such upstream movement of nutrients and chemical energy may be important, but has been little studied.

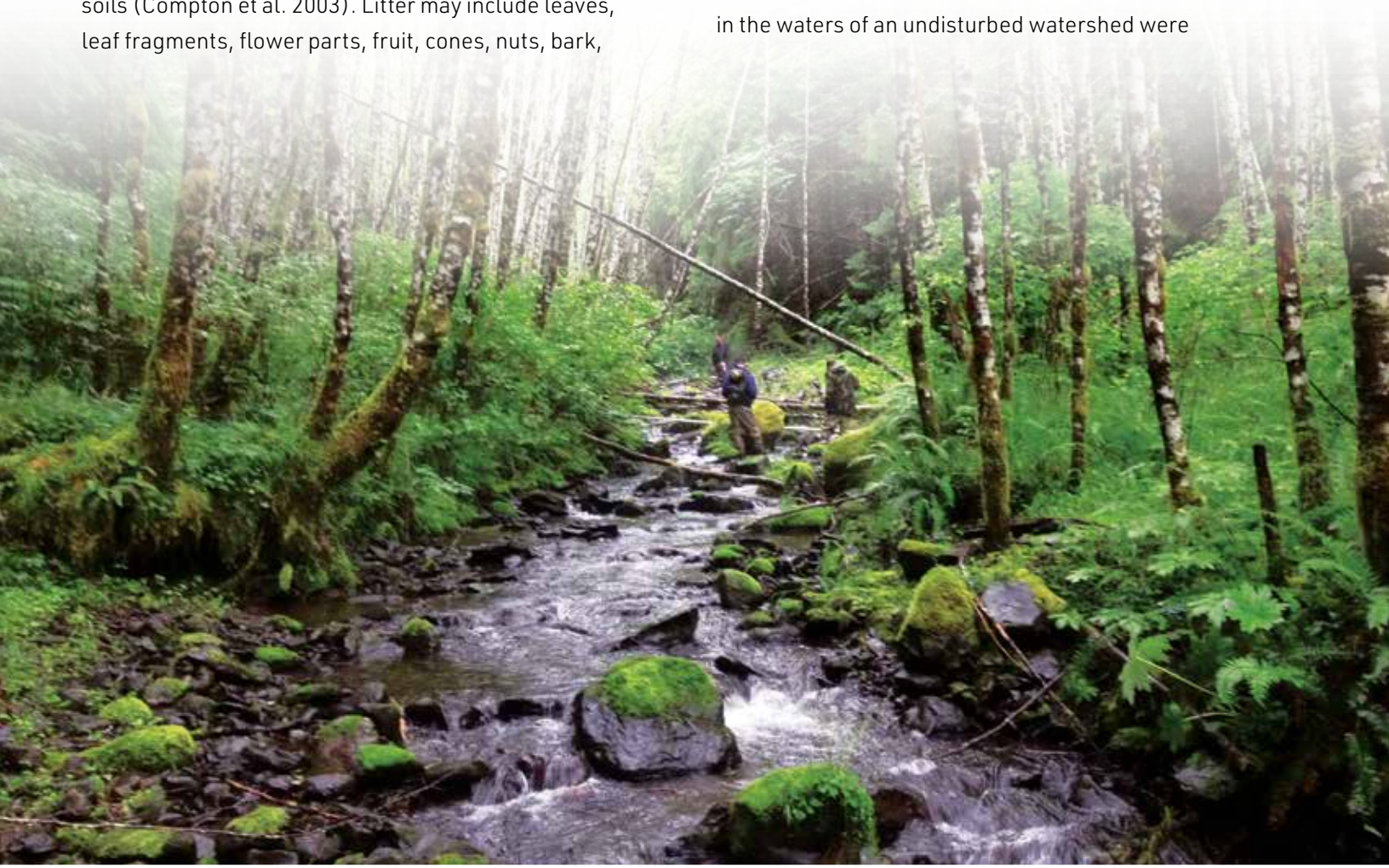
Large wood in stream channels can affect nutrient cycling by slowing the downstream transport of water, sediment, organic matter, and other materials (Chapter 3). Large wood in riparian areas ultimately decomposes, providing nutrients to the forest floor thereby increasing moisture holding capacity (Harmon et al. 1986). Woody material in streams can be a direct source of labile C to streams that can fuel microbial processes, though most C in wood is relatively recalcitrant, taking years or decades to decompose. Wood slows the flow of water thereby extending the residence time of water in the channel and facilitating accumulation of finer organic and inorganic sediments (Chapter 2) that support biofilms.

6.1.3. Nitrogen

Nitrogen is a component of proteins, necessary for all life, and often is a limiting nutrient for both terrestrial and aquatic organisms. N limitation of plant growth is common in PNW forests (Peterson and Hazard 1990). Ultimately, N comes from atmospheric N_2, which has a very strong triple bond that, aside from lightning and industrial processes, only a few specialized N-fixing organisms can break.

Nearly all N in lotic ecosystems of Washington is derived from allochthonous sources, and in undisturbed headwater watersheds, the source of nearly all N is terrestrial. Nitrogen can enter a river or stream via several pathways: litterfall, movement of soluble N from riparian soils into groundwater and hyporheic zones, and leaching and subsurface transport from upland soils (Compton et al. 2003). Litter may include leaves, leaf fragments, flower parts, fruit, cones, nuts, bark, branches and twigs (Benfield 1997), however, leaves account for 72% of total litter in broad-leafed forests and 80% in needle-leaved forests (Xiong and Nilsson 1997). Litter may enter surface waters through direct fall, lateral movement along the ground, or mobilization during floods.

For a headwater stream in the western Cascades of Oregon, Triska et al. (1984) found that more than 90% of annual N inputs to the stream were derived from biotic processes in the adjacent forest. Seventy-three percent of N entering the stream was dissolved organic N in water flowing through the subsurface from forest to stream and 21% was contained in organic matter (e.g., leaf litter, needles, and coarse woody debris) from the riparian forest. The headwater stream exported 74% of its annual N inputs to downstream waters; 22% of the exported N was contained in particulate organic matter. Edmonds et al. (1995) found that nitrate concentrations in the waters of an undisturbed watershed were



N-fixation by Red Alder is an important component of nutrient cycling in forests of western Washington and Oregon/Ned Pittman, WDFW

seasonal, with in-stream concentrations being highest in the fall and lowest in the summer when N uptake by terrestrial vegetation was greatest.

Red Alder fixes N_2 and enriches soil with N compounds through root and nodule secretions. Red Alder leaves contain N concentrations roughly 2 to 3.5 times greater than leaves or needles of other tree species (Tarrant et al. 1951). Because aquatic ecosystems in undisturbed watersheds are often N-limited, Red Alder can be a major source of allochthonous N to aquatic ecosystems, and more Red Alder litter can increase ecosystem productivity. For example, Wipfli and Musslewhite (2004) found that headwater streams with more Red Alder canopy cover exported greater biomass of both terrestrial and aquatic invertebrates to fish-bearing waters than riparian areas with less alder. This subsidy of prey from headwaters to fish-bearing streams is needed to maintain fish productivity (Wipfli and Baxter 2010).

Nitrogen cycles in the environment through multiple redox states, in solid, dissolved, and gaseous forms, and originates from multiple sources, making for one of the most challenging biogeochemical cycles to monitor and characterize (Figure 6.3). Shallow groundwater adjacent to stream channels often is a hot spot for N removal processes and a storage zone for other solutes (Hinkle et al. 2001; Zarnetske et al. 2011). The groundwater–surface water interface is characterized by dynamic gradients of dissolved oxygen, N, and organic C concentrations where biogeochemical reactions take place, including metabolism of organic C, denitrification, and nitrification (Sobczak et al. 2003). Denitrification is generally considered the most important biological process through which ecosystems lose N. Denitrification, and disturbances like tree harvest and fire, remove N from an ecosystem, whereas N uptake by plants eventually returns N to the system through litterfall or senescence and subsequent microbial decay. Organic C is required as an energy source for denitrification. Small streams can lose nitrate

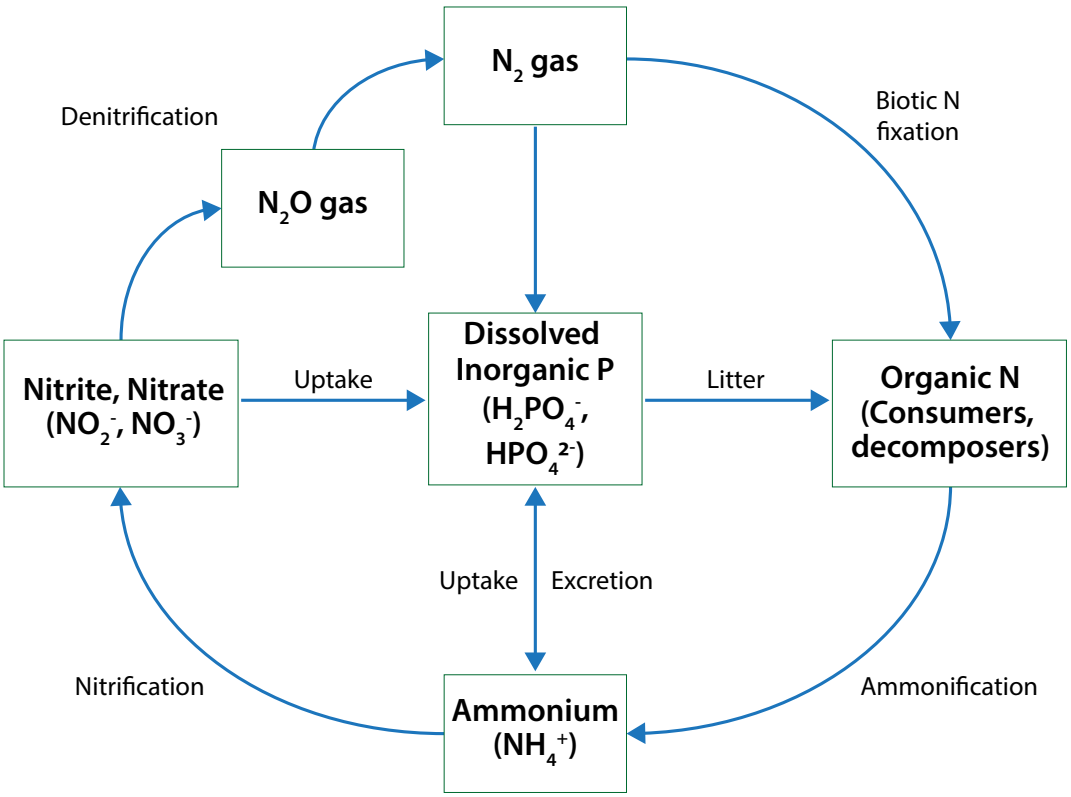


Figure 6.3. Nitrogen cycle pools and processes in ecosystems.

N efficiently because of their high ratio of streambed area to water volume, which brings more surface water in contact with the hyporheic zone. Small streams have a large cumulative influence on N transformation and loss because they account for most of the stream length within a network (Alexander et al. 2000; Peterson et al. 2001). Larger streams lose nitrate N because of longer transport distances over which more biological reactions can occur that consume N coupled with longer water residence times and higher N concentration which fuels the denitrification along with organic C (Mulholland et al. 2008).

Increased groundwater–surface water interaction can alter dissolved oxygen concentrations and redox conditions (Striz and Mayer 2008; Zarnetske et al. 2012), transporting N- and C-containing organic matter to microbes in subsurface sediments, leading to N loss via denitrification under favorable oxidation–reduction conditions (Hedin et al. 1998). The conditions that favor denitrification may change rapidly over time and space. Therefore, "hot spots" may form where denitrification occurs in small patches of the stream (e.g. under leaf packs) or "hot moments" where denitrification rates are high but for short periods of time due to rapid dynamic water movement (McClain et al. 2003; Vidon et al. 2010). However, biochemical processes in urban riparian soils such as denitrification may be impaired because of increased rates of erosion and limited groundwater–surface water interaction due to high proportions of impervious surfaces (Groffman et al. 2002).

The importance of riparian vegetation on transforming N inputs has been examined (Sweeney et al. 2004; Mayer et al. 2007; Sweeney and Newbold 2014). Riparian area characteristics such as width of vegetation, soil carbon, and hydrologic flowpaths, can influence the amount of N removed. Mayer et al. (2007) surveyed the available scientific literature containing data on riparian management and N concentration in streams and groundwater to identify relations between N uptake and riparian width, hydrological flow path, and vegetative cover. Removal efficiencies ranged from <0 (i.e., where the riparian ecosystem appeared to be a N source) to 100%, with a median removal rate of 91%. Wide vegetated riparian areas (>165 ft; 50 m) more consistently removed significantly higher proportions of N entering riparian areas than narrow bands of vegetation (0 - 82 ft; 0 - 25 m). The critical conclusions from this review were that riparian areas were effective at trapping and removing N when they were vegetated, wider, and allowed for subsurface movement of water where the interaction of nutrients dissolved in the water had prolonged contact with soils. Therefore, the hydrologic connection of riparian areas and streams is key to effective nutrient capture. Where channels are incised, riparian areas tiled for drainage, or where floodplains are disconnected via reinforced banks or channelization, nutrients will flow downstream with little interaction with riparian areas.

Subsurface hydrology (saturated vs. unsaturated soil conditions) and redox condition appear to be significant determinants of N-removal efficiency, regardless of vegetation (Mayer et al. 2007; Mayer et al. 2010b). When the water table fluctuates in response to precipitation events, buried relict hydric soil may become saturated, producing sub-oxic or anoxic conditions (Hefting et al. 2004; Weitzman et al. 2014), facilitating N removal. Where flow paths move through wetland riparian soils, great potential exists to remove large quantities of N in proportion to the loads (Jordan et al. 2011); where flows occur via deeper groundwater dynamics or via tile



Riparian vegetation: Red Elderberry Sambucus racemosa*/ Ned Pittman, WDFW*

drainage, N in solution may bypass the C-rich riparian soils and flow through zones where less potential exists for nutrient removal (Wigington et al. 2005). Hydrologic connectivity between riparian areas and streams is a critical factor in determining N removal rates.

Denitrification rates in the stream channel are linked to the organic C content of benthic sediments, respiration rates, and extent of stream water interaction with the streambed (Alexander et al. 2000; Mulholland et al. 2008), conditions that can be fostered by woody material (e.g., sticks, branches or tree trunks), and debris dams in streams. Woody material may function as microsites or hotspots of elevated biogeochemical cycling including denitrification (Groffman et al. 2005), and provides substrates for bacteria and fungi, which in turn consume N in streams (Ashkenas et al. 2004).

Biofilms are a matrix of algae, bacteria, and fungi embedded in a slick polysaccharide film that coats hard substrates in streambeds. These microbial communities consume, respire, and reduce inorganic N (Mulholland et al. 1995). Physical habitat heterogeneity and the biodiversity of the biofilms influence N uptake (Cardinale et al. 2002; Cardinale 2011). Biofilm structure, composition, and capacity for biogeochemical cycling are influenced by substrate composition, light penetration, nutrient concentration, flow rates, seasonality, sediment composition, and the community of invertebrate grazers in the vicinity (Sabater et al. 2002). Biofilms formed on wood substrates have been found to have higher respiration rates and greater N demand than biofilms developed on rock substrates (Sabater et al. 1998). Lazar et al. (2014) found that biofilms on wood substrates in a forested stream had significantly higher denitrification rates than those on non-organic substrates such as stone. In an old-growth forest system in Oregon, aquatic mosses and biofilm on large wood showed the highest N uptake rates among biota while, both vertebrate and invertebrate consumers took up substantial amounts of N, especially small invertebrate grazers (Ashkenas et al. 2004).

Furthermore, N in the stream was transported to the upland through uptake by terrestrial plants, likely through long, subsurface flow paths, demonstrating a strong link between terrestrial and aquatic systems (Ashkenas et al. 2004).

In addition to the biofilms on the streambed, microbial communities within the hyporheic zone can be hotspots for N dynamics. At the HJ Andrews Experimental Forest in Oregon, Zarnetske et al. (2011) found that the hyporheic zone was an important site for N dynamics in small forested streams, with residence time determining the dominance of different N transformation processes. Water pathways with residence times of less than 7 hours tended to be dominated by DO and DOC use as well as ammonium and nitrate production, while pathways with longer residence times removed N via denitrification. Further modeling suggested that water residence times and oxygen uptake rates of microbes are important determinants of whether hyporheic zones are net sources or sinks of nitrate N (Zarnetske et al. 2012). In large rivers like the Willamette, hyporheic zones can be important areas for nitrate removal from regional groundwater prior to entry into surface flow (Hinkle et al. 2001), as well as important for N removal and cooling as water moves in and out of hyporheic areas on its path downstream (Fernald et al. 2006).

The relationships between land use and N transport and fate can be complex, and are mediated by aquatic and riparian biota. Sobota et al. (2012) showed that N uptake differs substantially across forested, agricultural, and urban streams in the Willamette River basin in Oregon. Most nitrate N in forested streams was transported downstream without being taken up. N storage was high in algal biomass in unshaded agricultural and urban streams but turnover and subsequent recycling back to the stream may ultimately be high (Sobota et al. 2012). Collectively, this work indicates that uptake via heterotrophic organisms living on large wood is critical to long-term N capture in forested streams. Once the canopy is opened up, autotrophic algal production

becomes a more important process for uptake of excess nutrients, which leads to shorter-term storage and potential for negative consequences associated with freshwater algal blooms.

6.1.4. Phosphorus

Phosphorus (P) is an important component of adenosine triphosphate (ATP) and necessary for energy transformations in plant and animal cells. Like N, low P availability often limits primary production on land and can be particularly limiting to productivity in freshwater. This is because P tends to form complexes and be retained in soils and thus does not move as readily into ground and surface waters from the landscape as does nitrate N. P cycles in the environment through multiple organic and inorganic forms (Figure 6.4). P occurs in the environment in organic forms (e.g., organo-phosphate and polyphosphates like ATP) in plant and animal biomass, sewage, and pesticides. Inorganic forms of P, such as phosphate (PO_4^{3-}), and orthophosphate, are biologically reactive and thus can be used directly by plants and microorganisms (Carpenter et al. 1998). Orthophosphate is derived from phosphate-bearing minerals, fertilizers, detergents, and industrial chemicals. In the Pacific Northwest, bedrock is the major source of stream P loads, with fertilizer, manure, and wastewater inputs important in some locations (Wise and Johnson 2011). Overabundance of P can result in abnormally high primary production in water, leading to water quality problems such as algal blooms, production of cyanotoxins, and low oxygen events (Carpenter et al. 1998; Jacoby and Kann 2007).

P is commonly a limiting nutrient in aquatic ecosystems because it is highly insoluable and has an affinity for binding to soil particles. Nevertheless, riparian areas are sources of allochthonous P to streams in undisturbed watersheds. The amount of P that is contributed by riparian areas to aquatic habitats through litterfall

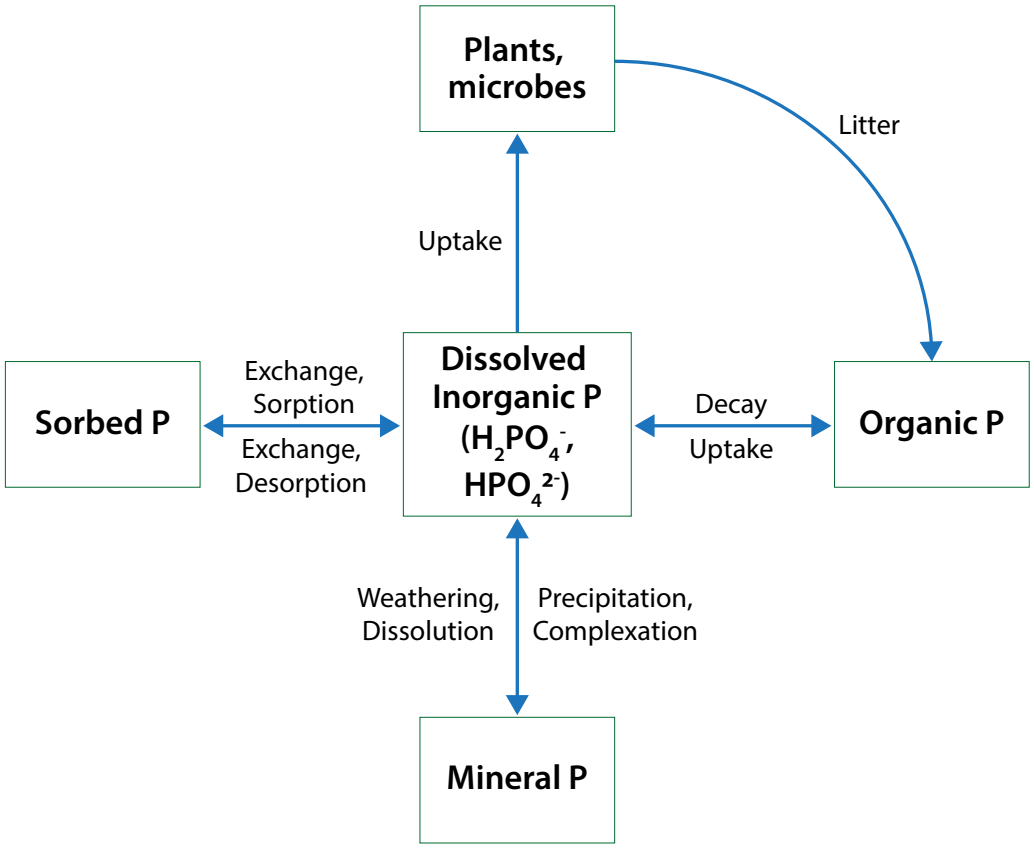


Figure 6.4. Phosphorus cycle pools and processes in ecosystems.

relative to other sources under natural, undisturbed conditions has yet to be quantified for riparian ecosystems in the Pacific Northwest.

P attenuation refers to declines in P concentration in water and soil through physical, chemical, and biological processes. Mineral content and pH are important factors determining P attenuation in soil. Because of their volcanic origins and the weathering environments, many soils in the PNW can bind tightly to large quantities of anions like phosphate, replacing reactive soluble P forms for particulate P forms, which are less biologically reactive (Johnson and Cole 1980; Bohn et al. 1985). Sorption, the chemical attachment of molecules to soil particles, may occur quickly (e.g., days) and includes adsorption and substitution between P and other anions on mineral surfaces. Sorption may also occur slowly (e.g., weeks), such as mineral dissolution and precipitation reactions between P and soil cations such as Ca and Mg or Al, Fe, and Mn oxide compounds depending on soil pH (Bohn et al. 1985). Phosphate is most soluble in slightly acid to neutral pH soils. Under reducing conditions, Fe is reduced and the P-Fe oxide compounds may dissolve, thereby releasing P (Denver et al. 2010). Minimally disturbed forests have a relatively tight P cycle, with low inputs from precipitation, and even lower leaching rates (Yanai 1992; Compton and Cole 1998). In the volcanically influenced soils of the Cascades, most of the ecosystem P is contained in soil, and organic and inorganic forms of sorbed P are the dominant forms as opposed to primary minerals or microbial P (Compton and Cole 1998). There is substantial recycling of P by plants and soil and biotic release of organic P via phosphatase enzyme activities is an important component of this cycle (Giardina et al. 1995). Several studies have shown that Red Alder increases rates of P cycling (Giardina et al. 1995; Zou et al. 1995), further supporting the important role that Red Alder plays in regulating both N and P nutrient cycles of the PNW. Vegetated riparian areas generally are expected to retain P by slowing water flow and by plant and microbial uptake.

Unlike N, which is ultimately constrained by atmospheric fixation and regulated by biologic cycling, P availability is controlled by weathering and a complex set of chemical and biological processes. P retention is regulated by the equilibrium P concentration (EPC), the concentration at which P sorption equals desorption (Hoffmann et al. 2009). Once soil P has reached its sorption capacity, excess P may be exported in water (Domagalski and Johnson 2012). Biological processes also play a role in P attenuation and release (Schechter et al. 2013). Bacteria, fungi, algae, and plants incorporate P into biomass; however, plants vary in P demand and uptake effectiveness, exhibiting numerous strategies for sustaining growth and maintenance (Shen et al. 2011). P is released from organic matter through decomposition, which is dependent on pH, litter quality (C:N:P ratios), Ca content, redox potential, soil moisture, and temperature (Schechter et al. 2013). Increases in P loading as well as soil disturbance and erosion have the potential to reduce this generally tight P cycle and increase transfer to aquatic ecosystems (Figure 6.2).

Microbial and plant uptake represent short-term, transient P pools (Richardson and Marshall 1986). Phosphate may be assimilated into plant tissues or in microorganisms but released upon death and senescence. Peat accumulation and P sorption and precipitation are important long-term P sequestration mechanisms (Richardson and Marshall 1986; Reddy et al. 1995). Long-term storage of P depends on sorption to inorganic sorbents; P sequestration is mainly associated with adsorption to Fe and Al oxides in acidic soils or precipitation of Ca phosphates in alkaline soils (Giesler et al. 2005). Phosphorus retention mechanisms differ widely depending on hydrological pathway through the riparian area. Sorption and desorption reactions are more important during subsurface flow, while sedimentation of particulate P may be the major retention mechanism during overland flow. Significant amounts of P can be stored in stream sediments and may be resuspended and released during storms. Retention of total P in riparian areas is controlled

mainly by sedimentation processes, dependent on morphology (e.g., width) and vegetation characteristics. However, riparian areas can become a net source of dissolved P released from soil or from plant material (Hoffman et al. 2009). Retention of dissolved P in riparian areas is often not as significant as retention of particulate P (Hoffman et al. 2009). Inundation of riparian areas or floodplains can deposit particulate P whereas plant uptake may temporarily immobilize P (Hoffman et al. 2009). Overall, riparian ecosystem retention efficiency varies widely and some riparian areas may become sources of P, especially ortho-phosphate (Schechter et al. 2013). Total P moving through the soil is not necessarily related to the width of the riparian area but rather on flow path and soil types (Hoffman et al. 2009; Schechter et al. 2013).

6.2. Hydrologic Connectivity and Nutrient Dynamics

Nutrients cycle at various spatial and temporal scales. Soils, vegetation, and water flows largely dictate the sources and processing of nutrients. Nutrients may enter the riparian ecosystem from the atmosphere (e.g., nitrogen oxides produced from fossil fuel combustion or ammonia released from agricultural areas), from terrestrial sources when rainwater flushes nutrients from upland soils and vegetation, or from floods that

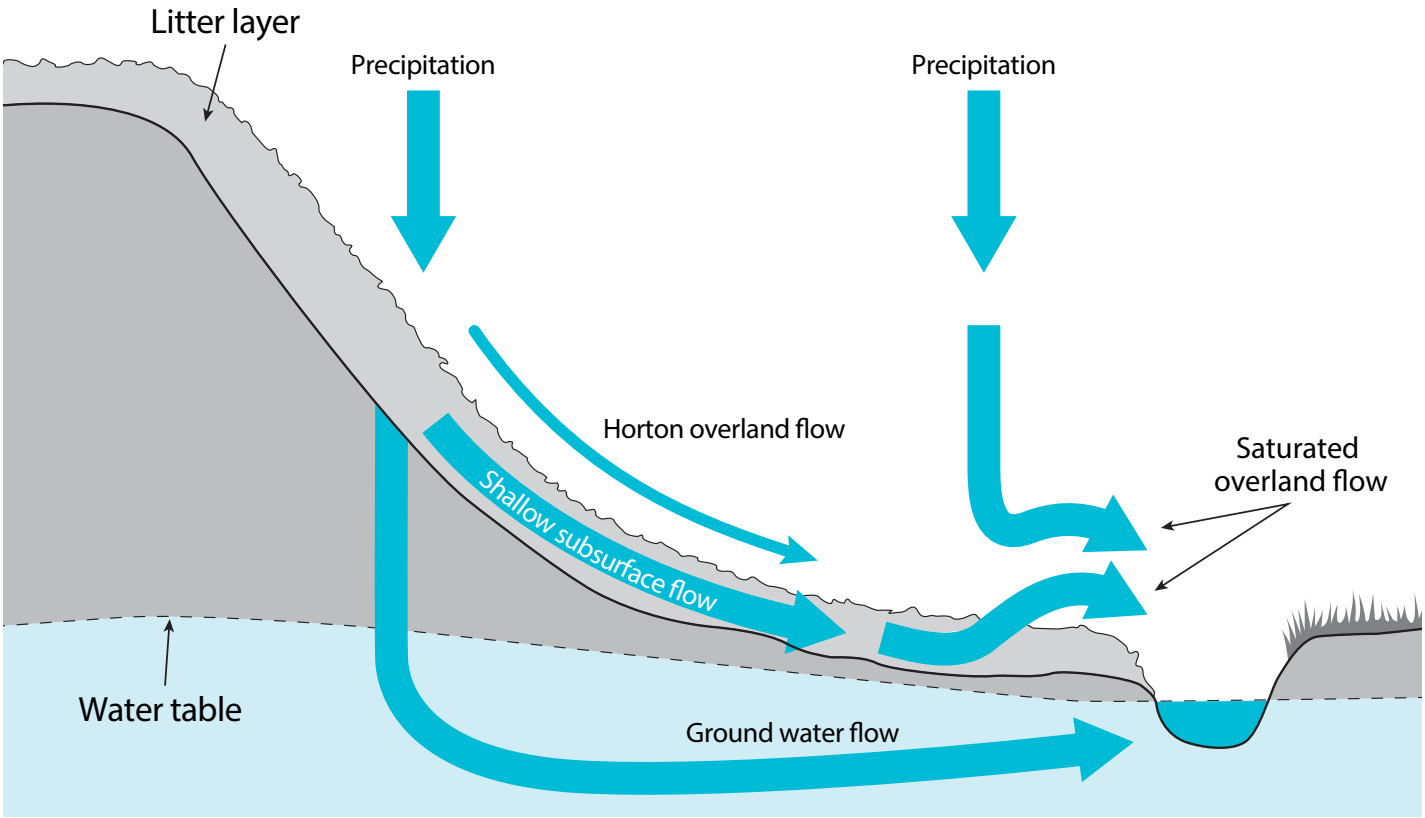


Figure 6.5. Water flow paths. Precipitation reaches a stream as surface runoff and by infiltration into the ground where it contributes to groundwater flow. The amount of water following each flow path depends on the capacity of the soil to absorb water, the amount of storage in surface depressions, and the amount, intensity, and duration of precipitation (image adapted from Stream Corridor Restoration Handbook; FISWRG, 1998).

bring in nutrients from upstream areas (Figure 6.5). As water moves downstream, it moves into and out of the hyporheic zone, carrying with it dissolved nutrients that react with the sediments and biota living in the interstitial spaces of the sediments (Fernald et al. 2006). Wondzell (2011) suggests that hyporheic exchange is likely to be most important in small streams but that hyporheic exchange through sand-bedded streams is substantial and may have an important influence on nutrient loads of large rivers. Regardless, large fractions of N are removed via denitrification in hyporheic sediments at all scales from headwater streams to large rivers (Peterson et al. 2001; Mulholland et al. 2004; Alexander et al. 2007).

Hydrology is the driving force for a range of physical and biogeochemical processes controlling retention and flux of nutrients entering the riparian ecosystem (Chapter 2). Nutrients may originate from neighboring areas via local flow systems throughout the riverscape, from regional groundwater flow systems, especially along reaches of the higher stream orders, or from a recirculation of river water in riparian areas during flooding (Dahl et al. 2007). Depending on flood intensity and frequency, water may overflow the streambanks and move into the floodplain where sediments may be deposited or, conversely, litter, woody material, and sediments may be mobilized and transported into the main channel.

Many floodplains in the Pacific Northwest are highly altered by human activities and are often artificially disconnected from stream channels by levees. Subsequently, natural flooding processes and nutrient exchange, both deposition and production, are severely altered often with negative consequences to riparian habitat.

Discharge volume, stream flow velocity, and temporal variability in flow, coupled with nutrient concentrations dictate the mass loading of each nutrient flowing downstream. Headwater streams commonly make up 75% or more of the total stream channel length in drainage basins (Benda et al. 2004) and have a disproportionately profound influence on the water quality and quantity for downstream ecosystems (Peterson et al. 2001). Alexander et al. (2007) found that fluxes from first-order headwater streams accounted for 70% of water volume and 65% of the N flux occurring from second-order streams. Research comparing perennial, intermittent, and ephemeral stream nutrient cycling processes indicates that flow intermittency can affect the concentrations, fluxes, and forms of nutrients moving from streams into downstream ecosystems (Von Schiller et al. 2011).

In western Oregon and Washington, floodplains experience extremes in water and sediment flux (Naiman et al. 2010). Floodplains often have saturated soils and shallow, upwelling groundwater. Such wet conditions influence N processing by creating anoxic, denitrifying conditions in organic soil horizons (Burt et al. 2002). However, many floodplains of the PNW are highly altered by human activities and are often artificially disconnected from the stream channel via levees constructed to convert lands to agriculture or other uses. Subsequently, nutrient exchange during flood events between aquatic and riparian ecosystems, via both mobilization and deposition of dissolved and suspended organic matter, is severely altered. River restoration often focuses on reconnecting floodplains and associated riparian areas to stream channels in order to restore natural hydrology and re-establish nutrient cycling functions (Bernhardt et al. 2005; Craig et al. 2008). The hydrologic interactions of uplands and

riparian soils control nutrient cycling and transport (Mayer et al. 2007; Weitzman et al. 2014). Therefore, it is critical to maintain riparian vegetation and to control soil erosion and nutrient runoff from uplands (Mayer et al. 2007; Hoffman et al. 2009; Zhang et al. 2010; Sweeney and Newbold 2014).

Impacts to riparian ecosystems may include historic events not well documented and not easily recognized today. Such impacts may lead to erroneous understanding of baseline conditions or misidentification of pristine areas. For example, recent research suggests that legacy sediments, referring to sediments deposited in floodplains from historic upland erosion in response to deforestation and construction of milldams and ponds, have altered nutrient cycling in riparian ecosystems throughout the mid-Atlantic region of the US (Walter and Merritts 2008; Merritts et al. 2011). Much of the fine sediment carried by these streams during storms is from streambank erosion, which often includes legacy sediments, thereby contributing substantially to sediment and nutrient loads in streams (Gellis and Noe 2013). While milldams may not have been as common in the Pacific Northwest, splash dams created to move logs downstream were common throughout the region historically until the mid-20th century (Phelps 2011). These dams and other historic logging activities may have altered riparian systems in ways not easily recognized today but which may have had a significant legacy effect on sediment deposition in floodplains. For example, splash dam releases exceeded the effects of 100-year flood events in headwater regions and were comparable to 100-year flows in lower reaches (Phelps 2011). Splash dams also may have contributed to simplification of stream channels when rocks and debris jams were removed to facilitate log transport (Sedell and Luchessa 1981; Wohl 2000). Overall, the long-term effects of splash dams are not well documented nor are they accounted for in current riparian assessments.



South Fork Sauk River/Wendy Cole, WDFW

Precipitation and runoff are master variables regulating transport and transformation of C, N, and P in watersheds (Dosskey et al. 2010; Vidon et al. 2010). The interaction between land use and climate variability can increase the amplitude and frequency of nutrient pulses, effecting rapid and large changes in concentrations and fluxes of materials (Kaushal et al. 2014). Shifting patterns in runoff and temperature due to land use and climate variability can amplify pulses of greenhouse gases (GHG) such as CO_2, CH_4, and N_2O emanating from watersheds (Kaushal et al. 2014). For example, Vidon et al. (2014) showed strong N_2O pulses in response to storm events in a riparian wetland. Warming increases production of some GHGs in wetlands (Inglett et al. 2012) because temperature affects reaction kinetics and equilibria. Higher stream temperatures may increase rates of both bacterial consumption of nutrients and production of GHGs in streams and rivers (Kaushal et al. 2014). Recent research shows that groundwater may also warm in response to climate (Menberg et al. 2014).

Most N and P enters receiving waterbodies during storm events and during cooler seasons when temperatures are lower than optimal for microbial activity (Kaushal et al. 2010) or when plants are senescent. During drought, residence times may be long, leading to more denitrification in riparian soils, however N loads may be small overall because stream flow may be much lower than normal (Mayer et al. 2010b; Filoso and Palmer 2011). However, drought may also lower moisture levels in riparian soils, potentially reducing the occurrence of anoxic conditions required for denitrification (Groffman et al. 2003). Conversely, high flow conditions during "flashy" storm events may greatly compromise nutrient retention processes (Booth 2005) flushing far more solutes downstream including N and P (Cooper et al. 2014). Consequently, high flows are also responsible for the vast majority of particulate C, N, and P transport in most streams (Alexander et al. 2000; Moore and Wondzell 2005).

Stream channel geomorphology and geologic setting, especially stream channel width, depth, and sediment lithology strongly influence groundwater behavior. In turn, nutrient movement in riparian ecosystems is dependent upon groundwater, which can be highly variable and follow preferential flow paths. Striz and Mayer (2008) showed that groundwater movement may shift considerably depending on seasonal precipitation trends. Streams may be gaining, that is, receiving water from the uplands when precipitation is high, or losing surface water to the ground when soils are dry and drought conditions prevail. Water movement through deep groundwater flow paths back to the stream can take years or decades (Hinkle 2009) and in some cases there is very little exchange with regional deep groundwater (Vaccaro 2011).

Mass removal of nutrients and contaminants in streambed sediments is dependent upon residence times because microbial processes, such as denitrification, require time for complete reaction (Zarnetske et al. 2012). Nutrient concentrations in soils and water may vary on time scales across minutes and hours as plants or algae take up nutrients. Yet, seasonal and annual cycles are also evident based on flow and temperatures. Nutrients may also vary on spatial scales of millimeters to meters depending on plant distribution or litter deposition, and can also vary at regional and global scales depending on land use, geomorphology, and precipitation patterns.

A better understanding of the role hyporheic connections play in the processing of nutrients will improve our ability to design riparian management strategies that protect water quality.

6.3. State of Riparian Nutrient Dynamics Science

Recent advances in stream nutrient research reveal spatially and temporally variable processes and resulting pulses of nutrient transformation, storage, and release that can differ among locations and through time at the same locations. We also know that freshwater and riparian ecosystems vary tremendously across the PNW based on soils, climate, organisms, and human activity. Because most stream nutrient research originates from case studies, the application of case study results to novel conditions should be done cautiously.

Most studies of riparian nutrient dynamics have been conducted in forested watersheds; grassland and desert ecosystems in our region are less well studied but share some common processes and dynamics. Much of the information provided here demonstrates that riparian areas can have important effects on nutrient transfer from land to water, which subsequently have implications for ecosystem goods and services (e.g., water for drinking, swimming, fishing, boating, etc.) and habitat conditions for aquatic species.

Generally, if the goal of riparian management involves nutrients, management should include efforts to shorten nutrient spiraling lengths, increase nutrient retention, provide substrates to support riparian food webs, and maintain natural shading in order to minimize algal blooms. However, stimulating algal and plant growth is one way to shorten nutrient spiraling lengths by enhancing nutrient uptake, at least temporarily as nutrients will be returned after senescence. A longer-term goal of riparian management is to avoid excessive nutrient delivery to streams. Maintaining riparian



The larvae of many caddisfly species use silk to make protective cases, which are often strengthened with gravel, sand, and twigs/ Ned Pittman, WDFW

vegetation, soil conditions, and flowpaths, etc. will fascilitate the removal of nutrients from surface and subsurface flow before entering the channel. If nutrient input is successfully controlled, light levels promoting algal blooms become much less of an issue.

Some of the critical gaps in our understanding occur where physical sampling for detecting water and material movement is most difficult. This occurs in the soil subsurface, the streambed, and hyporheic zones where determining flow dynamics requires multiple sampling wells (Striz and Mayer 2008) or surrogate measures such as stream temperature (Stonestrom and Constantz 2003). A better understanding of the role hyporheic connections play in the processing of nutrients will improve our ability to design riparian management strategies that protect water quality (Hinkle et al. 2001; Zarnetske et al. 2011, 2012), particularly by expanding these studies to better

represent the range of conditions in Washington. However, the use of stable isotopes of N, P, C, and also O and H in water have helped to illuminate some of the more obscure processes like water movement into and out of trees (Brooks et al. 2010) and the uptake of N along entire stream reaches (Ashkenas et al. 2004). Satellite monitoring data (e.g. GRACE) and lidar imaging, which can provide high-resolution topographic data for inaccessible areas, are proving to be valuable tools for the study of nutrient dynamics at the watershed scale. Drone technology may eventually further provide local and current information on condition and environmental variables. Coupling these new data sources with the development of powerful computer models (e.g., VELMA) that predict watershed-scale nutrient movement (Abdelnour et al. 2011; Abdelnour et al. 2013) will greatly enhance our ability to extrapolate field level data to watershed scales and to test land use riparian management scenarios and climate change impacts on nutrient cycling behavior.

6.4. The Role of Management

Litter from riparian areas is clearly an important source of limiting nutrients and chemical energy for aquatic ecosystems. Inorganic nutrients, such as those in artificial fertilizers, do not mimic the foodweb role of litter because inorganic nutrients feed the autotrophic components of foodwebs, such as algae. Litter feeds heterotrophic components of foodwebs, such as benthic macroinvertebrates, many of which are prey for resident salmonids and juvenile salmon. Consequently, providing adequate amounts of litter to streams is an important issue for riparian area management. The results of Bilby and Heffner (2016) suggest that 95% of full litter delivery to streams can be achieved with buffer widths between 40 to 60% of site-potential tree height, depending on site conditions. Numerous factors dictate the transport and fate of nutrients through riparian systems. Managing riparian systems to limit negative impacts of nutrients on downstream resources is inherently complex. The role of management is largely to offset the impacts of human activities that increase nutrient loads and runoff, exacerbate the impacts of nutrients, and/or alter the fluxes of nutrients. Table 6.1 identifies impacts of human activities in the context of factors influencing riparian areas and describes practical management and restoration approaches that are known to mitigate nutrient impacts. The primary objective with respect to offsetting nutrient impacts among all categories of land use is to maintain existing riparian systems, restore degraded systems, and plant riparian buffers where they do not currently exist. Overall, management should focus on where in the watershed important nutrient dynamics that affect aquatic system integrity (or fish life) occur, and how to reduce or ameliorate various human disturbances that can affect nutrient dynamics at those places.

Although salmon runs and associated nutrient fluxes have declined over time in Oregon, Washington, Idaho, and California (Gresh et al. 2000), salmon could still play an important role in stream ecosystems by greatly increasing the quantity of salmon carcasses planted in streams or by greatly increasing harvest escapement (Gende et al. 2002). Addition of inorganic nutrients will not mimic the food web role of salmon in PNW watersheds because they do not directly mimic the complex organic matter from salmon carcasses supplied to heterotrophs such as aquatic insects and juvenile salmonids (Compton et al. 2006). Maintaining structures, such as large wood, and processes that retain nutrients are expected to allow greater utilization of salmon-derived nutrients in aquatic food webs.

Table 6.1. Major factors influencing nutrient dynamics in riparian ecosystems and the role of management in reducing impacts

Factors influencing riparian areas	Impacts of human activities	Role of management in reducing impacts
Land use - agriculture	Excess nutrient application and leaching into groundwater and surface water	Improve nutrient management to reduce nutrient loading - right time, right place, right source, right rate (4Rs)
	Compaction and vegetation damage from poor livestock management near streams	Protect and restore riparian areas to attenuate sediment and nutrient loads
	Riparian disturbance or lack of natural vegetation in riparian area	Protect and restore riparian areas to reduce light inputs that drive algal overproduction and eutrophication
Land use - urbanization	Impervious surfaces increase nutrients and sediment transfer to surface waters	Disconnect direct runoff from impervious surfaces to streams to control nutrient and sediment inputs
	Increased nutrient application via yard fertilizer and pet waste	Educate the public and incentivize behaviors to reduce nutrient loads
	Leaky and ineffective sewer and septic systems	Improve sewer systems, sewage treatment, storm drainage, and septic systems
Land use - forestry (harvest and road building)	Small increase in nutrient loadings	Seek alternatives to clear cutting and protect riparian areas
	Small to moderate increase in sediment transport	Seek alternatives to clear cutting; improve harvest practices, slope and soil management, and road construction; and protect riparian areas
Forest age and composition	Recent clear-cuts may lose the most nutrients	Extend harvest rotations because mature forests likely retain more nutrients than young forests
	Red Alder fixes large amounts of N, which remains in the system and contributes to productive soils of the Coast Range and western Cascades mountains	Recognize the role that Red Alder forests can play in stream nutrient levels
Climate and seasonality	Rapid movement of water during fall and winter rains, sometimes bypass riparian zones	Slow water movement across the landscape
	Rapid N cycling during the summer but low flows mean this inorganic nitrogen accumulates in the soil, fall rains displace this N and transport it to streams	Consider timing of fertilizer applications
	Spring season usually has peak algal blooms because nutrient supplies are high as is light availability before full leaf out.	
	Slower processing of nutrients in cold weather, although conifer trees take up nurients year round	
Elevation and topography	Steep slopes lead to higher rates of runoff and sediment transport	Minimize disturbance to vegetation and soils on steeper slopes through forest and pasture management

Table 6.1. CONTINUED
Major factors influencing nutrient dynamics in riparian ecosystems and the role of management in reducing impacts

Factors influencing riparian areas	Impacts of human activities	Role of management in reducing impacts
Hydrology	Reduced connection between the channel and floodplain can limit nutrient uptake	Reconnect flood plains to increase water residence times, which can increase ground water-surface interactions and nutrient uptake
Nutrient concentrations, forms, and inputs	High concentration and multiple sources of bioavailable nutrient forms may overload capacity of riparian systems to process nutrient loads	Consider terrestrial versus atmospheric sources; carefully manage synthetic fertilizer and manure applications, and balance N and P
Soil properties and geology	Low permeability reduces infiltration and interaction with soils	Practice good soil management because rich, fertile soils can contribute organic carbon for denitrification
	Sandy soils can transmit more water and nutrients (e.g., pumice soils and septic systems)	Recognize that some soils are better at adsorbing P (e.g., volcanic and highly weathered soils)
Biota	Declines in salmon runs reduces supply of nutrients and organic matter for invertebrates, birds, mammals, and other fish	Restore salmon populations, which increases nutrients in ecosystem: nutrients are assimilated by vegetation, consumed by animals, and converted by microbial processes

6.5. Conclusions

Riparian areas are important sources and sinks of organic matter and nutrients for streams. Numerous sources of C, N, and P exist, each taking various organic and inorganic forms, and each moving through the environment continuously along multiple paths at various temporal and spatial scales. Transfers may be via subsurface flow, direct input of materials via litterfall, treefall, or animal movement. Nutrient and energy subsidies from riparian areas to streams and rivers have profound effects on the composition, structure, and functions of aquatic ecosystems.

In watersheds where excess nutrients are polluting surface waters, hydrology and flow paths are critically important when considering potential for nutrient removal by riparian areas. If a riparian area is physically disconnected from the stream, flow paths may not carry materials through the riparian area, particularly into the hotspots with appropriate conditions for denitrification, and thus N removal will not occur as readily. Thus, maintaining hydrologic connections between riparian areas and stream channels are critical. This includes allowing natural seasonal patterns of flow including flooding.

Historically, many watersheds in Washington have seen substantial inputs of salmon-derived N, P, and organic matter. Riparian areas serve as the critical connection for transferring these nutrients to uplands via animal consumption, plant uptake, and biogeochemical cycling.

Results of a large review of riparian ecosystem studies across the globe indicated that vegetated riparian areas were more effective in trapping N than unvegetated ecosystems, but that the type of vegetation did not matter tremendously. Wider riparian areas were more effective in N removal across studies (see Chapter 5).

N-fixation by Red Alder is an important component of nutrient cycling in forests of western Washington and

Oregon. In the PNW, deciduous riparian forests tend to produce more litter with higher nutrient content and nutritional quality for stream food webs than conifer riparian areas. However, conifers have a longer lifespan, produce larger wood and are a more consistent source of shade. In riparian areas with a mixture of deciduous and conifer trees, deciduous species enhance litter flux and nutrient delivery to terrestrial and aquatic food webs, thus, complementing the provision of shade and large wood by conifers. Both the food web and structural roles of tree species should be considered in riparian management plans in order to support aquatic production.

Structurally diverse habitats with variability in geomorphology and soils are likely to support correspondingly diverse biota including vegetation, animals, and microbial communities that will be best able to process and assimilate nutrient loads. Headwaters are especially controlled by riparian processes and thus, are important zones of active nutrient processing that can significantly affect downstream transport of nutrients. Therefore, maintaining riparian areas in headwater systems may be disproportionately important to stream function. Similarly, maintaining hydrologic connection of streams with their floodplains is important because rich, organic sediments are deposited on floodplains during flood events. Conversely, channelization and stream incision from erosion disconnects streams from their floodplains, causes flashy flows, further incises stream channels while starving floodplains of regular resupply of organic matter, and can lower groundwater tables below the rooting zone thereby contributing to the reduction of riparian vegetation in arid climates.

While more research will be necessary to answer important questions about nutrients in riparian ecosystems, the science is very clear about the importance of the condition of riparian areas on the flows of nutrients through stream systems. Riparian areas and their streams are much more than conduits for nutrients from the uplands to downstream systems; they are vitally important locations for the short- and long-term supply, storage, and transformation of nutrients.



Perennial fruiting bodies, or conks, of a polypore fungi/Ned Pittman, WDFW

6.6. Literature Cited[2]

Abdelnour, A., M. Stieglitz, F. Pan, and R. McKane. 2011. Catchment hydrological responses to forest harvest amount and spatial pattern. Water Resources Research 47: W09521 (i).

Abdelnour, A., R. McKane, M. Stieglitz, F. Pan, and Y. Cheng. 2013. Effects of harvest on carbon and nitrogen dynamics in a Pacific Northwest forest catchment. Water Resources Research 49:1292-1313. (i)

Alexander, R.B., R. A. Smith, and G.E. Schwartz. 2000. Effect of stream channel size on the delivery of nitrogen to the Gulf of Mexico. Nature 403:758–761. (i)

Alexander, R.B., E.W. Boyer, R.A. Smith, G.E. Schwarz, and R.B. Moore. 2007. The role of headwater streams in downstream water quality. Journal of the American Water Resources Association 43:41-59. (i)

Ashkenas, L.R., S.L. Johnson, S.V. Gregory, J.L. Tank, and W.M. Wollheim. 2004. A stable isotope tracer study of nitrogen uptake and transformation in an old-growth forest stream. Ecology 85:1725-1739. (i)

Beechie, T., and T.H. Sibley. 1997. Relationships between channel characteristics, woody debris and fish habitat in northwestern Washington streams. Transactions of the American Fisheries Society 126:217-229. (i)

Benda, L., N.L. Poff, D. Miller, T. Dunne, G. Reeves, G. Pess, and M. Pollock. 2004. The network dynamics hypothesis: how channel networks structure riverine habitats. BioScience 54:413-427. (i)

Benda, L., M.A. Hassan, M. Church, and C.L. May. 2005. Geomorphology of steepland headwaters: the transition from hillslopes to channels. Journal of the American Water Resources Association 41:835-851. (i)

Ben-David, M., T.A. Hanley, and D.M. Schell. 1998. Fertilization of terrestrial vegetation by spawning Pacific salmon: the role of flooding and predator activity. Oikos 83:47-55. (i)

Benfield, E.F. 1997. Comparisons of litterfall input to streams. Journal of the North American Benthological Society 16:104-108. (i)

Bernhardt, E.S., M.A. Palmer, J.D. Allan, G. Alexander, K. Barnas, S. Brooks, J. Carr, S. Clayton, C. Dahm, J. Follstad-Shah, D. Galat, S. Gloss, P. Goodwin, D. Hart, B. Hassett, R. Jenkinson, S. Katz, G.M. Kondolf, P.S. Lake, R. Lave, J.L. Meyer, T.K. O'Donnell, L. Pagano, B. Powell, and E. Sudduth. 2005. Synthesizing U.S. river restoration efforts. Science 308:636-637. (i)

Bilby, R.E., R.R. Fransen, and P.A. Bisson. 1996. Incorporation of nitrogen and carbon from spawning Coho Salmon into the trophic system of small streams: evidence from stable isotopes. Canadian Journal of Fisheries and Aquatic Sciences 53:164–173. (i)

Bilby, R.E., and J.T. Heffner. 2016. Factors influencing litter delivery to streams. Forest Ecology and Management 369:29-37. (i)

Bisson, P.A., and R.E. Bilby. 1998. Organic matter and trophic dynamics. Page 373-398 *in* R.J. Naiman and R.E. Bilby, editors. River ecology and management: lessons from the Pacific Coastal Ecoregion. Springer-Verlag, New York. (i)

Bohn, H.L., B.L. McNeal, and G.A O'Connor. 1985. Soil chemistry. John Wiley and Sons, New York. (i)

Booth, D.B. 2005. Challenges and prospects for restoring urban streams: a perspective from the Pacific Northwest of North America. Journal of North American Benthological Society 24:724–737. (i)

Brooks, J.R., H. Barnard, R. Coulombe, and J.J. McDonnell. 2010. Ecohydrologic separation of water between trees and streams in a Mediterranean climate. Nature Geoscience 3:100-104. (i)

Brown G.W., A.R. Gahler, and R.B Marston. 1973. Nutrient losses after clear-cut logging and slash burning in the Oregon Coast Range. Water Resources Research 9:1450-1453. (i)

2 References are classified according to RCW 34.05.271 (see Appendix 1) denoted by a lower case roman numeral (i – viii) in parentheses at the end of the citation.

Burt, T.P., G. Pinay, F.E. Matheson, N.E. Haycock, A. Butturini, J.C. Clement, S. Danielescu, D.J. Dowrick, M.M. Hefting, A. Hillbricht-Ilkowska, and V. Maitre. 2002. Water table fluctuations in the riparian zone: comparative results from a pan-European experiment. Journal of Hydrology 265:129–148. (i)

Cardinale, B.J., M.A. Palmer, C.M. Swan, S. Brooks, and N.L. Poff. 2002. The influence of substrate heterogeneity on biofilm metabolism in a stream ecosystem. Ecology 83:412–422. (i)

Cardinale, B.J. 2011. Biodiversity improves water quality through niche partitioning. Nature 472:86-89. (i)

Carpenter, S., N.F. Caraco, D.L. Correll, R.W. Howarth, A.N. Sharpley, and V.H. Smith. 1998. Nonpoint pollution of surface waters with phosphorus and nitrogen. Issues in Ecology No. 3, Ecological Society of America, Washington, D.C. (i)

Cederholm, C.J., D.B. Houston, D.I. Cole, and W.J. Scarlett. 1989. Fate of Coho Salmon *Oncorhynchus kisutch* carcasses in spawning streams. Canadian Journal of Fisheries and Aquatic Sciences 46:1347–55. (i)

Cederholm, C.J., M.D. Kunze, T. Murota, and A. Sibatani. 1999. Pacific salmon carcasses: essential contributions of nutrients and energy for aquatic and terrestrial ecosystems. Fisheries 24:6–15. (i)

Chappell, H.N., D.W. Cole, S.P. Gessel, and R.B. Walker. 1991. Forest fertilization research and practice in the Pacific Northwest. Fertilizer Research 27:129-140. (i)

Compton, J.E., M.R. Church, S.T. Larned, and W.E. Hogsett. 2003. Nitrogen export from forested watersheds of the Oregon Coast Range: the role of N_2-fixing Red Alder. Ecosystems 6:773–85. (i)

Compton, J.E., and D.W. Cole. 1998. Phosphorus cycling and soil P fractions in Douglas-fir and Red Alder stands. Forest Ecology and Management 110:101-112. (i)

Compton, J.E., C.P. Andersen, D.L. Phillips, J.R. Brooks, M.G. Johnson, M.R. Church, W.E. Hogsett, M.A. Cairns, P.T. Rygiewicz, B.C. McComb, and C.D. Shaff. 2006. Ecological and water quality consequences of nutrient addition for salmon restoration in the Pacific Northwest. Frontiers in Ecology and the Environment 4:18–26. (i)

Cooper, C.A., P.M. Mayer, and B.R. Faulkner. 2014. Effects of road salts on groundwater and surface water dynamics of sodium and chloride in an urban restored stream. Biogeochemistry 121:149-166. (i)

Craig, L.S., M.A. Palmer, D.C Richardson, S. Filoso, E.S. Bernhardt, B.P. Bledsoe, M.W. Doyle, P.M. Groffman, B.A. Hassett, S.S. Kaushal, P.M. Mayer, S.M. Smith, and P.R. Wilcock. 2008. Stream restoration strategies for reducing river nitrogen loads. Frontiers in Ecology and the Environment 6:529-538. (i)

Dahl, M., B. Nilsson, J.H. Langhoff, and J.C. Refsgaard. 2007. Review of classification systems and new multi-scale typology of groundwater–surface water interaction. Journal of Hydrology 344:1–16. (i)

Denver, J.M., C.A. Cravotta III, S.W. Altor, and B.D. Lindsey. 2010. Contributions of phosphorus from groundwater to streams in the Piedmont, Blue Ridge, and Valley and Ridge Physiographic Provinces, Eastern United States. Scientific Investigations Report 2010–5176. U.S. Geological Survey, Reston, Virginia. (viii)

Domagalski J.L., and H. Johnson. 2012. Phosphorus and groundwater: establishing links between agricultural use and transport to streams. U.S. Geological Survey, California Water Science Center, Sacramento. (viii)

Dosskey, M.G., P. Vidon, N.P. Gurwick, C.J. Allan, T.P. Duval, and R. Lowrance. 2010. The role of riparian vegetation in protecting and improving chemical water quality in streams. Journal of the American Water Resources Association 46:261-277. (i)

Dudley-Williams, D., and N.E. Williams. 1993. The upstream/downstream movement paradox of lotic invertebrates: quantitative evidence from a Welsh mountain stream. Freshwater Biology 30:199-218. (i)

Edmonds, R.L., T.B. Thomas, and R.D. Blew. 1995. Biogeochemistry of an old-growth forested watershed, Olympic National Park, Washington. Water Resources Bulletin 31:409-419. (i)

FISRWG (Federal Interagency Stream Restoration Working Group). 1998. Stream corridor restoration: principles, processes, and practices. NEH-653. Natural Resources Conservation Service, Washington, D.C. (viii)

FEMAT (Forest Ecosystem Management Assessment Team). 1993. Forest ecosystem management: an ecological, economic and social assessment. U.S. Department of Agriculture and U.S. Department of the Interior, Portland, Oregon. (viii)

Fernald, A.G., D.H. Landers, and P.J. Wigington. 2006. Water quality changes in hyporheic flow paths between a large gravel bed river and off-channel alcoves in Oregon, USA. River Research and Applications 22:1111-24. (i)

Filoso, S., and M.A. Palmer. 2011. Assessing stream restoration effectiveness at reducing nitrogen export to downstream waters. Ecological Applications 21:1989–2006. (i)

Gellis, A.C., and G.B. Noe. 2013. Sediment source analysis in Linganore Creek watershed, Maryland, USA, using the sediment fingerprinting approach: 2008 to 2010. Journal of Soils and Sediments 13:1735–1753. (i)

Gende, S.M., R.T. Edwards, M.F. Willson, and M.S. Wipfli. 2002. Pacific salmon in aquatic and terrestrial ecosystems. BioScience 52:917-28. (i)

Giardina, C., S. Huffman, D. Binkley, and B. Caldwell. 1995. Alders increase phosphorus supply in a Douglas-fir plantation. Canadian Journal of Forest Research 25:1652-1657. (i)

Giesler, R., T. Andersson, L. Lövgren, and P. Persson. 2005. Phosphate sorption in aluminum- and iron-rich humus soils. Soil Science Society of America 69:77–86. (i)

Greathouse, E.A., J.E. Compton, and J. Van Sickle. 2014. Linking landscape characteristics and high stream nitrogen in the Oregon Coast Range: Red Alder complicates use of nutrient criteria. Journal of the American Water Resources Association 50:1383-1400. (i)

Gresh, T., J. Lichatowich, and P. Schoonmaker. 2000. An estimation of historic and current levels of salmon production in the Northeast Pacific Ecosystem: evidence of a nutrient deficit in the freshwater systems of the Pacific Northwest. Fisheries 25:15-21. (i)

Groffman, P.M., N.J. Boulware, W.C. Zipperer, R.V. Pouyat, L.E. Band, and M.F. Colosimo. 2002. Soil nitrogen cycling processes in urban riparian zones. Environmental Science & Technology 36:4547-4552. (i)

Groffman, P.M., D.J. Bain, L.E. Band, K.T. Belt, G.S. Brush, J.M. Grove, R.V. Pouyat, I.C. Yesilonis, and W.C. Zipperer. 2003. Down by the riverside: urban riparian ecology. Frontiers in Ecology and the Environment 1:315–321. (i)

Groffman, P.M., A.M. Dorsey, and P.M. Mayer. 2005. Nitrogen processing within geomorphic features in urban streams. Journal of North American Benthological Society 24:613-625. (i)

Harmon, M.E., J.F. Franklin, F.J. Swanson, P. Sollins, S.V. Gregory, J.D. Lattin, N.H. Anderson, S.P. Cline, N.G. Aumen, J.R. Sedell, G.W. Lienkaemper, K. Cromack, Jr., and K.W. Cummins, 1986. Ecology of coarse woody debris in temperate ecosystems. Advances in Ecological Research 15:133-302. (i)

Hart, S.K., D.E. Hibbs and S.S. Perakis. 2013. Riparian litter inputs to streams in the central Oregon Coast Range. Freshwater Science 32:343-358. (i)

Hedin, L.O., J.C. von Fischer, N.E. Ostrom, B.P. Kennedy, M.G. Brownand, and G.P. Robertson. 1998. Thermodynamic constraints on nitrogen transformations and other biogeochemical processes at soil-stream interfaces. Ecology 79:684-703. (i)

Hefting, M., J.C. Clement, D. Dowrick, A.C. Cosandey, S. Bernal, C. Cimpian, A. Tatur, T. P. Burt, and G. Pinay. 2004. Water table elevation controls on soil nitrogen cycling in riparian wetlands along a European climatic gradient. Biogeochemistry 67:113-134. (i)

Helfield J.M., and R. Naiman. 2001. Effects of salmon-derived nitrogen on riparian forest growth and implications for stream productivity. Ecology 82:2403-2409. (i)

Hershey, A.E., J. Pastor, B.J. Peterson, and G.W. Kling. 1993. Stable isotopes resolve the drift paradox for Baetis mayflies in an arctic river. Ecology 74:2315-2325. (i)

Hinkle, S.R., J.H. Duff, F.J. Triska, A. Laenen, E.B. Gates, K.E. Bencala, D.A. Wentz, and S.R. Silva. 2001. Linking hyporheic flow and nitrogen cycling near the Willamette River–a large river in Oregon, USA. Journal of Hydrology 244:157-80. (i)

Hinkle, S.R. 2009. Tritium/helium-3 apparent ages of shallow ground water, Portland basin, Oregon, 1997–98: Scientific Investigations Report 2009-5057. U.S. Geological Survey, Reston, Virginia. (viii)

Hoffmann, C.C., C. Kjaergaard, J. Uusi-Kämppä, H.C. Bruun, and B. Kronvang. 2009. Phosphorus retention in riparian buffers: review of their efficiency. Journal of Environmental Quality 38:1942–1955. (i)

Ice, G., and D. Binkley. 2003. Forest streamwater concentrations of nitrogen and phosphorus: comparison with EPA's proposed water quality criteria. Journal of Forestry 101:21–28. (i)

Inglett K.S., P.W. Inglett, K.R. Reddy, and T.Z. Osborne. 2012. Temperature sensitivity of greenhouse gas production in wetland soils of different vegetation. Biogeochemistry 108:77-90. (i)

Jacoby J.M., and J. Kann. 2007. The occurrence and response to toxic cyanobacteria in the Pacific Northwest, North America. Lake Reservoir Management 23:123–143. (i)

Johnson, D.W., and D.W. Cole. 1980. Anion mobility in soils: relevance to nutrient transport from forest ecosystems. Environment International 3:79-90. (i)

Jordan, S.J., J. Stoffer, and J.A. Nestlerode. 2011. Wetlands as sinks for reactive nitrogen at continental and global scales: a meta-analysis. Ecosystems 14:144-155. (i)

Kaushal, S.S., M. Pace, P. Groffman, L. Band, K. Belt, P. Mayer, and C. Welty. 2010. Land use and climate variability amplify contaminant pulses. EOS Transactions of the American Geophysical Union 91:221-222. (i)

Kaushal, S.S., and W.M. Lewis Jr. 2005. Fate and transport of dissolved organic nitrogen in minimally disturbed streams of Colorado, USA. Biogeochemistry 74:303–321. (i)

Kaushal, S.S., P.M. Mayer, P.G. Vidon, R.M. Smith, M.J. Pennino, S. Duan, T.A. Newcomer, C. Welty, and K. Belt. 2014. Land use and climate variability amplify carbon, nutrient, and contaminant pulses: a review with management implications. Journal of the American Water Resources Association 50:585-614. (i)

Lazar, J.G., A.J. Gold, K. Addy, P.M. Mayer, K.J. Forshay, and P.M. Groffman. 2014. Instream large wood: denitrification hotspots with low N_2O production. Journal of the American Water Resources Association 50:615-625.

Martin, C.W., and R.D. Harr. 1989. Logging of mature Douglas-fir in western Oregon has little effect on nutrient output budgets. Canadian Journal of Forest Research 19:35-43. (i)

Masese, F.O., K.G. Abrantes, G.M. Gettel, S. Bouillon, K. Irvine, and M.E. McClain. 2015. Are large herbivores vectors of terrestrial subsidies for riverine food webs? Ecosystems 18:686-706. (i)

Mayer, P.M., A.H. Todd, J.A. Okay, and K.A. Dwire. 2010a. Introduction to the featured collection on riparian ecosystems and buffers. Journal of the American Water Resources Association 46:207-210. (i)

Mayer, P.M., P.M. Groffman, E. Striz, and S.S. Kaushal. 2010b. Nitrogen dynamics at the groundwater-surface water interface of a degraded urban stream. Journal of Environmental Quality 39:810–823. (i)

Mayer, P.M., K.A. Dwire, J.A. Okay, and P. Vidon. 2014. Introduction to the featured collection on riparian ecosystems. Journal of the American Water Resources Association 50:529-532. (i)

Mayer, P.M., S.K. Reynolds, M.D. McMutchen, and T.J. Canfield. 2007. Meta-analysis of nitrogen removal in riparian buffers. Journal of Environmental Quality 36:1172-1180. (i)

McClain, M.E., R.E. Bilby, and F.J. Triska. 1998. Biogeochemistry of N, P, and S in Northwest rivers: natural distributions and responses to disturbance. Pages 347-372 *in* R.J Naiman and R.E. Bilby, editors. River ecology and management: lessons from the Pacific Coastal Ecoregion. Springer-Verlag, New York. (i)

McClain, M.E., E.W. Boyer, C.L. Dent, S.E. Gergel, N.B. Grimm, P.M. Groffman, S.C. Hart, J.W. Harvey, C.A. Johnston, E. Mayorga, W.H. McDowel,l and G. Pinay. 2003. Biogeochemical hot spots and hot moments at the interface of terrestrial and aquatic ecosystems. Ecosystems 6:301–312. (i)

McDowell, W.H., and G.E. Likens. 1988. Origin, composition, and flux of dissolved organic carbon in the Hubbard Brook Valley. Ecological Monographs 58:177-195. (i)

Menberg, K., P. Blum, B.L. Kurylyk, and P. Bayer. 2014. Observed groundwater temperature response to recent climate change. Hydrology and Earth System Sciences 18:4453–4466. (i)

Merritts, D., R. Walter, M. Rahnis, J. Hartranft, S. Cox, A. Gellis, N. Potter, W. Hilgartner, M. Langland, L. Manion, C. Lippincott, S. Siddiqui, Z. Rehman, C. Scheid, L. Kratz, A. Shilling, M. Jenschke, K. Datin, E. Cranmer, A. Reed, D. Matuszewski, M. Voli, E. Ohlson, A. Neugebauer, A. Ahamed, C. Neal, A. Winter, and S. Becker S. 2011. Anthropocene streams and base-level controls from historic dams in the unglaciated mid-Atlantic region, USA. Philosophical Transactions of the Royal Society A 369:976–1009. (i)

Moore, R.D., and S.M. Wondzell. 2005. Physical hydrology and the effects of forest harvesting in the Pacific Northwest: a review. Journal of the American Water Resources Association 41:763-784. (i)

Moyle, P., A. Engilis, M. Escobar, C.M. Mosser, D. Purkey, L.C., and M.L. Truan. 2009. Progress report: innovative management options to prevent loss of ecosystem services provided by Chinook Salmon in California: overcoming the effects of climate change. US EPA NCER program. Available: http://cfpub.epa.gov/ncer_abstracts/index.cfm/fuseaction/display.abstractDetail/abstract/9070/-report/2009. (January 2019). (viii).

Mulholland, P.J., E.R. Marzolf, S.P. Hendricks, R.V. Wilkerson, and A.K. Baybayan. 1995. Longitudinal patterns of nutrient cycling and periphyton characteristics in streams: a test of upstream-downstream linkage. Journal of North American Benthological Society 14:357-370. (i)

Mulholland, P.J., A.M. Helton, G.C. Poole, R.O. Hall Jr., S.K. Hamilton, B.J. Peterson, J.L. Tank, L.R. Ashkenas, L.W. Cooper, C.N. Dahm, W.K. Dodds, S.E.G. Findlay, S.V. Gregory, N.B. Grimm, S.L. Johnson, W.H. McDowell, J.L. Meyer, H.M. Valett, J.R. Webster, C.P. Arango, J.J. Beaulieu, M.J. Bernot, A.J. Burgin, C.L. Crenshaw, L.T. Johnson, B.R. Niederlehner, J.M. O'Brien, J.D. Potter, R.W. Sheibley, D.J. Sobota, and S.M. Thomas. 2008. Stream denitrification across biomes and its response to anthropogenic nitrate loading. Nature 452:202-206. (i)

Murphy, M.L. 1998. Primary productivity. Pages 144-168 *in* R.J. Naiman and R.E. Bilby, editors. River ecology and management: lessons from the Pacific Coastal Ecoregion. Springer-Verlag, New York (i)

Naiman, R.J., J.S. Bechtold, T.J. Beechie, J.J. Latterell, and R. Van Pelt. 2010. A process-based view of floodplain forest patterns in coastal river valleys of the Pacific Northwest. Ecosystems 13:1-31. (i)

Naiman, R.J., and K.H. Rogers. 1997. Large animals and system level characteristics in river corridors. BioScience 47:521–9. (i)

Naiman, R.J., C.A. Johnston, and J.C. Kelley. 1988. Alteration of North American streams by Beaver. BioScience 38:753-762. (i)

Naiman, R.J., G. Pinay, C.A. Johnson, and J. Pastor. 1994. Beaver-induced influences on the long-term biogeochemical characteristics of boreal forest drainage networks. Ecology 75:905-921. (i)

Naiman, R.J., R.E. Bilby, D.E. Schindler, and J.M. Helfield. 2002. Pacific salmon, nutrients, and the dynamics of freshwater and riparian ecosystems. Ecosystems 5:399-417. (i)

Newbold, J.D., R.V. O'Neill, J.W. Elwood, and W. Van Winkle. 1982. Nutrient spiralling in streams: implications for nutrient limitation and invertebrate activity. The American Naturalist 120:628-652. (i)

Newcomer, T.A., S.S. Kaushal, P.M. Mayer, A.R. Shields, E.A. Canuel, P.M. Groffman, and A.J. Gold. 2012. Influence of natural and novel organic carbon sources on denitrification in forested, degraded-urban, and restored streams. Ecological Monographs 82:449–466. (i)

Perakis, S.S., D.A. Maguire, T.D. Bullen, K. Cromack, R.H. Waring, and J.R. Boyle. 2006. Coupled nitrogen and calcium cycles in forests of the Oregon Coast Range. Ecosystems 9:63-74. (i)

Peterson, B.J., W.M. Wollheim, P.J. Mulholland, J.R. Webster, J.L. Meyer, J.L. Tank, E. Marti, W.B. Bowden, H.M. Valett, A.E. Hershey, W.H. McDowell, W.K. Dodds, S.K. Hamilton, S. Gregory, and D.D. Morrall. 2001. Control of nitrogen export from watersheds by headwater streams. Science 292:86-90. (i)

Peterson, C.E., and J.W. Hazard. 1990. Regional variation in growth response of coastal Douglas-fir to nitrogen fertilizer in the Pacific Northwest. Forest Science 36:625–640. (i)

Phelps, J.D. 2011. The geomorphic legacy of splash dams in the southern Oregon Coast Range. Master's thesis. University of Oregon. Eugene. (i)

Pingram M.A., K.J. Collier, D.P. Hamilton, B.O. David, and B.J. Hicks. 2012. Carbon sources supporting large river food webs: a review of ecological theories and evidence from stable isotopes. Freshwater Reviews 5:85–103. (i)

Pollock, M.M., T.J. Beechie, and C.E. Jordan. 2007. Geomorphic changes upstream of Beaver dams in Bridge Creek, an incised stream channel in the interior Columbia River basin, eastern Oregon. Earth Surface Processes and Landforms 32:1174-1185. (i)

Reddy K.R., O.A. Diaz, L.J. Scinto, and M. Agami. 1995. Phosphorus dynamics in selected wetlands and streams of the Lake Okeechobee basin. Ecological Engineering 5:183–207. (i)

Richardson, C.J., and P.E. Marshall. 1986. Processes controlling movement, storage and export of phosphorus in a fen peatland. Ecological Monographs 56:279–302. (i)

Richardson, J.S., and R.J. Danehy. 2007. A synthesis of the ecology of headwater streams and their riparian zones in temperate forests. Forest Science 53:131-147. (i)

Royer, T.V., and M.B. David. 2005. Export of dissolved organic carbon from agricultural streams in Illinois, USA. Aquatic Sciences 67:465–471. (i)

Sabater, S., H. Guasch, A. Roman, and I. Munoz. 2002. The effect of biological factors on the efficiency of river biofilms in improving water quality. Hydrobiologia 469:149-156. (i)

Sabater S., S.V. Gregory, and J.R. Sedell. 1998. Community dynamics and metabolism of benthic algae colonizing wood and rock substrata in forest stream. Journal of Phycology 34:561-567. (i)

Schechter, S.P., T.J. Canfield, and P.M. Mayer. 2013. A meta-analysis of phosphorus attenuation in best management practices (BMP) and low impact development (LID) practices in urban and agricultural areas. EPA 600/R-13/208. National Risk Management Research Laboratory, Ada, Oklahoma. (viii)

Scrivener, J.C. 1975. Water, water chemistry, and hydrochemical balance of dissolved ions in Carnation Creek watershed, Vancouver Island, July 1971 - May 1974. Technical Report 564. Canadian Fisheries and Marine Service, Vancouver, British Columbia. (viii)

Sedell, J.R., and K.J. Luchessa. 1981. Using the historical record as an aid to salmonid enhancement. Pages 210-223 *in* N.B. Armantrout, editor. Acquisition and utilization of aquatic habitat inventory information. Western Division, American Fisheries Society, Portland, Oregon. (viii)

Shen, J., L. Yuan, J. Zhang, H. Li, Z. Bai, X. Chen, W. Zhang, and F. Zhang. 2011. Phosphorus dynamics: from soil to plant. Plant Physiology 156:997-1005. (i)

Silvester, W.B. 1989. Molybdenum limitation of asymbiotic nitrogen fixation in forests of Pacific Northwest America. Soil Biology and Biochemistry 21:283-289. (i)

Sobczak, W.V., S.E.G. Findlay, and S. Dye. 2003. Relationships between DOC bioavailability and nitrate removal in an upland stream: an experimental approach. Biogeochemistry 62:309–327. (i)

Sobota, D.J., S. Johnson, S.V. Gregory, and L.R. Ashkenas, LR. 2012. A stable isotope tracer study of the influences of adjacent land use and riparian condition on fates of nitrate in streams. Ecosystems 15:1-17. (i)

Sollins, P., C.C. Grier, F.M. McCorison, K. Cromack Jr., R. Fogel, and R.L. Fredriksen. 1980. The internal element cycles of an old-growth Douglas-fir ecosystem in western Oregon. Ecological Monographs 50:261-285. (i)

Stanley, E.H., S.M. Powers, N.R. Lottig, I. Buffam, and J.T. Crawford. 2012. Contemporary changes in dissolved organic carbon (DOC) in human-dominated rivers: is there a role for DOC management? Freshwater Biology 57:26-42. (i)

Stonestrom, D.A., and J. Constantz. 2003. Heat as a tool for studying the movement of groundwater near streams. Circular 1260. U.S. Geological Survey, Denver, Colorado. (viii)

Striz, E.A., and P.M. Mayer. 2008. Assessment of near-stream groundwater-surface water interaction (GSI) of a degraded stream before restoration. EPA/600/R-07/058, National Risk Management Research Laboratory, Ada, Oklahoma. (viii)

Swain, N.R., and J.D. Reynolds. 2015. Effects of salmon-derived nutrients and habitat characteristics on population densities of stream-resident sculpins. PLOS ONE 10(6): e0116090. (i)

Sweeney, B.W., and J.D. Newbold. 2014. Streamside forest buffer width needed to protect stream water quality, habitat, and organisms: a literature review. Journal of the American Water Resources Association 50:560-584. (i)

Sweeney, B.W., T.L. Bott, J.K. Jackson, L.A. Kaplan, J.D. Newbold, L.J. Standley, W.C. Hession, and R.J. Horwitz. 2004. Riparian deforestation, stream narrowing, and loss of stream ecosystem services. Proceedings of the National Academy of Sciences 101:14132-14137. (i)

Tague, C., and G.E. Grant. 2004. A geological framework for interpreting the low-flow regimes of Cascade streams, Willamette River Basin, Oregon. Water Resources Research 40:W04303. (i)

Tarrant, R.F., L.A. Issac, and R.F. Chandler. 1951. Observations on litter fall and foliage nutrient content of some Pacific Northwest tree species. Journal of Forestry 49:914-915. (i)

Triska, F.J., J.R. Sedell, K. Cromack Jr., S.V. Gregory, and F.M. McCorison. 1984. Nitrogen budget for a small coniferous forest stream. Ecological Monographs 54:119-40. (i)

USEPA ATTAINS database. Available: http://www2.epa.gov/nutrient-policy-data/waters-assessed-impaired-due-nutrient-related-causes. (June 2015). (vi)

Vaccaro, J.J. 2011. River-aquifer exchanges in the Yakima River basin, Washington: U.S. Geological Survey Scientific Investigations Report 2011-5026. U.S. Geological Survey, Reston, Virginia. (viii)

Vannote, R.L., G.W. Minshall, K.W. Cummins, J.R. Sedell, and C.E. Cushing. 1980. The river continuum concept. Canadian Journal of Fish and Aquatic Science 37:130-137. (i)

Vidon, P., C. Allan, D. Burns, T.P. Duval, N. Gurwick, S. Inamdar, R. Lowrance, J. Okay, D. Scott, and S. Sebestyen. 2010. Hot spots and hot moments in riparian zones: potential for improved water quality. Journal of the American Water Resources Association 46:278-298. (i)

Vidon, P., P.A. Jacinthe, X. Liu, K. Fisher, and M. Baker. 2014. Hydrobiogeochemical controls on riparian nutrient and greenhouse gas dynamics: 10 Years post-restoration. Journal of the American Water Resources Association 50:639-652. (i)

Von Schiller, D., V. Acuña, D. Graeber, E. Martí, M. Ribot, S. Sabater, X. Timoner, and K. Tockner. 2011. Contraction, fragmentation and expansion dynamics determine nutrient availability in a Mediterranean forest stream. Aquatic Sciences 73:485-497. (i)

Wallace, J.B., S.L. Eggert, J.L. Meyer, and J.R. Webster. 1997. Multiple trophic levels of a forest stream linked to terrestrial litter inputs. Science 277:102-104. (i)

Walter, R.C., and D.J. Merritts. 2008. Natural streams and the legacy of water-powered mills. Science 319:299–304. (i)

Weitzman, J.N., K.J. Forshay, J.P. Kaye, P.M. Mayer, J. Koval, and R.C. Walter. 2014. Potential nitrogen and carbon processing in a landscape rich in mill-dam legacy sediments. Biogeochemistry 120:337-357. (i)

Welch, E.B., J.M. Jacoby and C.W. May. 1998. Stream quality. Pages 69-94 *in* R.J. Naiman, and R.E. Bilby, editors. River ecology and management: lessons from the Pacific Coastal Ecoregion. Springer-Verlag, New York. (i)

Wigington, P.J. Jr., T.J. Moser, and D.R. Lindeman. 2005. Stream network expansion: a riparian water quality factor. Hydrological Processes 19:1715–1721. (i)

Wigington, P.J., M.R. Church, T.C. Strickland, K.N. Eshleman, and J. Van Sickle. 1998. Autumn chemistry of Oregon Coast Range streams. Journal of the American Water Resources Association 34:1035-49. (i)

Willson, M.F., and K.C. Halupka. 1995. Anadromous fish as keystone species in vertebrate communities. Conservation Biology 9:489–97. (i)

Wilzbach, M.A., B.C. Harvey, J.L. White, and R.J. Nakamoto. 2005. Effects of riparian canopy opening and salmon carcass addition on the abundance and growth of resident salmonids. Canadian Journal of Fisheries and Aquatic Sciences 62:58–67. (i)

Wipfli, M.S. 2005. Trophic linkages between headwater forests and downstream fish habitats: implications for forest and fish management. Landscape and Urban Planning 72:205-213. (i)

Wipfli, M.S., and C.V. Baxter. 2010. Linking ecosystems, food webs, and fish production: subsidies in salmonid watersheds. Fisheries 35:373-387. (i)

Wipfli, M.S., and J. Musslewhite. 2004. Density of Red Alder (*Alnus rubra*) in headwaters influences invertebrate and detritus subsidies to downstream fish habitats in Alaska. Hydrobiologia 520:153-163.

Wise, D.R., and H.M. Johnson. 2013. Application of the SPARROW model to assess surface-water nutrient conditions and sources in the United States Pacific Northwest. Scientific Investigations Report 2013–5103. U.S. Geological Survey, Reston, Virginia. Available: **http://pubs.usgs.gov/sir/2013/5103/.** (Januray 2019) (viii)

Wise, D.R., and H.M. Johnson. 2011. Surface-water nutrient conditions and sources in the United States Pacific Northwest. Journal of the American Water Resources Association 47:1110-1135. (i)

Wohl, E.E. 2000. Mountain Rivers. The American Geophysical Union, Washington, D.C. (viii)

Wondzell, S.M. 2011. The role of the hyporheic zone across stream networks. Hydrological Processes 25:3525-3532. (i)

Xiong, S., and C. Nilsson. 1997. Dynamics of leaf litter accumulation and its effects on riparian vegetation: a review. Botanical Review 63:240–264. (i)

Yanai, R.D. 1992. Phosphorus budget of a 70-yr-old northern hardwood forest. Biogeochemistry 17:1-22. (i)

Zarnetske, J.P., R. Haggerty, S.M. Wondzell, V.A. Bokil, and R. González-Pinzón. 2012. Coupled transport and reaction kinetics control the nitrate source-sink function of hyporheic zones. Water Resources Research 48: W11508. (i)

Zarnetske, J.P., R. Haggerty, S.M. Wondzell, and M.A. Baker. 2011. Dynamics of nitrate production and removal as a function of residence time in the hyporheic zone. Journal of Geophysical Research 116:G01025. (i)

Zhang, X., X. Liu, M. Zhang, R.A. Dahlgren, and M. Eitzel. 2010. A review of vegetated buffers and a meta-analysis of their mitigation efficacy in reducing nonpoint source pollution. Journal of Environmental Quality 39:76-84. (i)

Zou, X., D. Binkley, and B.A. Caldwell. 1995. Effects of dinitrogen-fixing trees on phosphorus biogeochemical cycling in contrasting forests. Soil Science Society of America Journal 59:1452-1458. (i)



Big Creek Trail/Rachel Blomker, WDFW



Chapter 7. Riparian Areas of the Columbia Plateau

By: George F. Wilhere

This chapter is dedicated Karin Divens who passed away unexpectedly on 12 October 2017. Karin made a significant contribution to this chapter by organizing a two-day, multi-disciplinary workshop that advanced our scientific understanding of riparian areas in the Columbia Plateau Ecoregion. Karin was an effective and well-respected habitat biologist at WDFW, who brought not only science to her work but a full heart.

7.1. Introduction

The Columbia Plateau Ecoregion (sensu Omernick 1987),[1] is classified as a cold desert (Sleeter 2012), and covers about one-third of Washington State (Figure 7.1). In the driest parts of the ecoregion, a rain shadow cast by the Cascades Mountains limits precipitation to 6 to 9 in (15 to 23 cm) per year, and even wettest parts of the ecoregion, the Palouse Hills Subregion, receive only 18 to 23 in (46 to 58 cm) per year (Bryce and Omernik 1997). Uplands of the Columbia Plateau are covered by either shrub-steppe or steppe[2] vegetation (i.e., sagebrush and bunchgrass communities, respectively), and, most notably, lack trees (Franklin and Dyrness 1988). The ecoregion's desert climate confines nearly all trees to riparian areas.[3]

Seventy-five years ago Daubenmire (1942) wrote, "The vegetation of the unforested regions in the Pacific Northwest has been less thoroughly studied and is consequently less perfectly understood than is that of the forested areas." The situation has not changed. Most of what is known about riparian areas in the Pacific Northwest is based on research conducted in forested ecoregions. During my review of the scientific literature, I found far less information about the composition, structure, and functions of riparian ecosystems in unforested ecoregions, such as the Columbia Plateau, than I found for forested ecoregions. However, many of the basic principles and qualitative relationships that have emerged from research in forested ecoregions are also valid in unforested ecoregions. For instance, while there are significant quantitative differences among ecoregions in the amount of wood or shade provided by riparian areas, the physical processes of large wood recruitment and stream shading should be very nearly the same. On the other hand, processes that are strongly affected by groundwater, such as nutrient dynamics and pollutant removal, should be different. To clarify current

[1] There are several different delineations of ecoregions (e.g., USFWS 1994; Bailey 1995; Olson et al. 2001). For this report WDFW used the ecoregions of Omernick (1987). The only non-forested ecoregion in Washington is the Columbia Plateau. Forested ecoregions surrounding the Columbia Plateau in Washington are the Eastern Cascades, North Cascades, Okanogan, Northern Rockies, and Blue Mountains.

[2] Steppe is also referred to as grassland or prairie. The steppe region of southeastern Washington is called the Palouse.

[3] A notable exception is the Juniper Dunes Wilderness Area, which preserves the northernmost Western Juniper Trees *Juniperus occidentalis* in North America. This 7100-acre area contains no surface water.



The amount of rain received by the Columbia Plateau Ecoregion each year is insufficient to support trees in the uplands/Justin Haug, WDFW

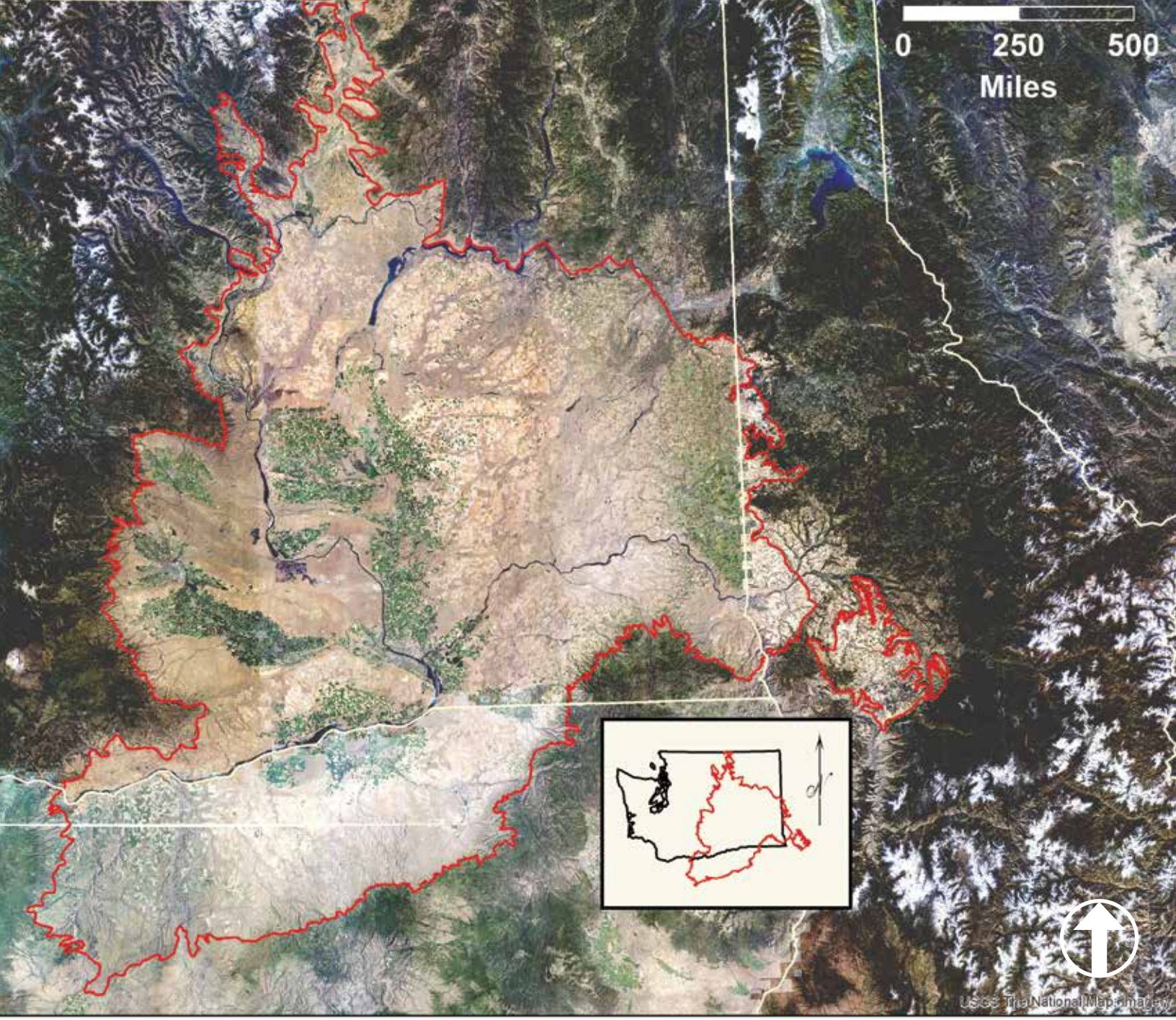


Figure 7.1. Boundary (in red) of the Columbia Plateau Ecoregion. State boundaries are white. Aerial photography for Washington State done in 2015 by the National Agriculture Imagery Program.

scientific understanding, throughout this chapter I point out differences between riparian areas in forested and unforested ecoregions.

The Columbia Plateau Ecoregion is comprised of both arid and semi-arid subregions (hereafter collectively known as drylands). Due to lack of information, I make few subregional distinctions regarding riparian areas. Most of what is known about the ecology of dryland riparian areas is based on research conducted in desert ecoregions of the southwestern United States (Patten 1998). Although these ecoregions have climate, hydrology, soils, and vegetation different from the Columbia Plateau, many of the basic principles and qualitative relationships that have emerged from research in other desert ecoregions should be valid for the Columbia Plateau.

7.1.1. Dryland Riparian Areas

Decades ago, the term "riparian" referred exclusively to areas adjacent to surface waters with moist soils that support distinctive vegetation (e.g., Thomas et al. 1979, Anderson 1987). Later definitions expanded the meaning of riparian. Sedell et al. (1989) and Naiman et al. (1992), for example, divided the "riparian ecosystem" or "riparian area" into two zones: a "riparian zone" with moist soils supporting wetland and riparian-dependent vegetation, and an upland "zone of influence" that significantly influences the exchanges of energy and matter between terrestrial and aquatic ecosystems (Figure 7.2). In forested ecoregions, the potential vegetation of both zones is commonly forest, and the ecological functions of the zones are similar. In the Columbia Plateau, vegetation within riparian ecosystems often exhibits an abrupt demarcation between the two zones. Phreatophytic[4] trees and shrubs and hydrophytic[5] herbaceous plants are confined to moist streamside areas, but the upland zone of influence may consist of sagebrush or bunchgrass communities. Consequently, the functions of the two zones may be quite different. Along some reaches, the riparian zone and zone of influence may both reside within a floodplain and exhibit similar composition and structure. For our purposes, the phrases riparian ecosystem and riparian area are synonymous.

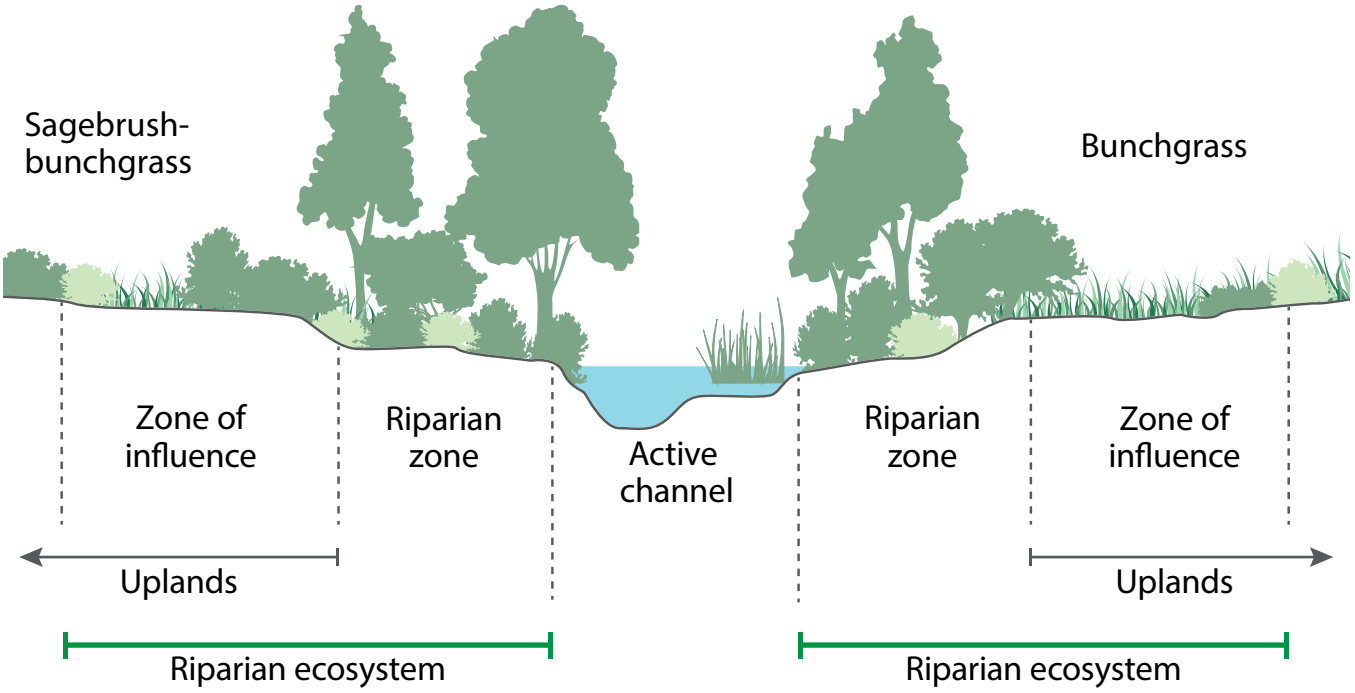


Figure 7.2. Dryland Riparian Ecosystem. The riparian ecosystem consists of two zones: riparian and zone of influence. The riparian zone extends from the edge of the active channel towards the uplands. This zone includes areas where terrestrial biota are influenced, at least periodically, by surface or subsurface waters. Beyond this is the riparian "zone of influence." This includes areas where ecological functions significantly influence the stream (diagram modified from USFS 2004).

[4] A phreatopyhtic plant is a species that obtains water from the subsurface zone of saturation either directly or through the capillary fringe (Thomas 2014).
[5] Hydrophytic plants are those that are adapted to growing conditions associated with periodically saturated soils. They include obligate wetland plants that almost always occur in wetlands under natural conditions, facultative wetland plants that usually occur in wetlands but are occasionally found in non-wetlands, and facultative plants that equally likely to occur in wetlands or non-wetlands (Lichvar et al. 2012).



In the semi-arid Columbia Plateau Ecoregion, trees are generally confined to riparian areas/Scott Fitkin, WDFW

In dryland ecoregions, riparian ecosystems are the ultimate expression of groundwater and surface-water interactions (Webb and Leake 2006). Soil moisture and water table elevation are key variables in the survival of riparian-dependent plants. Stream discharge affects soil moisture by saturating soils and recharging the alluvial aquifer during overbank flooding, and stream stage (i.e., surface elevation) directly affects water table elevation.

In dryland ecoregions, trees and dense shrubs exist only near surface water, such as a river, stream, or lake. In the Columbia Plateau, surface streamflow is highly dependent on its source. Rivers and perennial[6] streams generally originate in the adjacent mountainous ecoregions (Omernik and Gallen 1986), and their peak flows, if unaffected by dams, generally occur during fall or winter storms and/or during spring snowmelt (Reidy Liermann et al. 2012). Within the Columbia Basin, the flow source of most streams is groundwater (Reidy Liermann et al. 2012), and consequently, during the hot, dry summer, many streams originating within the ecoregion are intermittent (Daubenmire 1942; Bryce and Omernik 1997). This spatial and temporal variability in local hydrology affects the distribution, abundance, and species of plants in dryland riparian areas.

[6] A perennial stream is one which flows continuously. An ephemeral stream, or section of stream, is one that flows only in direct response to precipitation. It receives no water from springs and no long-continued supply from melting snow or other surface source. An intermittent stream is one that flows during protracted periods when it receives water from some surface or subsurface source, such as melting snow or a spring (Meinzer 1923).

The diversity[7] of riparian climax plant communities in the Columbia Plateau Ecoregion is greater than the diversity in surrounding forested ecoregions. In forested ecoregions, the potential natural vegetation of nearly all riparian areas along rivers and streams is forest. The species composition may vary, but the climax community's structure ultimately attains a closed-canopy of trees, with the upland zone of influence most often dominated by conifer species. In the Columbia Plateau, differences in hydrology and geomorphology manifest substantial site-level differences in composition and structure of riparian vegetation (Hough-Snee et al. 2015). A rudimentary classification system based on overstory conveys obvious differences in vertical structure: tall tree, short tree, tall shrub, shrub, grass-like, grass, and forb (Figure 7.3; Crawford 2003). The main tall tree types have an overstory consisting of Black Cottonwood *Populus trichocarpa*, White Alder *Alnus rhombifolia*, or Quaking Aspen *Populus tremuloides*. Short tree types have an overstory of Thinleaf Alder *Alnus incana*, Water Birch *Betula occidentalis*, or Black Hawthorn *Crataegus douglasii*.[8] Tree vegetation types are usually multi-layered with shrub and herbaceous layers under the tree canopy. Common shrubs are Redosier Dogwood *Cornus sericea*, Common Snowberry *Symphoicarpos albus*, Lewis' Mockorange *Philadelphus lewisii*, and Woods' Rose *Rosa woodsii*. Tall shrub vegetation types include those dominated by willow species (e.g., Yellow *Salix lutea*, Sandbar *S. exigua*) which can be up to 20 ft (6 m) tall.

The structural diversity of riparian vegetation in the Columbia Plateau causes differences in site-level functions. Large wood recruitment, for instance, cannot occur in all riparian areas, and the amount of stream shading will vary considerably due to site-to-site variation in vertical structure.



The most diverse and productive biological communities of the Columbia Plateau are riparian areas/Rex Crawford, WNHP



Nearly all woody vegetation in riparian areas of the Columbia Plateau consists of deciduous shrubs and trees/Scott Fitkin, WDFW

[7] Measures of biological diversity take into account two factors: species richness (i.e., the number of different types) and evenness (i.e., the relative abundance of different types). While the richness of riparian climax plant communities in forested ecoregions may be comparable to that of dryland ecoregions, the relative abundance of different riparian climax plant communities is more even in dryland ecoregions. This results in a greater diversity of types.

[8] Black Hawthorn might also be considered a tall shrub. Crawford (2003) reported Black Hawthorn in riparian areas to be 6 to 20 ft (2 to 6 m) tall, and Daubenmire (1970) found Black Hawthorn up to 27 ft (8 m) tall.

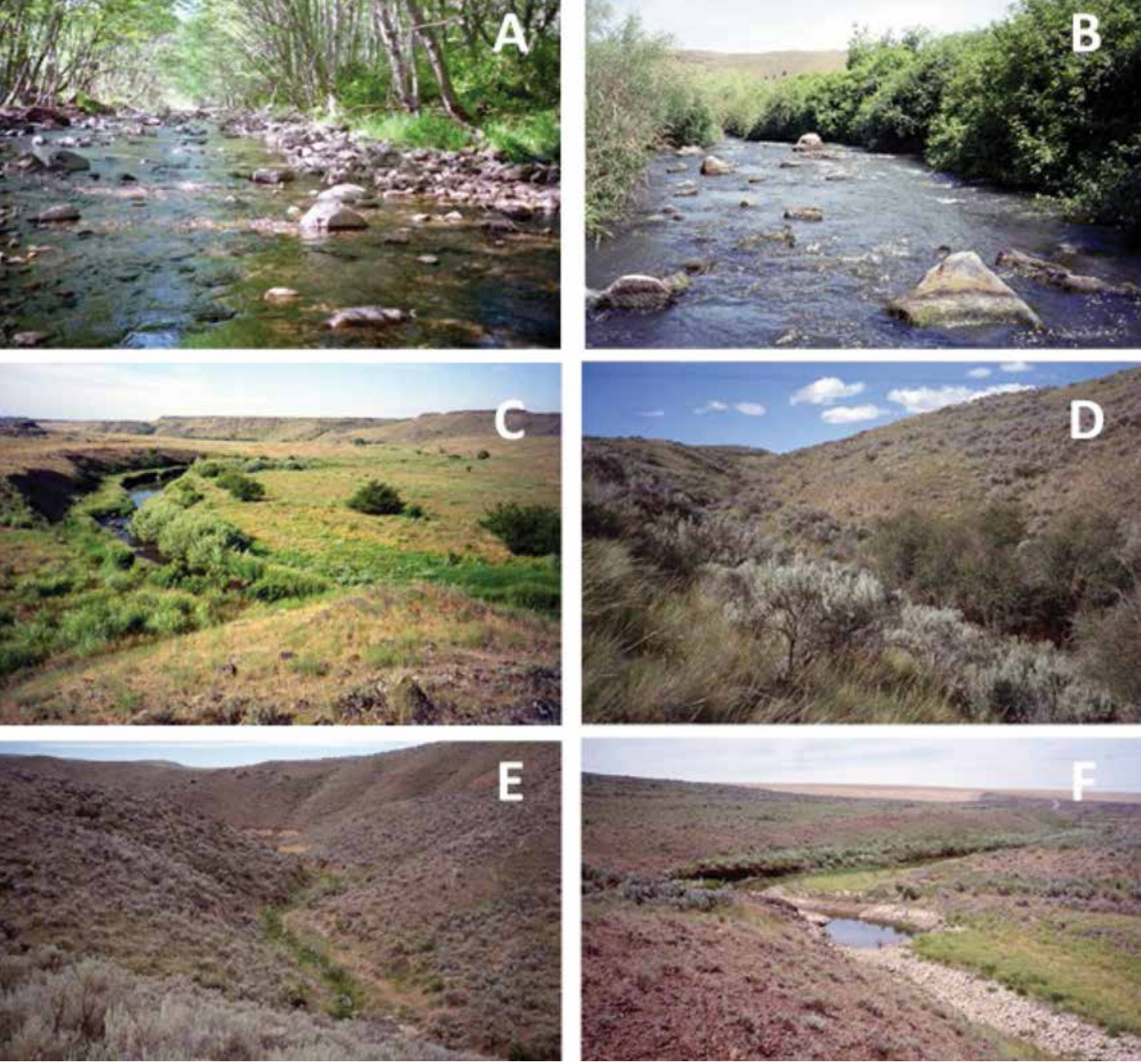


Figure 7.3. Different riparian vegetation structure types: A) tall tree, B) short tree, C) tall shrub, D) shrub on an intermittent stream, E) grass-like, F) forb/Rex Crawford, WNHP

7.2. Historical Context

Because western Washington and Oregon have a substantial amount of national park, wilderness, and roadless areas, the scientific literature contains many descriptions of unmanaged, natural riparian areas within forested ecoregions (e.g., Fonda 1974; Campbell and Franklin 1979; McKee et al. 1982; Sedell and Swanson 1984; Pabst and Spies 1999; Latterell and Naiman 2007; Fox and Bolton 2007). In the Columbia Plateau Ecoregion, however, nearly all riparian areas have been significantly impacted by human land use (grazing, intensive agriculture), resource exploitation (Beaver *Castor canadensis* trapping, timber harvest), water management (dams, diversions, reservoirs), or invasive species (Reed Canary Grass *Phalaris arundinacea*, Russian Olive *Elaeagnus angustifolia*). Daubenmire wrote in 1942, "few typical remnants of the original prairie and desert remain. These relics of the primeval vegetation likewise seem to be heading toward nearly complete extermination within a few years . . ." In short, the conditions of natural riparian areas in the Columbia Plateau Ecoregion are effectively unknown to science.

7.2.1. Beaver Trapping

The first major ecological impacts of Europeans on riparian areas in the Columbia Plateau Ecoregion were due to American Beaver (hereafter Beaver) trapping. In the early 1800s, Beaver hats were very fashionable and in high demand across Europe. The Hudson's Bay Company was determined to profit from that demand, and to obtain Beaver skins it managed a network of forts or trading posts throughout the Pacific Northwest (and throughout western North America). Several were established in and around the Columbia Plateau: Spokane House at the mouth of the Little Spokane River in 1810; Fort Okanagan at the confluence of Okanogan and Columbia rivers in 1811; a temporary post from 1812 to 1813 near confluence of Snake and Clearwater rivers; Fort Nez Perces[9] near the Walla Walla and Columbia rivers' confluence in 1818; and a temporary post at The Dalles from 1829 to 1830 (Meinig 1968). Most Beaver skins traded at these forts were obtained from the surrounding forested ecoregions.

Fort Nez Perces was situated near the center of the Columbia Plateau, and its district, which was delineated by The Dalles to the west, Priest Rapids to the north, and the Deschutes, John Day, and Grande Ronde watersheds to the south, was considered poor "fur country." Nevertheless, between 1827 and 1831 about 1,150 Beaver skins per year were traded at Fort Nez Perces (Meinig 1968). During that period, the number of Beaver skins traded per year at Fort Nez Perces dropped by 50%. Given the locations of trading posts and the high demand for Beaver skins, if Beaver could be trapped profitably in the Columbia Plateau, then they probably were. North of the Columbia Plateau, Beaver were also heavily exploited, and impacts to Beaver populations are indicated by trends in Beaver skins. The number of Beaver skins traded at the Hudson's Bay Company's Fort Colville (founded in 1825) dropped precipitously from 3600 per year in 1826 to 438 per year in 1850 (Johnson and Chance 1974).

The Hudson's Bay Company's annual Snake Country Expeditions operated out of Fort Walla Walla (formerly Fort Nez Perces). One goal of these expeditions was to create a "fur desert" which was intended to discourage America's westward expansion into lands controlled by Great Britain (Lorne 1993). George Simpson, the Hudson's Bay Company's governor at Fort Walla Walla, wrote in 1824, ". . . we have convincing proof that the country is a rich preserve of Beaver and which for

[9] In 1818 the North West Company opened a fur-trading post near the mouth of the Walla Walla River at the current location of Wallula, Washington. Originally called Fort Nez Perces, it was renamed Fort Walla Walla when the North West Company and the Hudson's Bay Company merged in 1821 (Denfeld 2011).

political reasons we should endeavor to destroy as fast as possible" (Ott 2003). In 1825 the trapper Peter Ogden and his party collected 3,577 Beaver skins in the Crooked River watershed, a semi-arid portion of the neighboring Blue Mountains Ecoregion, and on two subsequent expeditions trapped more Beaver in this area (Buckley 1993). During the 1825 expedition, Odgen noted that the Crooked River's tributaries were well lined with willows and aspen. By 1910, if not sooner, Beaver had been eliminated from some tributaries of the Crooked River, and the willow and aspen had vanished (Buckley 1993). The eradication of Beaver from dryland riparian areas is thought to have caused a cascade of adverse effects upon riparian ecosystems that I discuss in Section 7.3.

7.2.2. Open Range Grazing by Livestock

Open-range grazing by livestock was the next major ecological impact of Europeans in the Columbia Plateau Ecoregion. Around 1730, Native Americans on the Columbia Plateau acquired horses descended from those brought by Spanish explorers (Carlson 1940). In 1805, Lewis and Clark saw about 700 horses in one Indian village and thousands more in the nearby hills (Galbraith and Anderson 1971). Daubenmire (1970) believed that while most villages were on rivers, the impacts to riparian vegetation by horses were probably not extensive. A few cattle were brought to the Okanogan Valley in 1825 and to the Walla Walla Valley in 1834 (Carlson 1940). By 1855, roughly 200,000 cattle inhabited the Columbia Plateau of Washington (Daubenmire 1970). Sheep herding developed in the 1880s (Daubenmire 1970), and great numbers of sheep were brought to eastern Washington in 1892 (Galbraith and Anderson 1971). By the late 1800s, damage to rangeland from overgrazing was evident. Based on his 1893 expedition from Spokane to Steven's Pass, the botanist John Leiberg wrote, "We will never know the complete flora of these regions. Sheep and cattle are rapidly destroying the native plants and by the time private explorations reach these regions the flora will have been totally exterminated by such agencies" (as cited in Mack 1988; Weddell 2001).

Open-range management of livestock invariably results in excessive utilization of riparian areas (Ohmart 1996), and the destructive impacts of unmanaged grazing in riparian areas are well-documented (Kauffman and Krueger 1984; Ohmart 1996, Belsky et al. 1999). Riparian areas in arid and semi-arid lands of the western United States cover only 1 to 2% of land area, but produce 20% of available forage and nearly 80% of forage actually consumed by cattle (Fisher 1995). Therefore, it is reasonable to assume that the damage observed by Leiberg was greatest in riparian areas.

Restoration projects can indicate the density of woody plants that existed historically in riparian areas prior to intensive livestock grazing. For example, two years after the cessation of grazing within riparian areas in northeastern Oregon, the mean crown volume of willows and Thinleaf Alder tripled in size and that of Black Cottonwood increased nine-fold (Case and Kauffman 1997). Furthermore, shrub density increased by 50%. One possible reason for the severe impacts of grazing in the Columbia Plateau is that, unlike the Great Plains, Bison (*Bison bison*) have been rare or absent from the Columbia Plateau for close to 10,000 years (Jones 2000). According to Daubenmire (1970) and also Mack and Thompson (1982), ungulates played no significant role in the evolution of plant species in steppe and shrub-steppe communities of the Columbia Plateau, and consequently present-day vegetation cannot endure intensive grazing by livestock.

The impacts of both Beaver trapping and open-range livestock grazing may have acted synergistically to degrade riparian areas. Baker et al. (2005) suggest that Beaver and willow (*Salix* spp.) are mutualists because willow is an important food source for Beaver, and Beaver create environmental conditions suitable

as willow habitat. Baker et al. (2005) believed this relationship can persist indefinitely within a given area. They also speculated that heavy browsing by native ungulates or livestock disrupt the Beaver-willow mutualism, thus leading to degradation of the riparian ecosystem. Ohmart (1996), based on personal observation, suggested that overgrazing by livestock causes an imbalance in the Beaver-vegetation relationship that leads to collapse of riparian forests. A similar relationship has also been observed in Yellowstone National Park (Beschta and Ripple 2016) where decades of intensive grazing by Elk *Cervus canadensis* during the absence of Wolves *Canis lupus* resulted in riparian plant communities that could no longer support Beaver. The reintroduction of Wolves has led to a recovery of Beaver in Yellowstone (Beschta and Ripple 2016).

Today in the Columbia Plateau Ecoregion, the most severe impacts from grazing are caused by wild or feral horses (hereafter collectively known as wild horses). Until the mid-1900s, wild horses inhabited open rangelands in various parts of the Columbia Plateau. Today wild horses are confined to Native American reservations where the number of wild horses has fluctuated greatly over the past 140 years. The reservation of the Yakama Nation, for instance, supported roughly 16,000 horses in 1878, but a round up in 1957 left 300 horses on the reservation (Adams 2004). By 2010, the number of horses had rebounded to 12,000 (YN 2010), but the current carrying capacity of the Yakama Nation's reservation is only about 1,000 horses (Mapes 2010). Consequently, wild horses have destroyed rangelands, cultural resources, and wildlife habitats, including riparian areas (NTHC, no date). Wild horse populations also exceeded the carrying capacities of the Colville and Umatilla reservations (AP 2012; Tribal Tribune 2013). Effective management of wild horses on Native American reservations has been hampered by continual controversy regarding the most practical and ethical means of reducing their population sizes.

7.2.3. Wood Harvest and Wheat

The Donation Land Claim Act of 1850 and Homestead Act in 1862 were major impetuses for settlement of Oregon and Washington states. Settlers needed wood for fuel and construction. On the Columbia Plateau the closest source of wood, and in some places the only practical source, was riparian areas. Historians have little information on wood harvest in riparian areas by early settlers on the Columbia Plateau, however, the practices of pioneers and settlers on the Great Plains, as described by West and Ruark (2004), are likely to be similar to their practices on the Columbia Plateau. West and Ruark (2004) state that pioneers on their way west stripped virtually all trees from the Platte River valley, that riparian areas on the Great Plains were an important source of winter fuel for settlers, and that by 1900 most of the trees in riparian areas of the Great Plains had been harvested. Daubenmire (1970) speculated that Black Cottonwood, the largest tree species in the Columbia Plateau, was much more abundant before the arrival of settlers.

Impacts of Beaver trapping and open-range livestock grazing may have acted synergistically to degrade riparian areas. Baker et al. (2005) suggest that Beaver and willow are mutualists because willow is an important food source for Beaver, and Beaver create environmental conditions suitable as willow habitat.

River commerce on the Columbia and Snake rivers may have also impacted riparian areas. By 1859, steamboats were travelling upriver as far as Wallula, Washington and could reach Lewiston, Idaho at high water (Meinig 1968, cited in Evans 1989). HIstorians do not know how much wood was burned to power steamboats in the Columbia Basin, but estimates from other western watersheds suggest severe impacts to riparian forests along the Columbia and Snake. On the upper Missouri River in Montana, for instance, riparian forests along its banks were denuded of usable trees by the turn of the century (Evans 1989).

The soils and climate of the Palouse Hills subregion are suitable for dryland wheat agriculture. Consequently, the next major impact to riparian areas was converting native vegetation to wheat. The first wheat was planted in 1877, by 1895 most of the tillable land in the subregion had been plowed (Kaiser 1961), and during the 1970s industrial agriculture expedited the destruction of the last refugia for native plant communities (Black et al. 1998). Agriculture in the Palouse Hills had four major impacts on riparian areas, which were all poorly documented: 1) fields were plowed to the very edge of streambanks, thereby destroying riparian vegetation, 2) many ephemeral channels were plowed through and filled (Kaiser 1961; Bryce and Omernik 1997), 3) perennial and intermittent stream channels became deeply incised (Rockie 1939), and 4) some channels were filled with sediment from soil erosion (Rockie 1939; Bryce and Omernik 1997). Rockie (1939) reported a Nez Percé Indian telling him that some dry channels in the Palouse Hills were once perennial streams containing trout. According to Bryce and Omernik (1997), the original channel substrate, riparian vegetation, and flow regime (i.e., perennial or intermittent) are impossible to know in areas of intensive agriculture.



The least arid subregions of the Columbia Plateau support productive grasslands/Alan Bauer

7.2.4. Large-scale Irrigation Projects

Across the Columbia Plateau, the most obvious human impacts to native habitat types, including riparian areas, are those associated with irrigation projects. The U.S. Bureau of Reclamation manages two major projects on the Columbia Plateau, the Yakima and Columbia Basin, which service about 1,135,000 acres (459,318 ha) of farmland (USBR 2017a; 2017b). Another 37,000 acres (14,973 ha) are irrigated with water impounded by dams on the Snake River (USACE 2002). All 1.17 million acres (473,482 ha) of irrigated farmland were once shrub-steppe or steppe vegetation. However, these projects did not record how many acres of riparian area have been lost because ephemeral or intermittent stream channels were filled for agriculture or converted to irrigation ditches.

Construction of the Yakima Project began in 1906, and the last of 11 dams on the Yakima River or its tributaries was completed in 1939 (USBR 2017a). The Yakima Project's biggest impacts to riparian areas are along the Naches and Yakima rivers. Storage reservoirs and water diversions located upstream have truncated the rivers' natural hydrographs. This has substantially reduced river-floodplain interactions, such as inundation and lateral channel migration, which in turn have led to channel simplification and degraded aquatic and riparian habitats (Snyder and Stanford 2001; YSPB 2004).

Construction of the Columbia Basin Project began in 1933 with Grand Coulee Dam, and the first irrigation water was delivered in 1952 (USBR 2017b). The Columbia Basin Project includes a network of canals, drains, and wasteways over 5,800 miles (9,334 km) long. The reservoir behind Grand Coulee Dam, Lake Roosevelt, inundated roughly 84 miles (135 km) of riparian habitat within the Columbia Plateau Ecoregion along the Columbia, Spokane, and Sanpoil rivers.[10] Roughly 460 miles (740 km) of the Columbia River lie within the Columbia Plateau Ecoregion, but only 51 miles (82 km) of riparian habitat, the Hanford Reach, have not been inundated by reservoirs. When the dams were built, there was apparently some hope that vegetation would re-establish along new reservoir margins, but water level fluctuations appear to be too extreme for most plants to tolerate (Evans 1989). The other major impacts to riparian areas from the Columbia Basin Project are dramatic changes in hydrology. The groundwater table around lower Crab Creek, for instance, has risen between 50 and 150 ft (15 and 46 m) since 1952. Furthermore, the formerly intermittent lower Crab Creek is now perennial with four to five times the flow that occurred prior to irrigation (KWA 2004), and, as a consequence, willow species, which are adapted to the natural hydrologic regime, no longer regenerate along lower Crab Creek (Ortolano and Cushing 2000). In contrast, due to groundwater withdrawals, the groundwater table around upper Crab Creek (the Odessa subarea) has fallen 150 ft (46 m) (KWA 2004). I found no records on how the water table changes may have affected stream flow in upper Crab Creek.

Decades of hydrological alteration by dams and water diversions have altered vegetation composition and structure of riparian areas. Black Cottonwood and willow are successional pioneers that require barren sediments of disturbed alluvial floodplains for seedling germination (Patten 1998). Such conditions are produced by floods, but dams reduce peak flows and the erosive forces that scour sediments. Furthermore, the survival and growth of Black Cottonwood seedlings is highly dependent on water table elevation and its seasonal rate of change (Braatne et al. 1996). If the water table declines more rapidly than seedling root growth, then seedlings die. Braatne et al. (2007), for example, found that dams on the Yakima River created

[10] Estimated with Google Earth. Distance estimated along Spokane River comports with that reported by Ortolano and Cushing (2000).

hydrological conditions unsuitable for Black Cottonwood seedlings. They studied river reaches near Cle Elum, Union Gap, and Wapato and found: 1) no seedlings in any reaches, 2) Black Cottonwood stands less than 25 years old were extremely limited, 3) riparian areas were dominated by older age classes, and 4) altered hydrology promoted invasion of the floodplain by exotic tree species such as Silver Maple *Acer saccharinum*, Norway Maple *Acer platanoides*, and Chinese Elm *Ulmus parvifolia*. Hence, one could confidently infer that historical conditions have been altered by regulated flows. If artificial flow regimes are not changed, then as older individuals senesce and die, cottonwoods may be eliminated from some sections of the Yakima River. This would have adverse effects on multiple riparian area functions: streambank stability, shading, large wood recruitment, and detrital nutrients. Exotic tree species currently found along the Yakima River cannot provide the same ecological functions as Black Cottonwood because they cannot establish themselves in the barren, saturated sediments of recently disturbed floodplains.

Dams have also altered the flow of wood through watersheds. Historically, wood was transported from forested headwaters to dryland reaches of rivers and streams. This process is known to have occurred in other semi-arid and arid regions of the United States.

"We will never know the complete flora of these regions. Sheep and cattle are rapidly destroying the native plants and by the time private explorations reach these regions the flora will have been totally exterminated by such agencies."

- Botanist John Leiberg, 1893

Minckley and Rinne (1985) present historical evidence for the movement of large wood in desert rivers of the American southwest: wood originated in forested headwaters, moved sporadically through desert riparian areas during flood events, and was ultimately deposited at the mouth of the Colorado River in Mexico. Minckley and Rinne (1985) identified interception of large wood by dams as a major cause of large wood reduction in semi-arid and arid river basins. At artificial reservoirs in eastern Washington, such as Keechelus, Kachess, Cle Elum, Easton, Bumping, Clear, and Rimrock lakes, large wood that could potentially interfere with dam operations is removed and burned (W. Meyer, Washington Department of Fish and Wildlife, personal communication; B. Renfrow, Washington Department of Fish and Wildlife, personal communication). Large wood in dryland sections of the Wenatchee and Okanogan rivers may be effected in this way as well. How wood management at dams and smaller water diversions affects in-stream large wood in eastern Washington has not been investigated.

7.2.5. Invasive Non-native Plants

An ongoing historical anthropogenic impact is the introduction of exotic invasive plant species. After their botanical survey of the Columbia Plateau in 1893, Sandberg and Leiberg were not troubled by the meager abundance of exotic species at that time (Mack 1988), however, by 1929 about 200 exotic species were known to exist on the plateau (Mack 1988). Riparian areas in dryland landscapes are more vulnerable to invasion by exotic plant species than adjacent upland areas (Loope et al. 1988; Hood and Naiman 2000), and invasive plants in riparian areas can impact a variety of ecological processes: hydrology, sediment dynamics, nutrient dynamics, and species competition. Two invasive species of particular concern are Reed Canary Grass and Russian Olive.[11]

11 Other invasive species of concern in the Columbia Plateau Ecoregion are Crack Willow *Salix fragilis*, Yellow Flag Iris *Iris pseudacorus*, and Purple Loosestrife *Lythrum salicaria*.

Reed Canary Grass occurs as both exotic and indigenous strains (Tu 2006). The European cultivar has been present in the Pacific Northwest since the 1880s (Stannard and Crowder 2001), and, as of 2016, it is found in all Washington counties except Douglas (WSDA 2016). Reed Canary Grass forms dense stands that can exclude all other plant species, and such stands exhibit substantially higher transpiration per unit ground surface area than other species (Gebauer et al. 2015). This could alter water availability in riparian areas. Reed Canary Grass also has higher roughness values than native sedge species (Martinez and McDowell 2016). This could lead to greater sediment deposition and channel narrowing.

As of 2016, Russian Olive is found in most counties east of the Cascade crest and is most common in Grant County (WSDA 2016). In the late 1800s, it was introduced into the Pacific Northwest as an ornamental plant (Giblin 2006), but the species did not become prominent outside cultivated areas until two to five decades later, depending on location. Unlike many tree and shrub species in dryland riparian areas, Russian Olive does not require disturbed soils for germination. Hence, it can grow on sites where woody vegetation would not naturally occur (Katz and Shafroth 2003). It is also shade tolerant, and consequently, Russian Olive can establish beneath the canopy of native riparian trees or shrubs and compete with them for resources. Russian Olive exhibits about two times higher transpiration per unit basal area than cottonwood trees (Hultine and Bush 2011). This could alter water availability in riparian areas. The species is a nitrogen fixer that adds nitrogen to the soil. Tuttle et al. (2016) found that stands of Russian Olive had higher exotic plant ground cover than stands of native tree species, and they believed that the difference was due to higher available soil nitrogen that benefited fast growing exotics plants. Finally, according to Lesica and Miles (1999), Beaver foraging behavior indicates that Russian Olive is much less palatable than native cottonwood. They found that 77% of cottonwood trees along a river in Montana were damaged by Beaver but only 22% of Russian Olive trees were damaged. If Russian Olive replaces native cottonwood, then Beaver population density could be adversely affected.

7.2.6. Value of a Historical Perspective

Current scientific understanding of riparian ecosystems in the Columbia Plateau Ecoregion is mostly based on present-day conditions, which are unlikely to accurately represent historical composition and structure. History indicates that past human impacts in the Columbia Plateau may have erased fully functioning riparian ecosystems from many watersheds. For example, records of the U.S. Army cavalry at Fort Simcoe on the Yakama Indian Reservation from the 1850s describe small valleys with broad floodplains dissected by multi-threaded stream channels that are absent today. These valleys—such as the Wenas, Ahtanum, and Cowiche—historically contained a network of streams, wetlands, and Beaver ponds that supported extensive groves of willow, Redosier Dogwood, Black Cottonwood, and aspen. Cattle were said to be lost for weeks in these tangles (P. Harvester, Washington Department of Fish and Wildlife, personal communication). These same streams are now reduced to a single, incised channel with minimal riparian vegetation. The loss of riparian habitats indicated by the Fort Simcoe records is very likely to have occurred in other parts of the Columbia Plateau.

Rivers and streams of the Columbia Plateau Ecoregion have been degraded by a variety of human activities. This has adversely affected anadromous salmon—their populations are threatened with extinction and fisheries produce a small fraction of historical harvest. In response, salmon habitat restoration projects are occurring throughout the Columbia Plateau. Habitat restoration requires ecological reference information to determine site-level restoration potential, establish desired conditions, and formulate measures of success

(White and Walker 1997). Ecological reference information is generally based on historical conditions, natural areas, or minimally disturbed sites (White and Walker 1997; Stoddard et al. 2006; Higgs et al. 2014). In the Columbia Plateau Ecoregion, which lacks national parks, wilderness, or roadless areas containing natural reference sites, historical information may be the only basis for reference conditions (Wohl 2005).

Because the Columbia Plateau lacks undisturbed watersheds, even small ones, ecologists have a poor understanding of the composition, structure, and functions of natural riparian ecosystems. Historical reconstruction using journals of early explorers and naturalists, General Land Office survey notes, and historical drawings or photos (Figure 7.4) are ways to develop qualitative descriptions of riparian plant

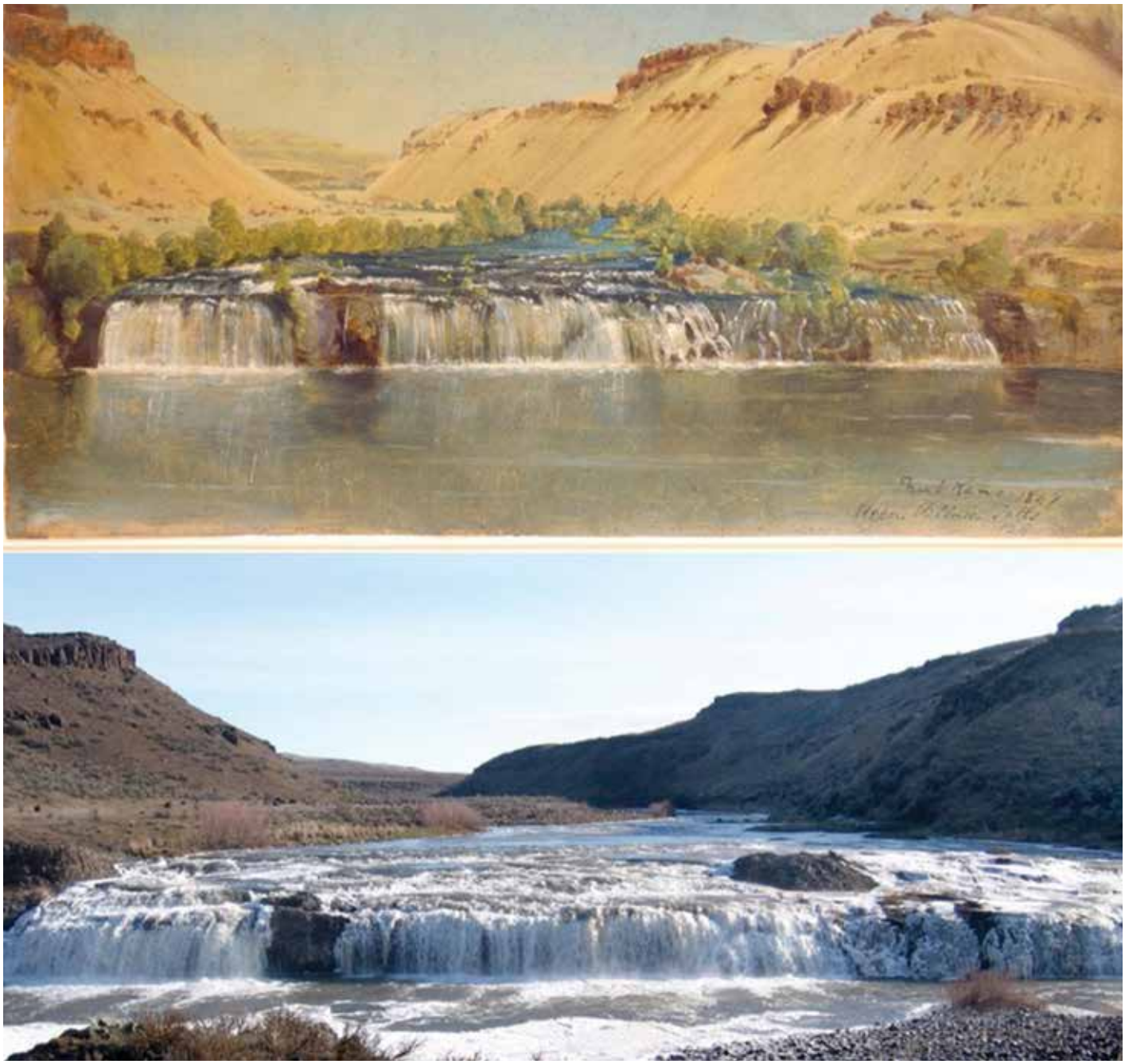


Figure 7.4. Historical drawings and paintings can provide invaluable information for riparian area restoration. A 1847 painting by Paul Kane of Upper Palouse Falls (top) shows extensive, uninterrupted small tree or tall shrub vegetation along the river banks. A recent photo by Jack Nisbet (bottom) although taken in winter, shows large gaps in small tree or tall shrub vegetation along the banks.

communities (McAllister 2008). Much work needs to be done on deducing the likely historical conditions of riparian areas in the Columbia Plateau. Studies of historical conditions in the Columbia Plateau, however, must be cognizant of one important caveat. If hydrology of a riparian area has been significantly altered by human activity, then the vegetation that site supported historically may have no relationship to the vegetation the site is capable of supporting now. Irrigation systems have altered hydrology in riparian areas throughout the Columbia Plateau, making some drier and others wetter. At such places, information on historical vegetation will often be of little value in establishing desired future conditions for restoration.

7.3. Beaver

Beaver may play an essential role in the restoration and future conservation of dryland riparian areas (Dremmer and Beschta 2008; Pollock et al. 2014). The ecosystem benefits of Beaver in dryland riparian areas have been known for over 80 years. Scheffer (1938) reported that in 1936 the Soil Conservation Service transplanted 10 Beaver to the Ahtanum Creek watershed for the purposes of increasing water storage. The Beaver constructed several large dams, one of which was 90 ft (27 m) long, 10 ft (3 m) high, and stored 5 acre-feet (6,167 m^3) of water. Scheffer (1938) implied that the dams reduced downstream flood damage and increased summer stream flows for irrigation. Finley (1937) reported the opposite situation for Silver Creek in eastern Oregon. Two trappers removed 600 Beaver in one winter. As a result, the Beaver ponds "disappeared," the water table lowered, grassy meadows "died out" and streams containing trout went dry.

The observations of Scheffer (1938) and Finley (1937) are anecdotes. More rigorous scientific research into the connections between Beaver and riparian ecosystems have found that Beaver have numerous positive effects.



Beaver viewed with night vision camera/Ned Pittman, WDFW

Beaver dams store organic nutrients and large quantities of sediment, reduce channel incision, remove excess nutrients from water, increase surface water storage and base flows, reduce peak flows, increase groundwater recharge, raise water table elevations, expand the area of riparian vegetation, and increase the salmonid habitat capacity of small streams (Naiman et al. 1988; Pollock et al. 2003; Gibson and Olden 2014). For dryland riparian areas where the extent of riparian vegetation depends on shallow groundwater, the hydrologic and geomorphic effects of Beaver dams may be necessary for the mere existence of a riparian zone at many sites. In dryland riparian areas, most ecosystem functions occur within the riparian zone.

The dramatic effects of Beaver on hydrology was shown by Westbrook et al. (2006), a multi-year study of two Beavers dams on a fourth order stream running through a dry meadow in the Rocky Mountains of Colorado. One dam diverted over half and the other diverted 70% of the stream onto the floodplain and terrace. Both dams increased substantially the area flooded by annual peak flows. One dam caused the equivalent of a 20-year flood over 30 acres (12 ha) of the valley floor during a peak flow event with a 1.6-year recurrence interval, and the other dam caused the equivalent of a 200-year flood over 21 acres (8 ha) of the valley floor during a peak flow event with a 1-year recurrence interval. One of the dams

studied by Westbrook et al. (2006) was breached by high flows. Westbrook et al. (2011) subsequently found that overbank flooding caused by that dam had deposited nutrient-rich sediments in some areas and scoured soils in other areas downstream of the dam site. These bare sediments were colonized by willow and aspen seedlings, which may eventually establish riparian plant communities.

In sagebrush steppe of Wyoming, Cooke and Zach (2008) found that the number of Beaver dams was positively associated with riparian zone width, riparian shrub height and percent cover by emergent wetland vegetation. These responses can at least partly be explained by changes in hydrology caused by Beaver dams.

Eradication of Beaver has been implicated in stream channel incision and desertification of riparian zones that has occurred throughout arid and semi-arid ecoregions of western North American (Parker et al. 1985; Pollock et al. 2003), including the Columbia Plateau (Pollock et al. 2007). According to Pollock et al. (2007), the exact mechanism that caused widespread incision of streambeds remains uncertain, however, incision almost invariably coincided with widespread trapping of Beaver and the onset of intensive livestock grazing. Channel incision, whatever the ultimate cause, occurs through an imbalance between sediment deposition and sediment mobilization. Assuming no changes in upstream sediment sources, incision is usually attributed to an increase in erosive forces or a decrease in channel resistance to erosive forces. The former can be caused by an increase in runoff, both can be caused by a decrease in channel roughness, and the latter can also be caused by loss of streamside vegetation. Therefore, channel incision can be prevented by controlling runoff caused by upstream land uses, maintaining roughness elements such as large wood, and retaining riparian vegetation. For many dryland riparian areas, Beaver are essential for the latter two. Beaver dams act as massive roughness elements that reduce flow velocities, thereby reducing hydraulic forces that cause erosion. Reducing flow velocities also results in sediment deposition, which raises the streambed elevation and creates microsites suitable for germination of riparian plants.

Several studies have suggested that reintroduction of Beaver can reverse channel incision (Pollock et al. 2007; Beechie et al. 2008), primarily by restoring sediment retention processes in the channel (Pollock et al. 2014). Sediment aggradation caused by Beaver dams fills the incision and raises the streambed elevation. As the bed elevation increases, hydrologic connectivity between the channel and former floodplain is improved both by raising the water table elevation and by reducing bank height, which allows overbank flooding to recharge the floodplain's alluvial aquifer. Increased soil moisture allows riparian plant species vegetation to re-establish. Development of a well-vegetated riparian zone provides Beaver with more food and building materials, enabling construction of more dams (Pollock et al. 2014).

The aforementioned impacts of Beaver on aquatic and riparian ecosystems are immensely beneficial to fish; however, Beaver may also have detrimental effects on fish. Sediment deposition in Beaver ponds may harm spawning beds, and Beaver dams can block upstream and downstream fish movements (Pollock et al. 2003). Water temperature in Beaver ponds can be warmer than nearby flowing waters, especially where the stream is largely under a closed canopy forest (Robison et al. 1999), but in areas with open or no canopy (such as dryland riparian areas), water temperatures tend to be similar between Beaver ponds and unimpounded reaches (Talabere 2002). Beaver ponds have also been found to provide productive habitats for non-native fish (Gibson et al. 2015) that may compete with or prey upon native fish.

7.4. Ecosystem Functions

FEMAT (1993) identified five key functions of riparian ecosystems that are important for fish habitats: streambank integrity affected by plant roots, litter fall that provides detrital nutrients, shading to limit stream temperatures, large wood recruitment, and pollution removal. Most of what is known about these key riparian functions was discovered through research conducted in forested ecoregions, in particular, the mesic forest ecoregions of the Pacific Northwest (e.g., Salo and Cundy 1987; Naiman and Bilby 1998; Richardson et al. 2005). Much of what is known about riparian areas in forested ecoregions is transferable to riparian areas in the Columbia Plateau, and therefore, where appropriate I repeat some of the knowledge and principles elucidated in chapters 1 through 6. However, as will become apparent, large gaps in knowledge remain.

In addition to FEMAT's key ecological functions, a sixth key function occurs in dryland riparian areas– alluvial water storage. Alluvial water storage occurs in riparian areas of all ecoregions, but it may be especially important in dryland ecoregions.

7.4.1. Streambank Stability

Streambank stability refers to a bank's resistance to change and its resilience after change (Bohn 1986). Streambank stability is the opposite of streambank erosion. Streambank erosion is commonly misinterpreted as a sign of adverse human impacts to riparian ecosystems, and it can be. However, a channel in dynamic equilibrium simultaneously exhibits both stable and unstable banks (Wohl et al. 2015). Streambank erosion is integral to a watershed's fluvial disturbance regime and necessary for long-term ecological sustainability (Florsheim et al. 2008) because the opposing processes of bank stability and bank erosion maintain the diversity of aquatic and riparian habitats within a watershed. Bank stability is also associated with overhanging/undercut banks which shade the water and provide cover for fish (Bohn 1986; Ohmart 1996).

The stability of streambanks is influenced by soil characteristics, groundwater, and vegetation. For the purposes of riparian area management, I focus on vegetation. Rooted vegetation is essential for streambank stability (Hupp and Osterkamp 1996; Gurnell 2014). Plants are said to provide "root strength" or "root reinforcement" along streambanks (FEMAT 1993; Pollen-Bankhead and Simon 2010). Soil is generally strong in compression, but weak in tension. Woody and herbaceous plant roots are strong in tension, but weak in compression. Consequently, the root-permeated soil of streambanks behaves as a composite material with enhanced strength (Simon and Collision 2002). Dense root networks also physically restrain or bind soil particles. Exposed roots on the bank surface increase channel roughness which dampens stream flow velocities, thereby reducing fluvial erosion (Griffin et al. 2005). Reduction of stream velocities by roots may also cause sediment deposition, which further stabilizes streambanks.

The stability provided by roots is species dependent (Polvi et al. 2014). Simon et al. (2006), for instance, found that Lemmon's Willow *Salix lemmonii* provided 10 times more root reinforcement of streambanks than Lodgepole Pine *Pinus contorta.* The difference was due to the greater root density and larger root area of Lemmon's Willow. On the southeastern slope of the Cascades Range in Washington, Liquori and Jackson (2001) found that different riparian plant communities manifested differences in bank erosion and channel form. They identified two types of riparian plant communities: a scrub-shrub community that exists within an open-canopy Ponderosa Pine *Pinus ponderosa* forest, and a dense, closed-canopy fir forest. The

Ponderosa Pine forest is maintained by regular wildfires while the fir forest was created by fire suppression. The scrub-shrub community was associated with stream channels that had less bank erosion, lower width-to-depth ratios, more pools, and more undercut banks than channels within the fir forest community. The channel morphology of scrub-shrub riparian communities also resulted in slightly lower summer stream temperatures. In the semi-arid Sierra Nevada Mountains, Micheli and Kirchner (2002) found that riparian areas comprised of sedges and/or rushes had banks five times stronger than riparian areas comprised of sagebrush and grasses, and that bank strength was correlated with the root mass to soil mass ratio. Sedges and/or rushes enabled the formation of undercut banks, and increased the width of an undercut bank by a factor of 10.

The composition and structure of riparian vegetation affects channel morphology which, in turn, affects riparian vegetation (Corenblit et al. 2007; Osterkamp and Hupp 2010). Toledo and Kauffman (2001) observed the effects of one such interactive feedback loop in semi-arid northeastern Oregon. Upland plants were found along incised channels and wetland-obligate plants (mostly sedges) were found along unincised channels, which had two times greater root biomass than incised channels. Along unincised channels, approximately 40% of root biomass was deeper than 8 in (20 cm) in the soil, but along incised channels less than 25% of root biomass was below 8 in (20 cm).

Compared to forested ecoregions, there is less large woody debris, and woody debris play a much smaller role in the fluvial processes of dryland river and streams.

Denser roots at deeper soil depths result in a larger volume of reinforced soil. According to Toledo and Kauffman (2001), the severely degraded conditions at their incised sites were caused by a positive feedback loop in which an initial channel incision led to a lower water table. The resulting reduction in soil moisture altered riparian vegetation which shifted to an upland plant community with reduced root mass. Bank erosion subsequently increased which led to channel widening and further incision.

The studies reviewed thus far have reported on the bank strength provided by hydric or wetland-obligate shrubs and herbaceous plants (sedges and rushes) in dryland riparian areas. Trees are also important for bank stability. Rood et al. (2015) studied the amount of bank erosion after major floods along Elk River in British Columbia. They found that floodplain locations occupied by grassland or small shrubs exhibited substantial erosion (>75 m of bank erosion) after major floods but locations occupied by forest, including Black Cottonwood stands, exhibited much less change (<15 m of bank erosion). Rood et al. (2015) concluded that "only big plants can resist big flows," and that other studies which demonstrated that grasses or shrubs are more erosion resistant had observed only low energy flows in smaller or shallower gradient streams.

Streambanks along incised channels of arid or semi-arid regions are particularly sensitive to changes in soil moisture. Much of the bank may be above the water table, and hence soils are unsaturated. Matric[12] suction above the water table, enhanced by transpiration of riparian vegetation, has the effect of increasing the apparent soil cohesion, and decreases in soil strength due to a loss of suction are a leading cause of bank failures in incised channels (Simon and Collison 2002).

12 Matric suction is a negative pore pressure that induces water to flow in unsaturated soil. It results from the combined effects of adsorption and capillarity of the soil matrix. Water flows from a soil with low matric suction (a wet soil) to soil with a high matric suction (a dry soil).

7.4.2. Wood

The main role of wood in aquatic ecosystems is roughness element (Bisson et al. 1987). Roughness elements are obstacles in a channel that deflect flow and change its velocity. The size, shape, and strength of large wood make it very effective at redirecting hydraulic forces and the flow of materials, such as sediment and fine organic matter. In-stream large wood increases hydraulic complexity, i.e., creates a wider range of flow velocities, which causes pool formation, streambed scour, sediment deposition, and channel migration. The net result is a diversity of aquatic habitat types.

I could find no studies conducted in the Columbia Plateau describing the density of trees or their spatial distribution in riparian areas. However, riparian areas in the Columbia Plateau certainly contain less large wood than forested ecoregions, even historically, for three reasons. First, trees are smaller in the Columbia Plateau than in forested ecoregions of Washington. Canopy dominant trees in old-growth riparian ecosystems of mesic forested ecoregions can be well over 48 in (122 cm) diameter at breast height (dbh) and over 150 ft (46 m) tall, but the maximum size of Black Cottonwood in the Columbia Plateau is much smaller (see below). Second, trees are fewer in the Columbia Plateau because in the Columbia Plateau trees inhabit the riparian zone but often do not inhabit the zone of influence. In forested ecoregions, trees inhabit both zones. Third, along some streams, particularly in the most arid subregions of the Columbia Plateau, even the riparian zone is unsuitable for tree species. At such sites, the riparian zone consists of tall shrub, shrub, grass-like, grass, and forb vegetation types. Therefore, compared to forested ecoregions, there is less large woody debris, and woody debris plays a much smaller role in the fluvial processes of dryland river and streams.

Knowledge regarding wood in aquatic and riparian ecosystems of Columbia Plateau is extremely limited at present, nevertheless, the historical abundance of woody plants in riparian areas is thought to have been much greater than it is today (Wissmar et al. 1994; Kauffman et al. 1997; Wissmar 2004). Riparian areas in the Columbia Plateau are inhabited by a variety of woody plants–Black Cottonwood, Quaking Aspen, White Alder, Thinleaf Alder, Water Birch, Black Hawthorn, and Yellow Willow (Crawford 2003). Conifer trees, including Ponderosa Pine and Douglas-fir *Pseudotsuga menziesii,* are widely scattered in eastern Washington riparian areas and were likely more common historically than at present. They are currently restricted to canyons or valleys with steep rocky walls along mid- to high-gradient streams where they are inaccessible to harvest and where microclimates are conducive to supporting trees (Evans 1989). The main causes of reduced wood are explained in Section 7.2.

The size and quantity of wood recruited to a stream depends on the size and density of woody plants, their distances from the channel, and the recruitment processes that deliver wood to the channel. Only a few tree species in riparian areas of the Columbia Plateau qualify as large wood, which is commonly defined as greater than 4 in (10 cm) in diameter and greater than 6 ft (2 m) in length.[13] Black Cottonwood is the largest riparian tree species in the Columbia Plateau Ecoregion and the largest deciduous species in western North America. The species has a typical lifespan of 100 to 200 years (Braatne et al. 1996), and can attain a dbh of about 30 to 35 in (76 to 90 cm) in the Pacific Northwest (Franklin and Dyness 1988), but sizes are smaller in the Columbia Plateau. The interior of British Columbia is less productive than the province's coastal ecoregion, and in the interior, Black Cottonwood attain an average size of 15 in (38 cm) dbh and 52 ft (16 m) tall at age 80 years, and 26 in (66 cm) dbh and 70 ft (21 m) tall at age 150 years (Roe 1958). Other tree species that might also

[13] Large wood is also known as large woody debris (LWD) or coarse woody debris. There is no universal definition of LWD. Another common definition is greater than 4 in (10 cm) in diameter and greater than 3 ft (1 m) in length. Small wood is also known as small woody debris or fine woody debris.



Large trees in riparian areas are a major source of instream large woody debris/Jim Cummins , WDFW

function as large wood are Quaking Aspen, White Alder, and Peachleaf Willow *Salix amygdaloides*. Daubenmire (1970) reported that Quaking Aspen and White Alder grow to about 8 and 23 in (10 and 58 cm) dbh, respectively, in riparian areas of the Columbia Plateau.

Substantial amounts of small wood may be recruited to and stored in stream channels through Beaver activity. Most dryland riparian areas lack large trees, but in dryland riparian areas Beaver create large roughness elements from small wood that mimic some effects of large wood (see section 7.3). In effect, Beaver convert small wood to large wood. Beaver dams consist mainly of mud and small wood. Published information on small wood sizes in dams of North American Beaver is lacking. However, Beaver most often forage on trees ranging from 1.2 to 3.2 in (3 to 8 cm) in diameter (Collen and Gibson 2001), and a large proportion of woody stems used as food are also used in dam construction (Barnes and Mallik 1996). In Maryland, Blersch and Kangas (2014) found that 98% of sticks (i.e., small wood) in a Beaver dam were less than 4 in (10 cm) in diameter and that 46% of those sticks were probably placed in the dam by Beaver. The other 54% of sticks in the dam were due to passive capture of transported wood.

Large wood recruitment processes in riparian areas of the Columbia Plateau should be very similar to those in forested ecoregions. Therefore, the main processes should be tree mortality caused by disease or senescence, bank erosion, and wind throw. Maximum recruitment distances for large wood will generally be either riparian zone width or site-potential tree height, whichever is smaller. I found no studies on recruitment mechanisms of small wood, nevertheless, the main mechanisms should be direct fall of branches into a stream channel, mobilization by overbank flooding, and Beavers. Consequently, depending on the relative distribution of small and large wood sources within a riparian area, the recruitment distance for small wood could be greater than the distance for large wood. That is, shrubs that lie farther from the stream channel than trees, could contribute small wood via flooding or Beaver.

7.4.3. Detrital Nutrients

With respect to riparian ecosystems, *detrital nutrients* most often refer to nutrients derived from terrestrial litter. Litter may consist of leaves, bark, seeds, cones, flowers, fruit, nuts, twigs, and other small plant parts (Benfield 1997). Terrestrial litter in an aquatic system is also called allochthonous nutrients.[14] Detrital nutrients are only one component of nutrient dynamics in riparian ecosystems. Riparian areas also mediate bi-directional exchange of dissolved nutrients between terrestrial and aquatic systems. Detrital nutrients in the larger context of nutrient dynamics (e.g., nitrogen cycle) are discussed in Chapter 6.

Besides research on marine derived nutrients (Naiman et al. 2002), the dynamics of macronutrients—nitrogen, phosphorus, and carbon (N, P, and C)—in riparian areas of the Pacific Northwest has been largely neglected by scientists (but see Naiman and Sedell 1980; Triska et al. 1984). I found one study related to nutrient dynamics in riparian areas that was conducted in the Columbia Plateau Ecoregion (e.g., Cushing and Wolf 1982; Cushing and Wolf 1984; Cushing 1988).

The availability of macronutrients has profound effects on the productivity, composition, and structure of ecosystems. In Washington, many streams and rivers in undisturbed watersheds are oligotrophic, i.e., exhibit low productivity associated with low N or P concentrations. Thut and Haydu reported in 1971 that roughly half of unpolluted surface waters in Washington were N-limited, and the other half were limited by P. Interestingly, N-limited waters, such as those in the Yakima River and lower Columbia River basins, most often arise from volcanic rock formations, while P-limited waters, such as those in the Okanogan River basin, flow from glacial deposits or granitic formations (Thut and Haydu 1971; Murphy 1998). Nutrient-limited waters are often sensitive to anthropogenic inputs of macronutrients, and when more N or P enters a stream than can be immediately metabolized, degradation of aquatic habitats often results. Artificial fertilizers, which are inorganic nutrients, cannot mimic the foodweb role of detrital nutrients. Artificial fertilizers are used by plants, but litter feeds heterotrophs such as macroinvertebrate detritivores (shredders and collectors), many of which are prey for salmonids. Therefore, providing adequate amounts of litter to streams is an important issue for riparian area management.

According to Xiong and Nilsson (1997), in drier and less productive grasslands, a certain amount of litter may help to conserve soil moisture and thus increase plant growth. The same effect may be obtained in dryland riparian areas. Hence, in addition to providing nutrients, litter from riparian vegetation may also retain soil moisture.

Little is known about nutrient dynamics in dryland riparian areas. Nitrogen cycling, for instance, is driven by microbes in soils, and microbial activity depends on water availability. In forested ecoregions, nitrogen cycling is rarely limited by water availability. Hence, microbial processes are active in both uplands and riparian soils, and can occur year round. In arid regions, nitrogen cycling in uplands may cease when soil moisture approaches zero. This is also true of nitrogen cycling in riparian areas, however, nitrogen dynamics are more complex in riparian areas because they are closely linked to seasonal water table elevations which are affected by site and watershed-scale hydrology (Belnap et al. 2005).

Particulate and dissolved organic carbon are important sources of energy in aquatic ecosystems. Both support organisms near the bottom of the food web. In forested ecoregions, productivity of headwater streams is typically light-limited by a closed canopy (Conners and Naiman 1984; Murphy 1998), and consequently, the main source of energy is allochthonous chemical energy

[14] Allochthonous means originating or formed in a place other than where found. In contrast, autochthonous means originating or formed in the place where found.

from riparian areas. In arid and semi-arid regions, the canopy over headwater streams tends to be more open, which allows more light to reach the aquatic ecosystem. Cushing and Wolf (1982) found that chemical energy for a small spring-fed stream in central Washington, Rattlesnake Springs, was predominantly autochthonous, i.e., produced within the stream by Watercress *Rorippa nasturtium-aquatica,*[15] Cattail *Typha latifolia*, and algae. Direct allochthonous inputs contributed 11% of total energy inputs, and all of it was consumed. Consequently, Cushing and Wolf (1982) concluded that the aquatic community exhibited both autotrophic and heterotrophic traits.

The amount of allochthonous carbon produced by dryland riparian areas varies considerably. The input rates of allochthonous organic matter (specifically, leaf litter from shrubs) in two dryland riparian areas were 1.1 oz/ft^2/yr (350 g/m^2/yr) at Rattlesnake Springs and 0.54 oz/ft^2/yr (165 g/m^2/yr) at Snively Springs (Fisher 1995). The former is about 1.2 to 2.1 times greater than the amount of leaf litter produced by riparian areas in mesic forests (Gregory et al. 1991; cited in Fisher 1995).

Nearly all N in lotic ecosystems in forested ecoregions of the Pacific Northwest is derived from allochthonous sources. Headwater streams in the western Cascades of Oregon, for instance, obtain more than 90% of annual nitrogen inputs from biotic processes in the adjacent forest (Triska et al. 1984). An important source of N in forests of western Oregon and Washington is N_2-fixing Red Alder *Alnus rubra*, which contributes both litter and dissolved organic N to streams (Compton et al. 2003). Small streams in the Columbia Plateau Ecoregion must also obtain N from allochthonous sources. The overstory of some riparian plant communities in that ecoregion consists of N_2-fixing White Alder *Alnus rhombifolia* or Thinleaf Alder *Alnus incana*. Evidence suggests that Black Cottonwood and willow species contain mutualistic organisms that fix nitrogen (Doty et al. 2009, Wuehlissch 2011). This helps to explain how these species can survive and grow on recently disturbed, barren, floodplain sediments. Litter from these pioneering plants also provides nitrogen for other plant species in subsequent successional stages and deliver allochthonous nitrogen to the aquatic ecosystem.

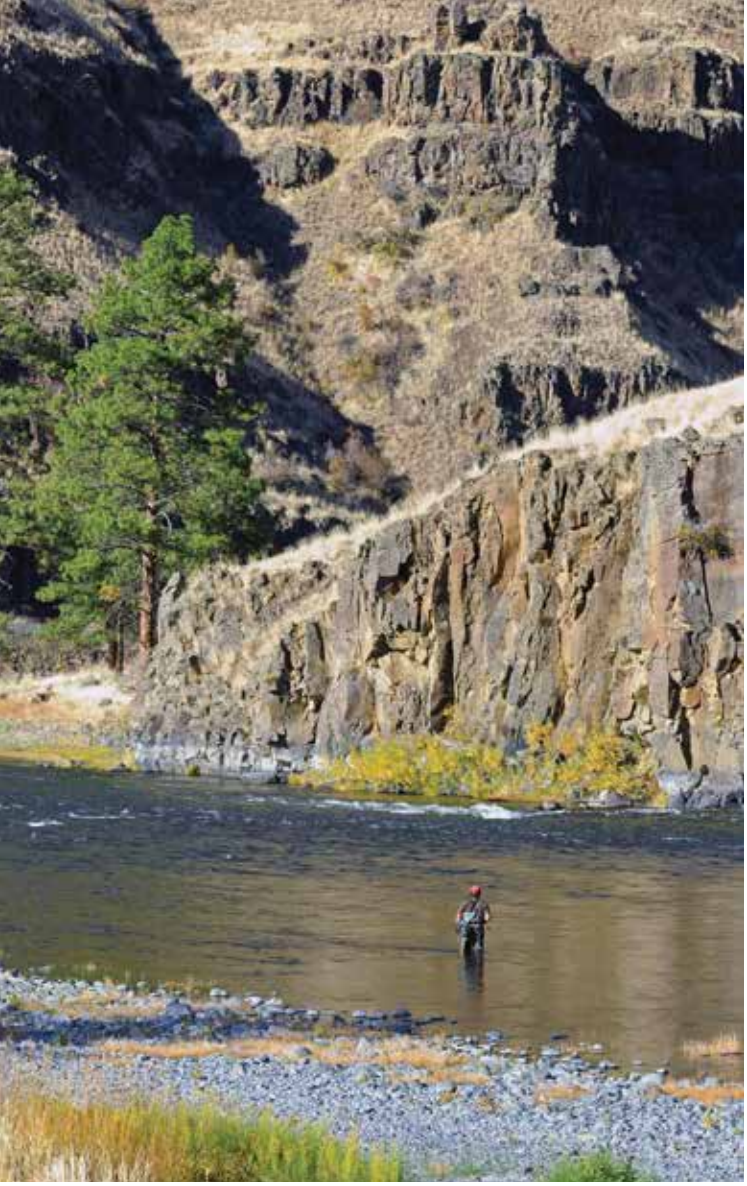
The only study I could find on litter source distances was conducted in mature conifer forest in western Washington. Bilby and Heffner (2016) found that about 95% of litter delivered to streams comes from distances between 39 and 54% of mean tree height, depending upon forest type, topography, and wind. For Snively Springs, a spring-fed small stream with a riparian area comprised of dense willow and wild rose in central Washington, Cushing (1988) found that roughly 40% of litter fell directly into the stream from overhanging vegetation and 60% was blown laterally from plants some distance from the streambank. He did not measure distances. These proportions were affected by factors that influence wind, such as vegetation density and topography.

7.4.4. Shade

For an in-depth discussion of shade and water temperature refer to Chapter 4.

Numerous studies in dryland riparian areas have shown that salmonid species abundance is negatively correlated with stream temperature (Platts and Nelson 1989; Li et al. 1994; Ebersole et al. 2003a; Zoellick 2004). Even when primary and secondary production increase in response to reduced shading, salmonid populations often respond negatively to high temperatures (Tait et al. 1994). Shade is important because it directly affects stream temperatures. Other factors can significantly affect stream temperature, such as topographic shading, channel azimuth, channel form, groundwater flow, and hyporheic exchange, but for the purposes of riparian area management, I focus on shade provided by vegetation. Vegetation also affects local air temperature,

15 Watercress (*Rorippa nasturtium-aquaticum*) is an exotic plant in Washington State.



In the Columbia Plateau, some stream reaches have no shade from vegetation/Alan Bauer

humidity, and air movement, which all affect stream temperature (Cristea and Janisch 2007).

Shading of a stream is affected by the vegetation's height and foliage density and by the stand's depth (or width) and stem density. In general, a taller, denser, or wider strip of vegetation will shade a larger proportion of a channel for a longer time, at both daily and annual time scales. Riparian vegetation also enables the formation of undercut banks, which provide shade along streambanks that has been shown to lower water temperatures of individual pools (Ebersole et al. 2003a; Ebersole et al. 2003b).

The classification system based on overstory underscores the substantial differences in shading provided by riparian vegetation types: tall tree, short tree, tall shrub, shrub, grass-like, grass, and forb (Crawford 2003). The obvious implication of these vegetation types is that some stream channels in the Columbia Plateau receive little or no shade from vegetation, even historically. However, the actual historical condition of many riparian areas is unknown. Studies show that restoration of riparian areas, especially restoration of incised channels, can alter vegetation type, increase shading, and reduce water temperatures. How spatial variation in vegetation type and consequent shading currently affects salmonid habitat regionally is also unknown. Ecologists lack a map of current and potential riparian vegetation types across the Columbia Plateau that would enable managers to assess impacts on fish-bearing streams from insolation (see Macfarlane et al. 2017 for a first approximation).

7.4.5. Pollutant Removal

For an in-depth discussion of pollutant removal by riparian areas refer to Chapter 5.

The capability of riparian areas to remove certain pollutants from runoff is well documented (Barling and Moore 1994; Hickey and Doran 2004; Polyakov et al. 2005; Dosskey et al. 2010). Management of riparian areas for pollutant removal differs from the other ecological functions discussed in this document in that the primary focus is on mitigating activities occurring outside the riparian area. The pollutant removal function is unique in that it only exists in the presence of human activities that generate polluted runoff, and it is only necessary when runoff from upland activities threatens to degrade in-stream water quality. Major nonpoint-source pollutants removed with riparian "buffers"[16] are sediments, excess nutrients (nitrogen or phosphorus), pesticides, and pathogens.

16 Riparian buffers are also known as riparian management zones (RMZs). "Buffer" refers to its purpose, which is to reduce or prevent adverse impacts to water quality, fisheries, and aquatic biodiversity from human activities occurring upslope of the buffer. Riparian buffers managed specifically for pollutant removal may also be called vegetated filter strips.

The processes in riparian areas affecting pollutant transport and fate are complex and often interrelated. Riparian areas can slow surface runoff and increase infiltration of water into the soil, thereby enhancing both deposition of solids and filtration of water-borne pollutants. Riparian areas also intercept and act on contaminants in subsurface flow through dilution, sorption, physical transformation, chemical degradation by various biogeochemical processes, and through uptake and assimilation by plants, fungi, and microbes. Hydrology, soils, and vegetation all affect pollutant transport and fate, but for the purposes of riparian area management I focus on vegetation.

Research on pollutant removal by riparian buffers conducted in arid or semi-arid ecoregions is very limited (Hook 2003). I could locate only three such studies (Tate et al. 2000; Fasching and Bauder 2001; Hook 2003), but all three have significant shortcomings. Hook (2003), for instance, simulated sediment-laden run-off from rangeland in western Montana. He reported that 20 ft (6 m) buffers removed at least 94% of sediment regardless of vegetation type in the buffer, but whether these simulations are realistic is unknown because he did not compare his run-off flow volumes and sediment concentrations to values from actual rangeland. Fasching and Bauder (2001), simulated sediment-laden run-off from tilled, bare cropland in central Montana. They found that 40 ft (12 m) wide buffers removed 75 to 80% of sediment during a simulated 50-year 24-hour storm event. However, while the buffer was 40 ft (12 m) wide, the bare cropland was only 15 ft (3 m) wide, which is certainly an unrealistic size for cropland. Tate et al. (2000) measured nitrate-nitrogen, total phosphorus, and suspended solids in run-off from irrigated pastures in the Central Valley of California. They reported that 33 ft (10 m) wide buffers did not significantly reduce nitrate-nitrogen concentration, total phosphorus concentration, or total suspended solid load. However, the strength of their inferences was compromised by extreme variability. Some buffered plots yielded higher concentrations of all three pollutants than unbuffered plots, which they attributed to differences in soil and microtopography among plots.

Despite the large quantity of research conducted around the world, no widely accepted recommendations have emerged on minimum buffer widths needed to protect water quality. The lack of agreement amongst scientists is due, in part, to the surprising complexity of the biogeochemical processes that remove pollutants from surface and subsurface flows, the many different environmental conditions among research sites, the variety of methods used to study pollutant removal, and the shortcomings of some research (as described above). One way to cut through this variability and develop quantitative relationships between buffer width and pollutant removal efficacy is meta-analysis.[17] I found five such meta-analyses in the literature (Mayer et al. 2007; Liu et al. 2008; Yuan et al. 2009; Zhang et al. 2010; Sweeney and Newbold 2014).

The number of studies in the five meta-analyses ranged from to 52 to 88. I could determine the geographic locations of all studies included in four of the meta-analyses; only one study was conducted in an arid or semi-arid region (i.e., Tate et al. 2000, cited in Zhang et al. 2010). Four meta-analyses analyzed sediment studies, three meta-analyses analyzed nitrogen studies, and 1 one meta-analysis (Zhang et al. 2010) analyzed phosphorus and pesticide studies. All meta-analyses show that: 1) removal efficacy increases as buffer width increases, 2) removal efficacy varies among pollutants, and 3) relationships between buffer width and removal efficacy follow a nonlinear law of diminishing returns. In other words, the marginal removal efficacy decreases as buffer width increases. Comparing the four pollutants, buffer width that resulted in 90% removal was narrowest for sediment and widest for nitrogen (surface and subsurface combined). See Chapter 5 for a complete summary of their results.

17 Meta-analysis refers to various approaches for drawing statistical inferences from many separate but similar experiments (Mann 1990).

Only one study from arid or semi-arid ecoregions was included in the meta-analyses. Therefore, actual removal efficacy versus buffer width relationships may be quite different for riparian buffers in the Columbia Plateau. Differences in soil, hydrology, and vegetation between arid or semi-arid ecoregions and other ecoregions are significant, and are likely to affect pollutant removal. Because soils in arid ecoregions with biological crusts may be less permeable (Warren 2014) and vegetation tends to be less dense, especially in the upland zone of influence, the meta-analyses may underestimate buffer widths needed for a given level of removal efficacy. This issue can only be resolved through research on pollutant removal by dryland riparian areas.

7.4.6. Alluvial Water Storage

Alluvial water storage, also known as bank storage, is an ecological function of riparian areas that is thought to be especially important for small streams in dryland ecoregions (Pollock et al. 2003). However, the idea that alluvium can supply enough water to maintain base flows is controversial because empirical data to support it are lacking (S. Wondzell, U.S. Forest Service, personal communication).

Alluvial water storage is thought to be part of a cyclic process. During annual floods, stream stage exceeds water table elevation, and surface waters flow into shallow alluvial aquifers (Winter et al. 1998). During the dry season, as stream stage declines, water flow reverses from aquifers to surface water, and the released water may comprise a substantial portion of the stream's base flow (Brunke and Gonser 1997; Whiting and Pomerants 1997). By absorbing some floodwaters, alluvial aquifers may also reduce the impacts of flood events (Whiting and Pomerants 1997). The water volume in bank storage depends on the duration of flooding, the area of inundated floodplain, hydraulic gradients between surface water and the aquifer, soil infiltration rate, the permeability and porosity of alluvial sediments, floodplain width, and thickness of the bank storage layer (Whiting and Pomerants 1997; Chen and Chen 2003).



Autumn foliage, brown grass, and low flows annually coincide in Columbia Plateau Ecoregion/Scott Fitkin, WDFW



Alluvial fans, such as these emanating from side canyons, store water from spring snow melt that contributes to a river's base flow during the dry season/Scott Fitkin, WDFW

On the semi-arid plains of Alberta, Meyboom (1961) found that groundwater released from bank storage is a substantial portion of dry-season stream flow in the Elbow River. Bank storage was 73% of total groundwater discharge during normal base-flow recession, and during late summer, discharge from bank storage comprised 50 to 70% of the river's daily mean discharge. On the eastern edge of the Great Plains in central Iowa, Kunkle (1968) determined that base flow characteristics of Four Mile Creek were related mainly to the adjacent alluvial sand reservoir. Bank storage discharge accounted for 37 to 42% of the annual base flow.

Hydrological studies in the Yakima River basin (Synder and Stanford 2001, and studies cited therein) have suggested that prior to irrigation projects extensive exchange between surface and ground waters occurred in riparian areas and floodplains. Annual inundation of floodplains, including riparian areas, would recharge shallow surficial aquifers, including the alluvial aquifer. Synder and Stanford (2001) asserted for the Yakima River, "Based on fundamental hydrologic principles, there is no question that groundwater recharge of this nature would not only have maintained base flows, but would have provided areas of cooler thermal refugia." A salient characteristic of alluvial water

storage is residence time, which can vary from days to years, depending upon floodplain width and hydraulic connectivity of alluvial sediments (Whiting and Pomereants 1997). The historical hydrology of rivers in the Columbia Plateau was water entered alluvial aquifers during spring peak flows and exited the aquifer weeks later during the low flows of late summer and fall of that same year (Synder and Stanford 2001). The historical timing and magnitudes of aquifer recharge and discharge may have been altered by dams, diversions, and levees.

Riparian and floodplain vegetation affect alluvial water storage in four ways. First, vegetation may reduce water storage through evapotranspiration. In fact, removing riparian vegetation can increase annual water yield from a watershed (Salemi et al. 2012). However, the timing of the additional surface water may not coincide with annual low flows when it is most needed. Second, through root growth and decay, vegetation creates soil macropores that increase soil permeability (Fisher and Binkley 2000) and thus enhance infiltration of floodwaters. Third, vegetation increases the residence time of floodwaters in floodplains by increasing surface roughness (Thomas and Nisbet 2007). The increased residence time provides more time for floodwaters to percolate through soils and into the alluvial aquifer. Vegetation increases surface roughness through stems, organic litter, large woody debris, and by altering micro-topography. Fourth, riparian vegetation helps to maintain cooler temperatures of shallow groundwater. Heat conduction from the soil surface into groundwater affects groundwater temperatures. Consequently, shallow groundwater temperatures are cooler in winter and warmer in summer. During the summer, shade from riparian vegetation and the riparian microclimate, which is cooler than adjacent uplands, may result in cooler groundwater. Stanford et al. (2002), for example, collected data suggesting that intact riparian forest moderated the rate of increase in groundwater temperatures along several reaches of the Yakima River.

Alluvial aquifers typically underlie floodplains (Vaccaro 2011), including riparian areas. The alluvial water storage function of floodplains has been degraded by dams that reduce flood magnitudes, levees that reduce the area of flooding, and the channelization or loss of distributary channels across alluvial fans. To replace natural recharge pathways, water managers are trying artificial recharge of shallow alluvial aquifers (USBR & WDOE 2012; WWBWC 2013). While artificial recharge may replace the aquifer recharge function of floods, it cannot replace the fluvial disturbances caused by flooding that are needed to maintain riparian vegetation and aquatic habitats.

7.5. Conclusions

The goal for riparian areas of the Columbia Plateau Ecoregion is the same as the goal for forested ecoregions—maintain or restore key ecological functions. However, management to achieve that goal is more complicated in dryland riparian areas for three reasons. First, there is a greater diversity of plant communities within riparian ecosystems of the Columbia Plateau than in the surrounding forested ecoregions—the vegetation heights of dryland riparian ecosystems range from sedges to tall trees. Several key ecological functions of riparian areas—namely, shade, wood, and detrital nutrients for aquatic habitats—are dependent on vegetation height. The other three functions—bank stability, pollutant removal, and alluvial water storage—are largely dependent on processes occurring at or below the soil surface. In forested ecoregions, the total capacity of a riparian area to provide five of the key functions typically occurs within a site-potential tree height (FEMAT 1993). In other words, with respect to aquatic habitats, full function for five of the key riparian ecological functions is typically provided by an area that is one site-potential tree height wide.[18]

[18] Site-potential" is a concept related to forest productivity. A site's productivity is often expressed as the height a particular tree species growing on that site is expected to attain by a specified age. FEMAT (1993) defined site-potential tree height as the average maximum height of the tallest dominant trees (200 years old or greater).

In dryland ecoregions, the width of the riparian ecosystem is based on the ecological function that creates the widest zone of influence. At most sites, this will be either the wood (large and small) or pollutant removal functions. For grass, herb, shrub, and small tree vegetation types, the zone of influence based on wood, which depends on vegetation height, will be narrower than the zone of influence based on pollutant removal. Therefore, if pollutants, including sediments due to ground disturbance, are a concern at a particular site, then riparian ecosystem width should be based on the desired removal efficacy for pollutants created at that site. If, for instance, surface run-off containing excess nitrogen is a concern and a 95% removal is desired, then the zone of influence is 170 ft (52 m) wide, measured from the active channel, see Table 5.4. If pollutant removal is not a concern, then riparian ecosystem width should be based on site-potential vegetation height (i.e., trees or shrubs), which should provide maximum wood and shade for aquatic habitats.



Some trees (Pinus ponderosa) *have all the luck/Scott Fitkin, WDFW*

The second reason management of riparian ecosystems is more complicated in the Columbia Plateau Ecoregion is water. The existence of dryland riparian areas depends on soil moisture and water table elevations. Many dryland riparian plant communities evolved under an annual hydrological cycle of flooding followed by gradual recession of stream flows. This cycle has been disrupted by dams and water diversions. The consequences of water management on riparian areas were documented by Braatne et al. (2007) who found an unsustainable age-class distribution of cottonwoods along the Yakima River. Two long-term impacts for these reaches of the Yakima could be reductions in shade and large wood for aquatic habitats. Water management is likely to have caused adverse changes to riparian plant communities along other rivers and streams in the Columbia Plateau. Under state law (RCW 90.03), in-stream flows are managed only to maintain flows above a specified minimum flow. Little consideration is given to mimicking the natural seasonal hydrograph for the sake of riparian ecosystems. To restore riparian ecosystems and aquatic habitats in the Columbia Plateau, that may need to change.

Third, management will be more complicated because many riparian areas in the Columbia Plateau have been highly altered by human activities, and ecologists do not know their historical or "properly functioning" conditions. Lacking such information will hamper the success of site-scale riparian restoration projects and regional restoration plans. An initial step toward grappling with this issue might be a subregional or WRIA-level mapping of potential riparian vegetation types. The mapping could include the capacity to support Beaver (e.g., Macfarlane et al. 2017) and the vegetation that would develop in the presence of Beaver. The map would serve three purposes: 1) a vegetation guide for riparian restoration projects, 2) a historical baseline for fish habitat conditions in the Columbia Plateau, and 3) habitat restoration objectives for the recovery of salmon and other aquatic species.

Historical information on riparian areas will serve three other purposes. First, knowledge of historical conditions will enable an accounting of lost ecosystem services. The losses incurred by fisheries are well recognized, but losses of wildlife, both game and nongame species, due to altered riparian areas have not been rigorously evaluated. Another major ecosystem service is the contribution to perennial stream flow from short-term storage of water in shallow alluvial aquifers that lie beneath floodplains (USBR & WDOE 2012; WWBWC 2013). Losses of this ecosystem service caused by disconnecting floodplains from streams also have not been rigorously evaluated. Second, knowledge of historical conditions may enable an estimate of the past quantity and quality of salmon habitats. Historical knowledge of past salmon habitats can be used in salmon recovery plans to establish habitat restoration objectives and priorities. The third purpose is partly political. Knowledge of past habitat loss can influence policy decisions to conserve remaining habitats or to restore habitats where practicable.

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7.7. Literature Cited[19]

Adam, S. 2004. Appendix E *in* B.E. Jamison and M.F. Livingston. Sage-Grouse habitat evaluation in the shrub-steppe ecosystem of the Yakama Reservation. Project final report. Wildlife, Range & Vegetation Resources Management Program, Confederated Tribes and Bands of the Yakama Nation, Toppenish, Washington. (vii)

AP (Associated Press). 2012. Umatilla tribes hope to trim wild horse numbers without slaughtering any. Available: http://www.oregonlive.com/pacific-northwest-news/index.ssf/2012/10/umatilla_tribes_hope_to_trim_w.html. (February 2018). (vii)

Anderson, E.W. 1987. Riparian area definition – a viewpoint. Rangelands 9(2):70. (i)

Bailey, R.G. 1995. Description of the ecoregions of the United States (2nd ed.). Misc. Pub. No. 1391. U.S. Forest Service, Washington, D.C. (viii)

Baker, B.W., H.C. Ducharme, D.C.S. Mitchell, T.R. Stanley, and H.R. Peinetti. 2005. Interaction of Beaver and Elk herbivory reduces standing crop of willow. Ecological Applications 15:110–118. (i)

Barling, R.D., and I.D. Moore. 1994. Role of buffer strips in management of waterway pollution: a review. Environmental Management 18:543-558. (i)

Barnes, D.M., and A.U. Mallik. 1996. Use of woody plants in construction of Beaver dams in northern Ontario. Canadian Journal of Zoology 74:1781-1786. (i)

Beechie, T.J., M.M. Pollock, and S. Baker. 2008. Channel incision, evolution and potential recovery in the Walla Walla and Tucannon River basins, northwestern USA. Earth Surface Processes and Landforms 33:784–800. (i)

Belnap, J., J.R. Welter, N.B. Grimm, N.N. Barger, and J.A. Ludwig. 2005. Linkages between microbial and hydrologic processes in arid and semi-arid watersheds. Ecology 86:298–307. (i)

Belsky, A.J., A. Matzkem, and S. Uselman. 1999. Survey of livestock influences on stream and riparian ecosystems in the western United States. Journal of Soil and Water Conservation 54:419-431. (i)

Benfield, E.F. 1997. Comparisons of litterfall input to streams. Journal of the North American Benthological Society 16:104-108. (i)

Beschta, R.L., and W.J. Ripple. 2016. Riparian vegetation recovery in Yellowstone: the first two decades after Wolf reintroduction. Biological Conservation 198:93-103. (i)

Bilby, R.E., and J.T. Heffner. 2016. Factors influencing litter delivery to streams. Forest Ecology and Management 369:29-37. (i)

Bisson, P.A., R.E. Bilby, M.D. Bryant, C.A. Dollof, G.B. Grette, R.A. House, M.L. Murphy, K.V. Koski, and J.R. Sedell. 1987. Large woody debris in forested streams in the Pacific Northwest: past, present, and future. Pages 143-190 *in* E.O. Salo and T.W. Cundy, editors. Streamside management: forestry and fishery interactions. Contribution No. 57. Institute of Forest Resources, University of Washington, Seattle. (i)

Black, A.E., E. Strand, P. Morgan, J.M. Scott, R.G. Wright, and E. Watson. 1998. Biodiversity and land-use history of the Palouse bioregion: pre-European to present. Pages 85-99 *in* T.D. Sisk, editor. Perspectives on the land use history of North America: a context for understanding our changing environment. Biological Science Report USGS/BRD/BSR-1998-0003. U.S. Geological Survey, Reston, Virginia. (viii)

Blersch, D.M., and P.C. Kangas. 2014. Signatures of self-assembly in size distributions of wood members in dam structures of *Castor Canadensis*. Global Ecology and Conservation 2:204-213. (i)

Bohn, C. 1986. Biological importance of streambank stability. Rangelands 8(2):55-56. (i)

Braatne, J.H., R. Jamieson, K.M. Gill, and S.B. Rood. 2007. Instream flows and the decline of riparian cottonwoods along the Yakima River, Washington, USA. River Research and Applications 23:247–267. (i)

[19] References are classified according to RCW 34.05.271 (see Appendix 1) denoted by a lower case roman numeral (i – viii) in parentheses at the end of the citation.

Braatne, J.H., S.B. Rood, and R.E. Heilman. 1996. Life history, ecology and conservation of riparian cottonwoods in North America. Pages 57-85 *in* R.F. Stettler, H.D. Bradshaw, P.E. Heilman, and T.M. Hinckley, editors. Biology of *Populus* and its implications for management and conservation. NRC Research Press, Ottawa, Ontario. (i)

Brunke. M., and T. Gonser. 1997. The ecological significance of exchange processes between rivers and groundwater. Freshwater Biology 37:1-33. (i)

Bryce, S.A., and J.M. Omernik. 1997. Level IV ecoregions of the Columbia Plateau Ecoregion of Oregon, Washington, and Idaho. Pages 11-22 *in* S.E. Clark and S.A. Bryce, editors. Hierarchical subdivisions of the Columbia Plateau and Blue Mountains ecoregions. PNW-GTR-395. U.S. Forest Service, Pacific Northwest Forest Station, Portland, Oregon. (viii)

Buckley, G.L. 1993. Desertification of the Camp Creek drainage in central Oregon. Yearbook of the Association of Pacific Coast Geographers 55:91-126. (i)

Campbell, A.G., and J.F. Franklin. 1979. Riparian vegetation in Oregon's western Cascade Mountains: composition, biomass, and autumn phenology. Bulletin No. 14. Coniferous Forest Biome Ecosystem Analysis Studies, University of Washington, Seattle. (i)

Carlson, N.K. 1940. The history of grazing and livestock development in the Pacific Northwest. Range Division, Region 9, Soil Conservation Service. (viii)

Case, T.L., and J.B. Kauffman. 1997. Wild ungulate influence on the recovery of willows, Black Cottonwood, and Thin-Leaf Alder following cessation of cattle grazing in northeastern Oregon. Northwest Science 71:115-126. (i)

Chen, X., and X. Chen. 2003. Stream water infiltration, bank storage, and storage zone changes due to stream fluctuations. Journal of Hydrology 280:246-264. (i)

Collen, P., and R.J. Gibson. 2001. The general ecology of beavers (*Castor* spp.), as related to their influence in stream ecosystems and riparian habitats, and the subsequent effects on fish – a review. Reviews in Fish Biology and Fisheries 10:439–461. (i)

Compton, J.E., M.R. Church, S.T. Larned, and W.E. Hogsett. 2003. Nitrogen export from forested watersheds of the Oregon Coast Range: the role of N_2-fixing Red Alder. Ecosystems 6:773–85. (i)

Conners, M.E., and R.J. Naiman. 1984. Particulate allochthonous inputs: Relationships with stream size in an undisturbed watershed. Canadian Journal of Fisheries and Aquatic Sciences 41:1473–1488. (i)

Cooke, H.A., and S. Zack. 2008. Influence of Beaver dam density on riparian areas and riparian birds in shrubsteppe of Wyoming. Western North American Naturalist 68:365-373. (i)

Corenblit, D., E. Tabacchi, J. Steiger, and A.M. Gurnell. 2007. Reciprocal interactions and adjustments between fluvial landforms and vegetation dynamics in river corridors: a review of complementary approaches. Earth-Science Reviews 84: 56-86. (i)

Crawford, R.C. 2003. Riparian vegetation classification of the Columbia Basin, Washington. Natural Heritage Program Report 2003-03. Washington Department Natural Resources. Olympia, Washington. (viii)

Cristea, N., and J. Janisch. 2007. Modeling the effects of riparian buffer width on effective shade and stream temperature. Ecology Publication No. 07-03-028. Environmental Assessment Program, Washington State Department of Ecology, Olympia, Washington. (viii)

Cushing, C.E. 1988. Allochthonous detritus inputs to a small, cold desert spring-stream. Vereinigung fur Theoretische und Angewandte Limnologie 23:1107-1113. (i)

Cushing, C.E., and E.G. Wolf. 1982. Organic energy budget of Rattlesnake Springs, Washington. American Midland Naturalist 107:404-407. (i)

Cushing, C.E., and E.G. Wolf. 1984. Primary production on Rattlesnake Springs, a cold desert spring-stream. Hydrobiologica 114:229-236. (i)

Daubenmire, R.F. 1942. An ecological study of the vegetation of southeastern Washington and adjacent Idaho. Ecological Monographs 12:53-79. (i)

Daubenmire, R.F. 1970. Steppe vegetation of Washington. Washington State Experimental Station Technical Bulletin 62. Washington State University Cooperative Extension, Pullman, Washington. (viii)

Denfeld, D.C. 2011. Fort Walla Walla. Essay 9649, HistoryLink.org. Available: http://www.historylink.org/File/9649. (January 2019). (viii)

Dosskey, M.G., P. Vidon, N.P. Gurwick, C.J. Allan, T.P. Duval, and R. Lowrance. 2010. The role of riparian vegetation in protecting and improving chemical water quality in streams. Journal of the American Water Resources Association 46:261-277. (i)

Doty, S.L., B. Oakley, G. Xin, J.W. Kang, G.L. Singleton, Z. Khan, A. Vajzovic, and J.T. Staley. 2009. Diazotrophic endophytes of native Black Cottonwood and willow. Symbiosis 47:23–33. (i)

Dremmer, R., and R.L. Beschta. 2008. Recent history (1988-2004) of Beaver dams along Bridge Creek in central Oregon. Northwest Science 82:309-318. (i)

Ebersole, J. L., W.J. Liss, and C.A. Frissell. 2003a. Thermal heterogeneity, stream channel morphology, and salmonid abundance in northeastern Oregon streams. Canadian Journal of Fisheries and Aquatic Sciences 60:1266-1280. (i)

Ebersole, J. L., W.J. Liss, and C.A. Frissell. 2003b. Cold water patches in warm streams: physicochemical characteristics and the influence of shading. Journal of the American Water Resources Association 39:355-368. (i)

Evans, S. 1989. Provisional riparian and aquatic wetland plant communities on the Columbia Plateau. Report prepared under contract No. C0089098. Report to Washington Department of Ecology. Natural Heritage Program, Washington Department of Natural Resources, Olympia, Washington. (viii)

Fasching, R.A., and J.W. Bauder. 2001. Evaluation of agricultural sediment load reductions using vegetative filter strips of cool season grasses. Water Environment Research 73:590-596.

FEMAT (Forest Ecosystem Management Assessment Team). 1993. Forest ecosystem management: an ecological, economic, and social assessment. United States Department of Agriculture and United States Department of Interior, Portland, Oregon. (viii)

Finley, W.L. 1937. The Beaver – conserver of soil and water. Pages 295-297 *in* Transactions of the Second North American Wildlife Conference. American Wildlife Institute, Washington, D.C. (viii)

Fisher, S.G. 1995. Stream ecosystems of the western United States. Pages 61-87 *in* C.E. Cushing, K.W. Cummins, and G.W. Minshall, editors. River and stream ecosystems of the world. University of California Press, Berkley, California. (i)

Fisher, R.F., and D. Binkley. 2000. Ecology and management of forest soils. Wiley, New York.

Florsheim, J.L., J.F. Mount, and A. Chin. 2008. Bank erosion as a desirable attribute of rivers. BioScience 58:519-529. (i)

Fonda, R.W. 1974. Forest succession in relation to river terrace development in Olympic National Park, Washington. Ecology 55:927-942. (i)

Fox, M., and S. Bolton. 2007. A regional and geomorphic reference for quantities and volumes of instream wood in unmanaged forested basins of Washington State. North American Journal of Fisheries Management 27:342-359. (i)

Franklin, J.F., and C.T. Dyrness. 1988. Natural vegetation of Oregon and Washington. Oregon State University Press, Corvallis, Oregon. (i)

Galbraith, W.A., and E.W. Anderson. 1971. Grazing history of the Northwest. Journal of Rangeland Management 24:6-12. (i)

Gebauer, A.D., R. Brown, S. Schwab, C. Nezat, and C. McNeely. 2015. Effects of an invasive grass (*Phalaris Arundinacea*) on water availability in semi-arid riparian zones. Wetlands 36:59–72. (i)

Giblin, D. 2006. Russian Olive, *Elaeagnus angustifolia*. Pages 78–79 *in* P.D. Boersma, S.H. Reichard, and

A.V. van Buren, editors. Invasive species in the Pacific Northwest. University of Washington Press, Seattle. (i)

Gibson, P.P., and J.D. Olden. 2014. Ecology, management, and conservation implications of North American Beaver (*Castor canadensis*) in dryland streams. Aquatic Conservation: Marine and Freshwater Ecosystems 24:391-409. (i)

Gibson, P.P., J.D. Olden, and M.W. O'Neill. 2015. Beaver dams shift desert fish assemblages toward dominance by non-native species (Verde River, Arizona, USA). Ecology of Freshwater Fish 24:355–372. (i)

Gregory, S.V., F.J. Swanson, W.A. McKee, and K.W. Cummins. 1991. An ecosystem perspective of riparian zones. Bioscience 41: 540–551. (i)

Griffin, E., J. Kean, K. Vincent, J. Smith, and J. Friedman. 2005. Modeling effects of bank friction and woody bank vegetation on channel flow and boundary shear stress in the Rio Puerco, New Mexico. Journal of Geophysical Research 110:F04023. (i)

Gurnell, A. 2014. Plants as river system engineers. Earth Surface Processes and Landforms 39:4-25. (i)

Hickey, M.B., and B. Doran. 2004. A review of efficiency of buffer strips for the maintenance and enhancement of riparian ecosystems. Water Quality Research Journal of Canada 39:311-317. (i)

Higgs, E., D.A. Falk, A. Guerrini, M. Hall, J. Harris, R.J. Hobbs, S.T. Jackson, J.M. Rhemtulla, and W. Throop. 2014. The changing role of history in restoration ecology. Frontiers in Ecology and the Environment 12:499–506. (i)

Hood, W.G., and R.J. Naiman. 2000. Vulnerability of riparian zones to invasion by exotic vascular plants. Plant Ecology 148:105-114. (i)

Hook, P.B. 2003. Sediment retention in rangeland riparian buffers. Journal of Environmental Quality 32:1130-1137. (i)

Hough-Snee, N., B.B. Roper, J.M. Wheaton, and R.L. Lokteff. 2015. Riparian vegetation communities of the American Pacific Northwest are tied to multi-scale environmental filters. River Research and Applications 31:1151-1165. (i)

Hultine, K.R., and S.E. Bush. 2011. Ecohydrological consequences of non-native riparian vegetation in the southwestern United States: A review from an ecophysiological perspective. Water Resources Research 47: W07542. (i)

Hupp, C.R., and W.R. Osterkamp. 1996. Riparian vegetation and fluvial geomorphic processes. Geomorphology 14:277-295. (i)

Johnson, D.R., and D.H. Chance. 1974. Presettlement overharvest of upper Columbia River Beaver populations. Canadian Journal of Zoology 52:1519-1521. (i)

Jones, A. 2000. Effects of cattle grazing on North American arid ecosystems: a quantitative review. Western North American Naturalist 60:155-164. (i)

Kaiser, V.G. 1961. Historical land use and erosion in the Palouse – a reappraisal. Northwest Science 35:139-153. (i)

Katz, G.L., and P.B. Shafroth. 2003. Biology, ecology and management of *Elaeagnus angustifolia* L. (Russian Olive) in western North America. Wetlands 23:763-777. (i)

Kauffman, J.B., R.L. Beschta, N. Otting, and D. Lytjen. 1997. An ecological perspective of riparian and stream restoration in the western United States. Fisheries 22:12-24. (i)

Kauffman, J.B., and W.C. Krueger. 1984. Livestock impacts on riparian ecosystems and streamside management implications: a review. Journal of Range Management 37:430-438. (i)

Kunkle, G.R. 1968. A hydrogeologic study of the ground-water reservoirs contributing base runoff to Four Mile Creek, east-central Iowa. Geological Survey Water-Supply Paper 1839-O. U.S. Geological Survey, Washington, D.C. (i)

KWA. 2004. Crab Creek subbasin plan. KWA Ecological Sciences Inc., Duvall, Washington. (viii)

Latterell, J.J., and R.J. Naiman. 2007. Sources and dynamics of large logs in a temperate floodplain river. Ecological Applications 17:1127-1141. (i)

Lesica, P., and S. Miles. 1999. Russian olive invasion into cottonwood forests along a regulated river in north-central Montana. Canadian Journal of Botany 77: 1077-1083. (i)

Li, H.W., G.A. Lamberti, T.N. Pearsons, C.K. Tait, and J.L. Li. 1994. Cumulative effects of riparian disturbance along high desert trout streams of the John Day Basin, Oregon. Transactions of the American Fisheries Society 123:627-640. (i)

Lichvar, R.W., N.C. Melvin, M.L. Butterwick, and W.N. Kirchner. 2012. National wetland plant list indicator rating definitions. ERDC/CRREL TN-12-1. U.S. Army Corps of Engineers, Washington, D.C. (viii)

Liu, X., X. Zhan, and M. Zhang. 2008. Majors factors influencing the efficacy of vegetated buffers on sediment trapping: a review and analysis. Journal of Environmental Quality 37:1667-1674. (i)

Liquori, M., and C.R. Jackson. 2001. Channel response from shrub dominated riparian communities and associated effects on salmonid habitat. Journal of the American Water Resources Association 37:1639-1651. (i)

Loope, L.L., P.G. Sanchez, P.W. Tarr, W.L. Loope, and R.L. Anderson. 1988. Biological invasions of arid land nature reserves. Biological Conservation 44:95-118. (i)

Lorne, L. 1993. Marketing wildlife: the Hudson's Bay Company and the Pacific Northwest, 1821-1849. Forest & Conservation History 37(January):14-24. (i)

Macfarlane, W.W., J.T. Gilbert, M.L. Jensen, J.D. Gilbert, N. Hough-Snee, P.A. McHugh, J.M. Wheaton, and S.N. Bennett. 2017. Riparian vegetation as an indicator of riparian condition: detecting departures from historic condition across the North American West. Journal of Environmental Management 202:447-460. (i)

Macfarlane, W.W., J.M. Wheaton, N. Bouwes, M.L. Jensen, J.T. Gilbert, N. Hough-Snee, and J.A. Shivik. 2017. Modeling the capacity of riverscapes to support Beaver dams. Geomorphology 277:72-99. (i)

Mack, R.N. 1988. First comprehensive botanical survey of the Columbia Plateau, Washington: the Sandberg and Leiberg Expedition of 1893. Northwest Science 62:118-128. (i)

Mack, R.N., and J.N. Thompson. 1982. Evolution in steppe with few large, hooved mammals. American Naturalist 119:757-773. (i)

Mann, C. 1990. Meta-analysis in the breech. Science 249:476-480. (i)

Mapes, L.V. 2010. Northwest tribes seek solutions to unwanted horses. The Seattle Times. Available: **https://www.seattletimes.com/seattle-news/northwest-tribes-seek-solutions-to-unwanted-horses/**. (February 2018). (viii)

Martinez, A.E., and P.F. McDowell. 2016. Invasive Reed Canarygrass (*Phalaris arundinacea*) and native vegetation roughness. Invasive Plant Science and Management 9:12-21. (i)

Mayer, P.M., S.K. Reynolds, M.D. Marshall, D. McCutchen, and T.J. Canfield. 2007. Meta-analysis of nitrogen removal in riparian buffers. Journal of Environmental Quality 36:1172-1180. (i)

McAllister, L.S. 2008. Reconstructing historical riparian conditions for two river basins in eastern Oregon, USA. Environmental Management 42:412-425. (i)

McKee, A., G. LaRoi, and J.F. Franklin. 1982. Structure, composition, and reproductive behavior of terrace forests, South Fork Hoh River, Olympic National Park. Pages 22-29 *in* E.E. Starkey, J.F. Franklin, and J.W. Matthews, technical coordinators. Ecological Research in National Parks of the Pacific Northwest. Oregon State University Research Laboratory Publication, Corvallis, Oregon. (i)

Meinig, D.W. 1968. The great Columbia Plain: a historical geography. University of Washington Press, Seattle, Washington. (i)

Meinzer, O.E. 1923. Outline of ground-water hydrology. Water Supply Paper 494. U.S. Geological Survey, Washington, D.C. (i)

Meyboom, P. 1961. Estimating ground-water recharge from stream hydrographs. Journal of Geophysical Research 66:1203-1214. (i)

Micheli, E.R., and J.W. Kirchner. 2002. Effects of wet meadow riparian vegetation on streambank erosion. 2. Measurements of vegetated bank strength and consequences for failure mechanics. Earth Surface Processes and Landforms 27:687–697. (i)

Minckley, W.L., and J.N. Rinne. 1985. Large woody debris in hot-desert streams: an historical overview. Desert Plants 7(3):142-153. (i)

Murphy, M.L. 1998. Primary productivity. Pages 144-168 *in* R.J. Naiman and R.E. Bilby, editors. River ecology and management: lessons from the Pacific Coastal Ecoregion. Springer-Verlag, New York. (i)

Naiman, R.J., and R.E. Bilby, editors. 1998. River ecology and management: lessons from the Pacific Coastal Ecoregion. Springer-Verlag, New York. (i)

Naiman, R.J., R.E. Bilby, D.E. Schindler, and J.M. Helfield. 2002. Pacific salmon, nutrients, and the dynamics of freshwater and riparian ecosystems. Ecosystems 5:399-417. (i)

Naiman, R.J., T.J. Beechie, L.E. Benda, D.R. Berg, P.A. Bisson, L.H. MacDonald, M.D. O'Conner, P.L. Olsen, and E.A. Steel. 1992. Fundamental elements of ecologically healthy watersheds in the Pacific Northwest Coastal Ecoregion. Pages 127-188 *in* R.J. Naiman, editor. Watershed management: balancing sustainability and environmental change. Springer, New York. (i)

Naiman, R.J., C.A. Johnston, and J.C. Kelley. 1988. Alteration of North American streams by Beaver. BioScience 38:753-762. (i)

Naiman, R.J., and J.R. Sedell. 1980. Relationships between metabolic parameters and stream order in Oregon. Canadian Journal of Fisheries and Aquatic Sciences 37:834-847. (i)

NTHC (Northwest Tribal Horse Coalition). no date. Managing excess feral horses in the Inland Northwest. Available: **https://www.ynwildlife.org/Wildhorsecoalition.php.** (February 2018). (viii)

Ohmart, R.D. 1996. Historical and present impacts of livestock grazing on fish and wildlife resources in western riparian habitats. Pages 245-279 in P.R. Krausman, editor. Rangeland wildlife. Society for Range Management, Denver, Colorado. (i)

Olson, D.M., E. Dinerstein, E.D. Wikramanayake, N.D. Burgess, G.V.N. Powell, E.C. Underwood, J.A. D'Amico, H.E. Strand, J.C. Morrison, C.J. Loucks, T.F. Allnutt, J.F. Lamoreux, T.H. Ricketts, I. Itoua, W.W. Wettengel, Y. Kura, P. Hedao, and K. Kassem. 2001. Terrestrial ecoregions of the world: A new map of life on Earth. BioScience 51:933-938. (i)

Omernik, J.M. 1987. Ecoregions of the conterminous United States. Annals of the Association of American Geographers 77(1):118-125. (i)

Omernik, J.M. and A.L. Gallant. 1986. Ecoregions of the Pacific Northwest. EPA/600/3-86/033. U.S. Environmental Protection Agency, Corvallis, Oregon. (i)

Ortolano, L.K., K. Cushing, and contributing authors. 2000. Grand Coulee Dam and the Columbia Basin Project, USA. World Commission on Dams, Cape Town, South Africa. (viii)

Osterkamp, W.R., and C.R. Hupp. 2010. Fluvial processes and vegetation – glimpses of the past, the present, and perhaps the future. Geomorphology 116:274-285. (i)

Ott, J. 2003. "Ruining" the rivers in the Snake country. Oregon Historical Quarterly 104(2):166-195. (i)

Pabst, R.J., and T.A. Spies. 1999. Structure and composition of unmanaged riparian forests in the coastal mountains of Oregon, USA. Canadian Journal of Forest Research 29:1557-1573. (i)

Parker, M., F.J. Wood, B.H. Smith, and R.G. Elder. 1985. Erosional downcutting in lower order riparian ecosystems: have historical changes been caused by the removal of Beaver? Pages 35-38 in R.R. Johnson, C.D. Ziebell, D.R. Patton, P.F. Ffolliott, R.H. Hamre, editors. Riparian ecosystems and their management: reconciling conflicting uses. RMRS-GTR-RM-120. U.S. Forest Service, Rocky Mountain Forest and Range Experimental Station, Fort Collins, Colorado. (viii)

Patten, D.T. 1998. Riparian ecosystems of semi-arid North America: diversity and human impacts. Wetlands 18:498–512. (i)

Platts, W.S., and R.L. Nelson. 1989. Stream canopy and its relationship to salmonid biomass in the intermountain west. North American Journal of Fisheries Management 9:446-457. (i)

Pollen-Bankhead, N., and A. Simon. 2010. Hydrologic and hydraulic effects of riparian root networks on streambank stability: Is mechanical root-reinforcement the whole story? Geomorphology 116:353-362. (i)

Pollock, M.M., T.J. Beechie, and C.E. Jordan. 2007. Geomorphic changes upstream of Beaver dams in Bridge Creek, an incised stream channel in the interior Columbia River basin, eastern Oregon. Earth Surface Processes and Landforms 32:1174-1185. (i)

Pollock, M.M., T.J. Beechie, J.M. Wheaton, C.E. Jordan, N.Bouwes. N. Weber, and C. Volk. 2014. Using Beaver dams to restore incised stream ecosystems. Bioscience 64:279-290. (i)

Pollock, M.M., M. Heim, and D. Werner. 2003. Hydrological and geomorphic effects of Beaver dams and their influence on fishes. Pages 213-233 in S.V. Gregory, K.L. Boyer, and A.M. Gurnell, editors. The ecology and management of wood in world rivers. American Fisheries Society, Bethesda, Maryland. (i)

Polvi, L.E., E.E. Wohl, and D.M. Merritt. 2014. Modeling the functional influence of vegetation type on streambank cohesion. Earth Surface Processes and Landforms 39:1245-1258. (i)

Polyakov, V., A. Fares, and M.H. Ryder. 2005. Precision riparian buffers for the control of nonpoint source pollutant loading into surface water: a review. Environmental Reviews 13:129-144. (i)

Reidy Liermann, C.A., J.D. Olden, T.J. Beechie, M.J. Kennard, P.B. Skidmore, C.P. Konrad, and H. Imaki. 2012. Hydrogeomorphic classification of Washington state rivers to support emerging environmental flow management strategies. River Research and Applications 28:1340–1358. (i)

Richardson, J.S., R.J. Naiman, F.J. Swanson, and D.E. Hibbs. 2005. Riparian communities associated with Pacific Northwest headwater streams: assemblages, processes, and uniqueness. Journal of the American Water Resources Association 41:935-947.

Robison, G.E., J. Runyon, and C. Andrus. 1999. Cooperative stream temperature monitoring: project completion report for 1994–1995. Forest Practices Technical Report 2, Oregon Department of Forestry, Salem, Oregon. (viii)

Rockie, W.A. 1939. Man's effects on the Palouse. The Geographical Review 29(1):34-45. (i)

Roe, A.L. 1958. Silvics of Black Cottonwood. Miscellaneous Publication 17. U.S. Forest Service, Intermountain Forest and Range Experiment Station, Ogden, Utah. (viii)

Rood, S.B., S.G. Bigelow, M.L. Polzin, K.M. Gill, and C.A. Coburn. 2015. Biological bank protection: trees are more effective than grasses at resisting erosion from major river floods. Ecohydrology 8:772-779. (i)

Salemi, L.F., J.D. Groppo, R. Trevisan, J.M. de Moraes, W. de Paula Lima, and L.A. Martinelli. 2012. Riparian vegetation and water yield: a synthesis. Journal of Hydrology 454–455:195–202. (i)

Salo, E.O., and T.W. Cundy, editors. 1987. Streamside management: forestry and fishery interactions. Contribution No. 57. Institute of Forest Resources, University of Washington, Seattle. (viii)

Scheffer, P.M. 1938. The Beaver as an upstream engineer. Soil Conservation 3:178-181. (i)

Sedell, J.R., F.H. Everest, and D.R. Gibbons. 1989. Streamside vegetation management for aquatic habitat. Pages 115-125 in Proceedings of the National Silviculture Workshop: silviculture for all resources. U.S. Forest Service, Washington, D.C. (i)

Sedell, J.R., and F.J. Swanson. 1984. Ecological characteristics of streams in old-growth forest of the Pacific Northwest. Pages 9-16 in W.R. Meehan, T.R. Merrell, and T.A. Hanley, editors. Fish and wildlife relationships in old-growth forests. American Institute of Fishery Research Biologists. (i)

Simon, A., and A.J.C. Collison. 2002. Quantifying the mechanical and hydrologic effects of riparian vegetation on streambank stability. Earth Surface Processes and Landforms 27:527–546. (i)

Simon, A., N. Pollen, and E. Langendoen. 2006. Influence of two woody riparian species on critical conditions for streambank stability: upper Truckee River, California. Journal of the American Water Resources Association 42:99-113. (i)

Sleeter, B.M. 2012. Columbia Plateau Ecoregion. Pages 299- 236 in B.M. Sleeter, T.S. Wilson, and W. Acevedo, editors. Status and trends of land change in the Western United States – 1973 to 2000: U.S. Geological Survey Professional Paper 1794–A. U.S. Geological Survey, Reston, Virginia.

Stannard, M., and W. Crowder. 2001. Biology, history, and suppression of Reed Canarygrass (Phalaris arundinacea L.). Technical Note Plant Materials No. 40. Natural Resources Conservation Service, Boise, Idaho. (viii)

Stanford, J.A., E.B. Snyder, M.N. Lorang, D.C. Whited, P.L. Matson, and J.L. Chaffin. 2002. The reaches project: ecological and geomorphic studies supporting normative flows in the Yakima River basin, Washington. Flathead Lake Biological Station, Polson, Montana. (viii)

Stoddard, J.L., D.P. Larsen, C.P. Hawkins, R.K. Johnson, and R.H. Norris. 2006. Setting expectations for the ecological condition of streams: the concept of reference condition. Ecological Applications 16:1267–1276. (i)

Snyder, E.B., and J.A. Stanford. 2001. Review and synthesis of river ecological studies in the Yakima River, Washington, with emphasis on flow and salmon habitat interactions. Flathead Lake Biological Station, Polson, Montana. (viii)

Sweeney, B.W., and J.D. Newbold. 2014. Streamside buffer width needed to protect stream water quality, habitat, and organisms: a literature review. Journal of the American Water Resources Association 50:560-584. (i)

Talabere, A.G. 2002. Influence of water temperature and Beaver ponds on Lahontan Cutthroat Trout in a high-desert stream, southeastern Oregon. Master's thesis. Oregon State University, Corvallis. (i)

Tait, C.K., J.L. Li, G.A. Lamberti, T.N. Pearsons, and H.W. Li. 1994. Relationships between riparian cover and the community structure of high desert streams. Journal of the North American Benthological Society 13:45-56. (i)

Tate, K., G. Nader, and D. Lewis. 2000. Evaluation of buffers to improve the quality of runoff from irrigated pastures. Journal of Soil and Water Conservation 55:473–478. (i)

Thomas, F.M. 2014. Ecology of phreatophytes. Progress in Botany 75:335-375. (i)

Thomas, J.W., C. Maser, and J. E. Rodiek. 1979. Wildlife habitats in managed rangelands – the Great Basin of southeastern Oregon: riparian zones. GTR-PNW-80. U.S. Forest Service, Pacific Northwest Experimental Station, Portland, Oregon. (viii)

Thomas, H., and T.R. Nisbet. 2007. An assessment of the impact of floodplain woodland on flood flows. Water and Environment Journal 21:114-126. (i)

Thut, R.N., and E.P. Haydu. 1971. Effects of forest chemicals on aquatic life. Pages 159-171 in J.T. Krygier and J.D. Hall, editors. A symposium on forest land uses and the stream environment. Continuing Education Publications, Oregon State University, Corvallis. (i)

Toledo, Z.O., and J.B Kauffman. 2001. Root biomass in relation to channel morphology of headwater streams. Journal of the American Water Resources Association 37:1653-1663. (i)

Tribal Tribune. 2013. Horses on the landscape. Available: http://www.tribaltribune.com/news/article_3abf8d87-e606-54b1-9e42-5ef6c0fb1036.html. (February 2018). (viii)

Triska, F.J., J.R. Sedell, K. Cromack Jr, S.V. Gregory, and F.M. McCorison. 1984. Nitrogen budget for a small coniferous forest stream. Ecological Monographs 54:119-40. (i)

Tu, M. 2006. Reed Canarygrass, *Phalaris arundinacea*. Pages 12–13 *in* P.D. Boersma, S.H. Reichard, and A.V. van Buren, editors. Invasive species in the Pacific Northwest. University of Washington Press, Seattle. (i)

Tuttle, G.M., G.L. Katz, J.M. Friedman, and A.P. Norton. 2016. Local environmental context conditions the impact of Russian Olive in a heterogeneous riparian ecosystem. Invasive Plant Science and Management 9:272-289. (i)

USACE (U.S. Army Corps of Engineers). 2002. Final Lower Snake River juvenile salmon migration feasibility report/environmental impact statement, Appendix I: Economics. Walla Walla District, Washington. (i)

USBR (U.S. Bureau of Reclamation). 2017a. Yakima Project. Available: https://www.usbr.gov/projects/index.php?id=400. (September 2018). (viii)

USBR (U.S. Bureau of Reclamation). 2017b. Columbia Basin Project. Available: https://www.usbr.gov/projects/index.php?id=438. (September 2018). (viii)

USBR & WDOE (U.S. Bureau of Reclamation and Washington Department of Ecology). 2012. Final programmatic environmental impact statement Yakima River basin integrated water resource management plan. Yakima, Washington. (viii)

USFS (U.S. Forest Service). 2004. Riparian restoration. 0423 1201–SDTDC. Technology & Development Program, San Dimas, California. (viii)

USFWS (U.S. Fish and Wildlife Service). 1994. An ecosystem approach to fish and wildlife conservation. Washington, D.C. (viii)

Vaccaro, J.J. 2011. River-aquifer exchanges in the Yakima River basin, Washington. U.S. Geological Survey, Reston, Virginia. (viii)

Warren, S.D. 2014. Role of biological soil crusts in desert hydrology and geomorphology: implications for military training operations. Reviews in Engineering Geology 22:177-186. (i)

Webb, R.H., and S.A. Leake. 2006. Ground-water and surface-water interactions and long-term change in riverine riparian vegetation in the southwestern United States. Journal of Hydrology 320:302-323. (i)

Weddell, B.J. 2001. Changing perspectives in nineteenth century written descriptions of Palouse and canyon grasslands. Technical Bulletin No. 01-13. Bureau of Land Management, Cottonwood District, Cottonwood, Idaho. (viii)

West, E., and G. Ruark. 2004. A long, long time ago: historical evidence of riparian forests in the Great Plains and how that knowledge can aid with restoration and management. Journal of Soil and Water Conservation 59:105A-110A. (i)

Westbrook, C.J., D.J. Cooper, and B.W. Baker. 2006. Beaver dams and overbank floods influence groundwater-surface water interactions of a Rocky Mountain riparian area. Water Resources Journal 42:W06404. (i)

Westbrook, C.J., D.J. Cooper, and B.W. Baker. 2011. Beaver assisted river valley formation. River Research and Applications 27:247–256. (i)

White, P., and J.L. Walker. 1997. Approximating nature's variation: selecting and using reference information in restoration ecology. Restoration Ecology 5:338-349. (i)

Whiting, P.J., and M. Pomerants. 1997. A numerical study of bank storage and its contribution to streamflow. Journal of Hydrology 202:121-136. (i)

Winter, T.C., J.W. Harvey, O.L. Franke, and W.M. Alley. 1998. Ground water and surface water: a single resource. Circular 1139. U.S. Geological Survey, Denver, Colorado. (viii)

Wissmar, R.C. 2004. Riparian corridors of eastern Oregon and Washington: functions and sustainability along lowland-arid to mountain gradients. Aquatic Sciences 66:373-387. (i)

Wissmar, R.C., J.E. Smith, B.A. McIntosh, H.W. Li, and G.H. Reeves. 1994. A history of resource use and disturbance in riverine basins of eastern Oregon and Washington (early 1800s-1990s). Northwest Science 68 (special issue):1-35. (i)

Wohl, E. 2005. Compromised rivers: understanding historical human impacts on rivers in the context of restoration. Ecology and Society 10(2):2. (i)

Wohl, E., B.P. Bledsoe, R.B. Jacobson, N.L. Poff, S.L. Rathburn, D.M. Walters, and A.C. Wilcox. 2015. The natural sediment regime in rivers: broadening the foundation for ecosystem management. Bioscience 65:358-371. (i)

WSDA (Washington State Department of Agriculture). 2016. Washington State noxious weed general distribution maps. Olympia, Washington. Available: https://agr.wa.gov/washington-agriculture/maps/weed-distribution. (January 2020). (viii)

Wuehlisch, G.V. 2011. Evidence for nitrogen-fixation in the Salicaceae family. Tree Planter Notes 54(2):38-41. (i)

WWBWC (Walla Walla Basin Watershed Council). 2013. Walla Walla basin aquifer recharge strategic plan. Milton-Freewater, Oregon. (viii)

Xiong, S., and C. Nilsson. 1997. Dynamics of leaf litter accumulation and its effects on riparian vegetation: a review. Botanical review 63:240–264. (i)

YN (Yakama Nation). 2010. Wild Horse (K'u-See) Project. Wildlife, Range & Vegetation Resources Management Program, Confederated Tribes and Bands of the Yakama Nation, Toppenish, Washington. Available: https://www.ynwildlife.org/wildhorseprogram.php. (February 2018) (viii)

YSPB (Yakima Subbasin Planning Board). 2004. Yakima subbasin plan. Yakima Subbasin Fish and Wildlife Planning Board, Benton and Yakima counties, Washington. (viii)

Yuan, Y., R.L. Bingner, and M.A. Locke. 2009. A review of effectiveness of vegetative buffers on sediment trapping in agricultural areas. Ecohydrology 2:321-336. (i)

Zhang, X., X. Liu, M. Zhang, and R.A. Dahlgren. 2010. A review of vegetated buffers and a meta-analysis of their mitigation efficacy in reducing nonpoint source pollution. Journal of Environmental Quality 39:76-84. (i)

Zoellick, B.W. 2004. Density and biomass of redband trout relative to stream shading and temperature in southwestern Idaho. Western North American Naturalist 64:18-26. (i)

Chapter 8. Watersheds

By: Derek B. Booth

8.1. Introduction

This chapter on watershed-scale processes and management looks beyond the typical site-by-site perspective at which riparian management and stream protection is normally applied. This chapter also considers the interactions between site-specific treatments, whose collective effects may be greater (or less) than anticipated by the individual actions themselves, and it uses these insights to offer a broader approach to riparian management for the protection of aquatic systems. Given this expanded focus, the conditions and influences discussed here may lie outside the framework of normal guidance and regulatory mandates, but they nonetheless affect the health and productivity of riparian areas and their associated aquatic systems. Thus, the conceptual framework provided here should be useful when considering the likely effects of riparian management policies or practices.

The purpose of this chapter is to explore the relationship (and the importance) of watershed-scale management to achieving the goal of abundant, self-sustaining fish and wildlife populations. It assumes that a broader watershed-scale perspective on aquatic ecosystems will ultimately enhance the beneficial effects of management applied at all scales.

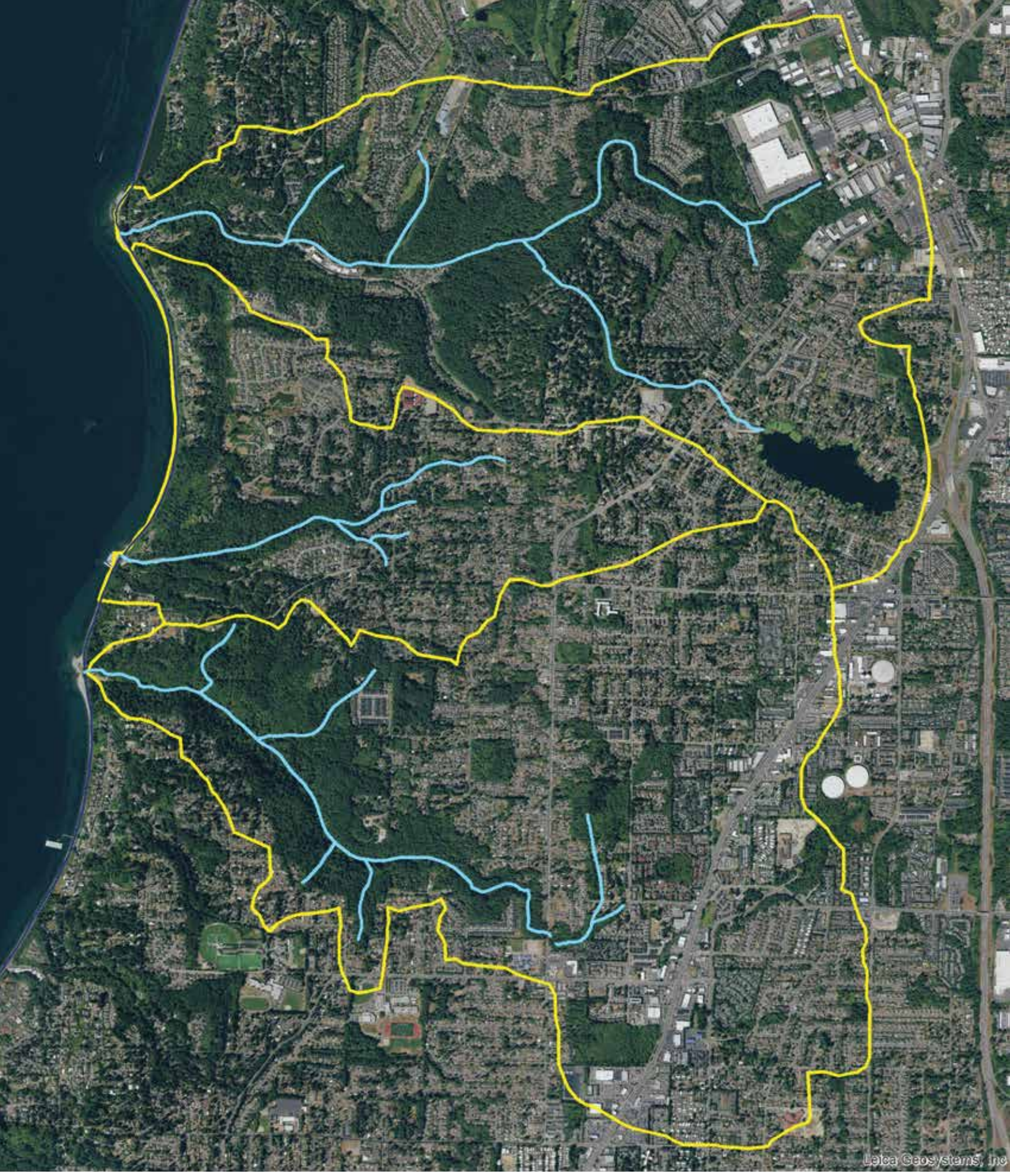
The chapter is divided into four primary sections:

1. A conceptual framework that identifies the key watershed processes and their primary influences on riparian ecosystems and their watercourses, a perspective with a long history in the scientific literature. However, advances in the discipline of landscape ecology over the past two decades—particularly the recognized importance of interrelationships between landscape elements in both spatial (e.g., connectivity and discontinuities) and temporal (e.g., disturbances and recovery) domains—have changed how biological and physical scientists view aquatic ecosystems and the riverine landscape that they occupy.

2. A discussion of how riparian management at the site scale, the emphasis of the other chapters in this document, can best support ecological functions and improve habitat conditions for fish and wildlife, even if a complementary set of watershed-scale management actions (e.g., land use at the watershed scale) cannot be implemented.

3. A description of how individual site-scale management actions, and their recognized site-scale benefits, relate to one another across a channel network and/or landscape. In other words, how do the consequences and overall value/benefit of isolated actions integrate along a channel network? Are the effects of individual actions simply additive, or are there synergistic effects that are revealed by a landscape ecology perspective?

4. Guidance, developed from an understanding of watershed processes and the perspective of landscape ecology, for improving the management of riparian ecosystems. This goal is complicated by the fact that most watersheds are managed under diverse and often uncoordinated responsibility: different landowners and managers have different goals and objectives. Furthermore, many of these managers have neither responsibility nor a process by which to coordinate their



Three watersheds (outlined in yellow) in urban areas of north Seattle/Terry Johnson, WDFW

actions, especially over the long durations necessary for riparian management actions to achieve their greatest effects. This chapter offers no prescription for resolving these challenges, but it proceeds under the belief that greater awareness of these interactions will ultimately lead to more successful protection of riparian systems, streams, and their biota.

8.2. Conceptual Framework

This chapter seeks to integrate the functions of riparian ecosystems into the overall landscape in which they interact–the riverine landscape or *riverscape*. This riverine landscape differs from the contributing watershed of the river or stream: although the flux of water and water-borne biota respect the drainage divides of a watershed almost exactly, other components do not. In particular, mobile organisms (e.g., birds, and large mammals such as American Beaver *Castor canadensis*, and bear (*Ursus* spp.), wind-borne seeds, and wildfire all have the potential to affect and be affected by landscape elements both within and beyond the boundaries of any given watershed, and so they must be included in any comprehensive conceptual framework (Figure 8.1). Despite these watershed-crossing elements, the lotic (flowing-water) environment itself is strongly organized by the unidirectional flow of water, a property that is distinct from terrestrial environments, and so rivers commonly display systematic patterns in the downstream direction (e.g., the "river continuum" of Vannote 1980.) They also display systematic cross-stream patterns, notably the spatial, physical, and ecological relationships between the channel and its adjacent floodplain; and to a less visible but still significant degree in the vertical dimension as well, particularly the interaction of shallow groundwater with stream water in the hyporheic zone (Boulton et al. 1998).

Landscape ecology is the scientific discipline best suited to this larger perspective of the riverine landscape: "...we perceive a need to conceptualize rivers not as sampling points, lines, or gradients, but as spatially continuous longitudinal and lateral mosaics. As such, heterogeneity in the river landscape, or riverscape, becomes the focus of study" (Fausch et al. 2002:485) (Figure 8.2). The foundational premise of landscape ecology is that both biotic and abiotic elements of the landscape interact with one another, and those interactions are spatially mediated (Malanson 1995).

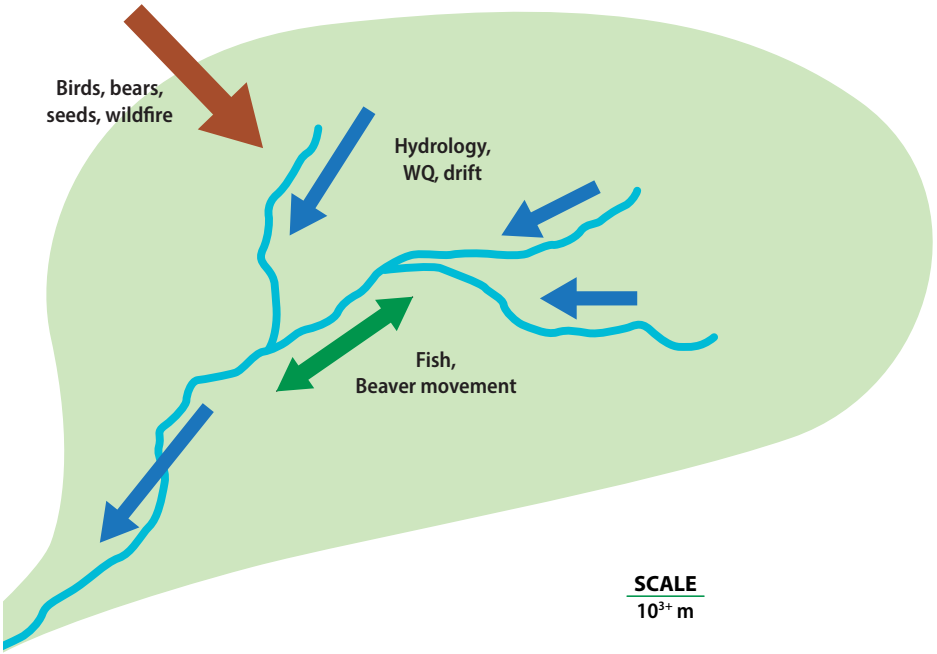


Figure 8.1. Movement of water and biota at the whole-watershed scale. WQ refers to water quality, and drift refers to the downstream transport of bottom-dwelling invertebrates by flowing water.

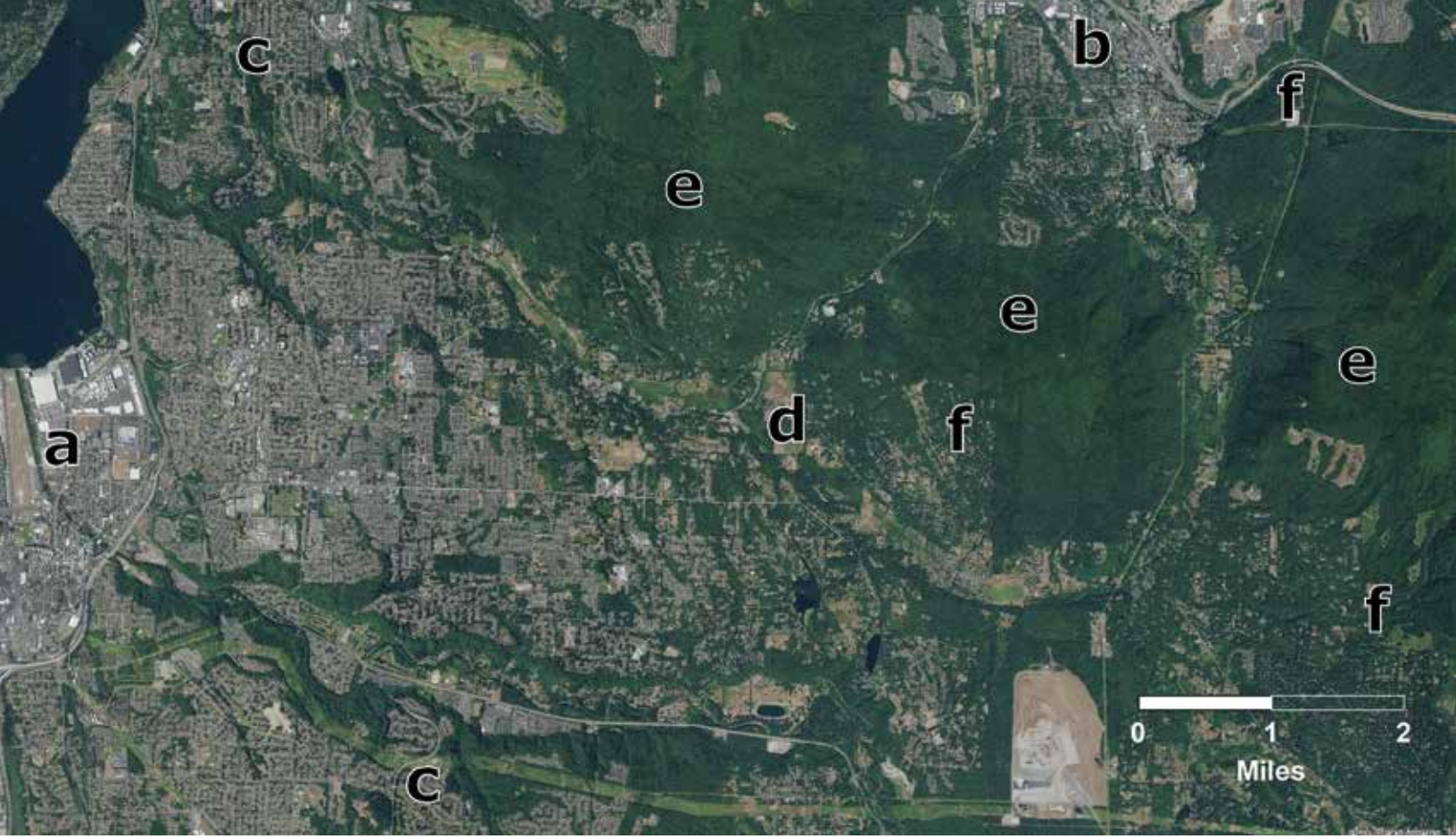


Figure 8.2. An example of landscape heterogeneity at multiple scales in an aerial view that includes the urban centers of Renton (west edge, labeled a) and Issaquah (northeast corner, b); suburban development throughout the south-central and northwest parts of the image (c); agriculture and rural-residential development, particularly in the valleys of May Creek and McDonald Creek trending NW across the center of the image (d); and extensive forest lands of Cougar, Squak, and Tiger Mountains (e) in the north-central and east parts. At finer spatial scales within the largely undeveloped areas in the eastern part of the image, fragmentation is nonetheless widespread from roads, utility lines, and clearing for residential lots and subdivisions (f).

This perspective emphasizes the importance of spatial heterogeneity; it also acknowledges the key role of episodic disturbances in determining the flux of energy and materials, the movement of organisms, and the creation of unique dynamics within the watershed (Wiens 2002).

At a finer spatial scale, water and biota interact across the permeable and dynamic boundary between riparian areas and a watershed's uplands (Figure 8.3, left panel). These areas comprise multiple components. Within riparian areas, these components include surface waters, in-channel bars and islands, floodplains, marshes, wet meadows, alluvial forests, and woody debris. For the uplands, these components might include unstable slopes, aquifer recharge areas, wetlands, seeps, forests, and areas of intensive human modification. Both areas also include the vast variety of organisms that occupy one or more of these habitats.



River running through rural residential area/Jane Atha, WDFW

Riparian areas occupy a particularly dynamic and disturbance-prone region (Figure 8.3, right panel) that can experience decadal, annual, or even more frequent flood events that locally alter, rearrange, or obliterate its components altogether.

> *In the natural state, riverine landscapes exemplify the* new paradigm in ecology *(sensu Talbot 1996), in which ecological systems are widely recognized as non-deterministic, open systems in continual states of flux, rather than internally regulated, homeostatic systems exhibiting equilibrium conditions. Yet, despite their highly dynamic nature, riverine landscapes provide predictable ecological conditions. Although individual landscape components exhibit high turnover, largely as a function of interactions between fluvial dynamics and successional phenomena, their relative abundances in the river corridor as a whole tend to remain constant over ecological time. [From Ward et al. 2002:518.]*

So, for example, a flood may scour a gravel bar at one location in a river and deposit sediment in another; but along any given channel reach the relative frequency of pools and bars may not vary substantially over time. The resulting transience and diversity of habitats provide a variety of habitats that, although ideally always present in aggregate, are not necessarily static in place or time (Robinson et al. 2002). Thus, managers should recognize this dynamic equilibrium as the key attribute of a truly functional riparian–aquatic ecosystem and make the protection of its dynamic *behavior* (rather than any specific *feature*) the overarching goal of riparian management.

Existing policies, however, generally do not facilitate management for dynamic conditions:

> *Policies setting underlying riparian goals that are essentially static and homogenous have become an integral part of many of the management guidelines that drive the goals for riparian management on federal, state and private lands in western Washington. Discussions [at a statewide forest management symposium] did not indicate that current management and policy guidelines necessarily preclude practices that might produce dynamic and heterogeneous riparian conditions. Because they promote uniform conditions over large areas, however, current policy and management guides do little to encourage treatments that would lead to ecologically diverse landscapes that could maintain critical functions that were formerly produced by natural disturbance regimes... [From Ryan and Calhoun 2010:viii-ix].*

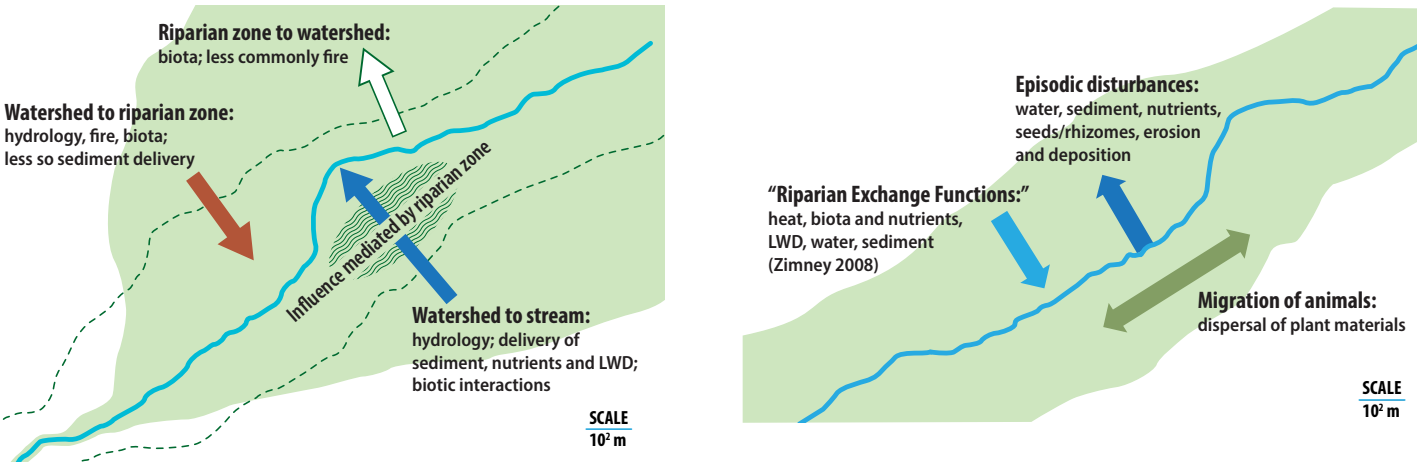


Figure 8.3. Movement of water, biota, and other elements of the aquatic system from the watershed into and through riparian areas (left) and between riparian areas and the stream (right).

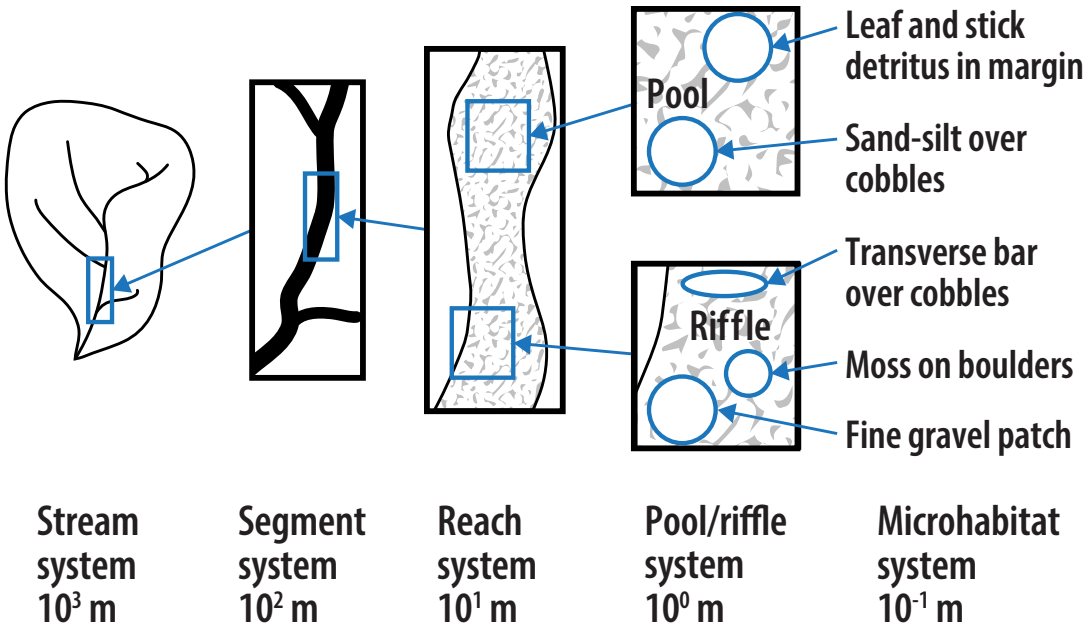


Figure 8.4. Hierarchical spatial organization of a watershed and its aquatic habitats. Approximate spatial scale, appropriate to second or third-order mountain stream (modified from Frissell et al. 1986).

On the other hand, riparian areas have experienced high levels of anthropogenic disturbance, both directly (e.g., harvest, road building) and indirectly (e.g., windthrow, landslides, and forest fire) due to forest management, which also compromises the dynamic equilibrium in riparian-aquatic ecosystems. In response, policy makers have reduced forest management-related disturbances in riparian areas, with the intent of passively reestablishing underrepresented late-seral classes (such as mature forest) which should improve riparian ecological functions, and conserve fish and wildlife species dependent on older forest. Such policies are all likely necessary parts of a successful riparian management strategy. However, because they do not address watershed-scale processes, these policies by themselves are almost surely insufficient to achieve desired riparian and aquatic ecosystem outcomes.

8.2.1. What are Watershed Processes?

Although the immediate goal of riparian management is the protection of species and their habitats, Frissell et al. (1986:199) suggested that "[w]e begin with the assumption that structure, operation, and other aspects of the organization and development of stream communities are largely determined by the organization, structure, and dynamics of the physical stream habitat." (Using the terminology elsewhere in this document, these terms correspond to the structure, composition, and functions of physical habitat). If so, "the problem becomes one of understanding these physical patterns across time and space. This requires a broad, integrative framework that places streams, their habitats, and their

communities in wider geographic context" (Frissell et al. 1986:200). Frissell et al. (1986) developed this wider context by describing a spatial hierarchy that recognizes the influence of larger scale conditions and processes acting primarily (but not exclusively) unidirectionally on smaller scales (Figure 8.4). Factors that are best characterized over the largest extents, and that exert their influence over longest time frames, can be thought of as the ultimate "drivers" of the conditions and processes at lower levels in the hierarchy.

Three overarching process drivers—climate, geology, and topography—structure the suite of landscape-forming processes that are distributed over a landscape and that, in turn, govern watershed characteristics and processes (paraphrasing the framework of Montgomery 1999). At management time scales (i.e., years to decades), these process drivers are invariant and immutable—they are the "givens" under which a watershed evolves. The physical habitat features of any watershed do not simply arise from these process drivers directly, however; instead, they are created and continuously modified by the fluxes of materials (particularly water and sediment) and energy that arise from these process drivers and are widely termed watershed processes. Watershed processes are defined as "[t]he dynamic physical and chemical interactions that form and maintain the landscape and ecosystems on a geographic scale of watershed to basins (i.e., hundreds to thousands of square miles)" (Stanley et al. 2011:8).

To this simple, unidirectional, physical model of watershed influences must be added a few complications of lesser but still critical importance. First, the flow of influence is not always one-way: although topography exerts the dominant influence on the flow of water, over time the erosion by that flowing water will alter the topography to some degree (which, over geologic time scales, may be sufficient to change the very boundaries of the watershed). Second, biota are not always passive respondents to the presence and changes of physical habitat, but instead can also influence that physical habitat in ways that are only slowly being recognized (see Moore 2006 for an overview of such effects). Robinson et al. (2002) emphasizes the role of fauna as ecosystem engineers of riverine landscapes, for which the modification of stream substrates by spawning salmon (Montgomery et al. 1996) or the rearrangement of floodplain dynamics by Beaver (Pollock et al. 2003) are two widely recognized examples. Biological conditions and processes are also of fundamental importance to the expression of some watershed processes: the flux of nutrients may not alter the physical habitat but is key to the health of the ecosystem; the character and extent of vegetative cover will greatly mediate the effects of topography, climate, and geology on the movement of runoff, the downslope transport of sediment, and the potential for dramatic, process-altering wildfire. Finally, the effects of people and human activities cannot be ignored in any useful conceptual framework applied to the modern landscape. Although direct modification of habitat and streams is an obvious impact with a long historical legacy in the Pacific Northwest (and beyond), the aggregate effects of human activities across whole watersheds can be even more consequential to instream resources, to the extent that land use, in many settings, becomes no less of a process driver (i.e., a determinant in a watershed) than is topography or climate.

These concepts are integrated into Figure 8.5, which emphasizes the unidirectional, hierarchical flow of influence from the large-scale process drivers onto the watershed processes that, in turn, give rise to the instream physical and ecological conditions and responses. This representation is not intended to deny the *upstream* influences that also occur (see Beechie et al. 2010, Figure 1 as an alternative representation), but it sacrifices completeness for clarity in acknowledging the overriding importance of this unidirectional perspective. This conceptual model also articulates the variety of processes that are embraced within each of the major watershed processes we

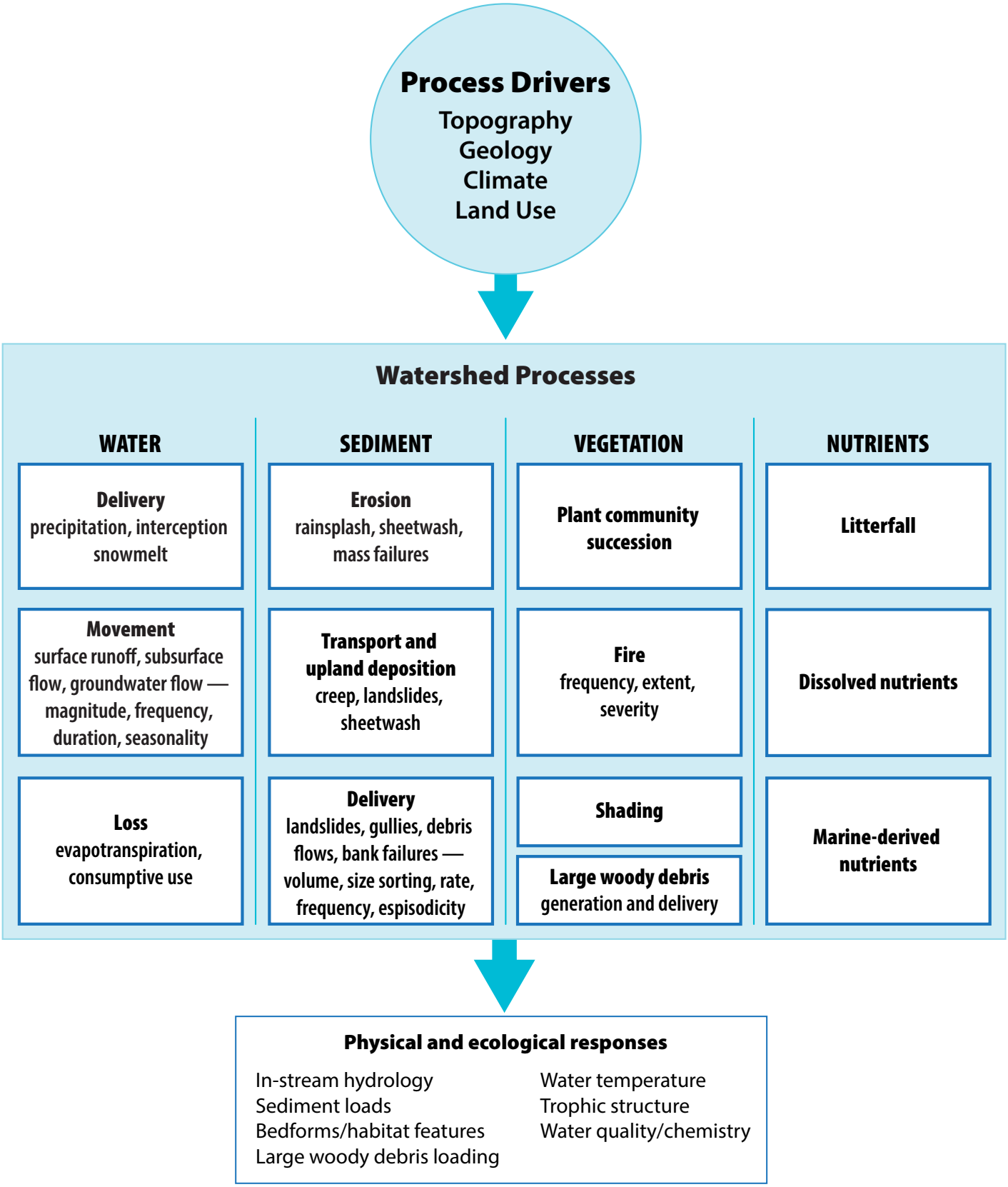


Figure 8.5. Conceptual framework for the hierarchical relationship of invariant, large-scale process drivers, the suite of watershed processes that are determined by these drivers, and the instream physical and biological responses to those processes. Multiple additional interactions between elements and levels are not shown on this diagram to emphasize the primary influences; but in any given setting, one or more of these secondary interactions may temporarily achieve equivalent importance. This framework embraces the definition of watershed processes from Stanley et al. (2011:8): "[t]he dynamic physical and chemical interactions that form and maintain the landscape and ecosystems."

recognize (water, sediment, vegetation, and nutrients), and it reminds us of the major instream responses to these dynamic watershed processes.

8.2.2. How Does the Watershed Affect Instream Conditions?

The direct effects (both physical and biological) of watershed processes on the stream channel are most commonly understood as the delivery of material from the watershed, with or without some attenuation or other modifications as they pass through the riparian ecosystem: water, sediment, nutrients, pollutants, and large wood. These materials are delivered primarily by surface water flow, subsurface flow, landslides and debris flows (Figure 8.6). These fluxes of material and energy from the broader riverine landscape interact with those arising from the riparian corridor itself, to different degrees and over different time scales, with a resulting complexity that defies our current efforts to quantitatively predict their expression in the physical form or biological condition of a stream.

The complexity of these interactions is highlighted by relatively weak correlations reported between various instream features and landscape predictors, regardless of the spatial scale being evaluated (e.g., whole-watershed vs. riparian areas). For example, Anlauf et al. (2011) evaluated the correlation between eleven instream habitat features with landscape variables characterizing both process drivers (e.g., watershed gradient, rainfall) and management-influenced factors (e.g., forest cover, disturbance history, road density) across 121 coastal Oregon streams. The strongest relationships showed unexceptional correlations between particular habitat features and the suite of landscape variables (active channel width, R^2 = 0.72; percentage of fine sediments, R^2 = 0.48). Other habitat features expressed essentially no relationship (percentage gravel, R^2 = 0.05; pools per 328 ft (100 m), R^2 = 0.11; percentage secondary channel area, R^2 = 0.12). Including management-influenced predictors increased adjusted R^2 values only modestly (by up to 16%). Many of the strongest relationships followed intuitive expectations, such as: "Wood volume was associated with several landscape predictors reflecting wood availability (% non-forest, % small trees, and % remnant forests), whereas pools per 328 ft (100 m) were associated with disturbances affecting pool retention (cow density, road density) and pool formation (% small trees)" (Anlauf et al. 2011:708). However, no relationship was sufficiently strong to suggest that either deterministic understanding or statistical correlations are sufficient to precisely characterize the influence of watershed-scale processes on a stream.

Our inability to predict instream conditions from watershed processes and riparian conditions with any useful degree of accuracy is widely recognized. In part, this inability is because the riparian corridor itself has significant, complex effects on the stream (see other chapters in this document). In addition, all of these influences—at every spatial scale—occur within a time-dependent framework mediated by rates of vegetation growth and decay, seasonal variations in flow, and episodic disturbances from floods, and even less frequent but potentially long-lasting channel impacts from fire or landslides (Lake 2000; Roper et al. 2007; Luce et al. 2012; Jellyman et al. 2013).

> ***[E]mpirical associations between land use and stream response only varyingly succeed in implicating pathways of influence. This is the case for a number of reasons, including (a) covariation of anthropogenic and natural gradients in the landscape; (b) the existence of multiple, scale-dependent mechanisms; (c) nonlinear responses; and (d) the difficulties of separating present-day from historical influences. [From Allan 2004:257.]***

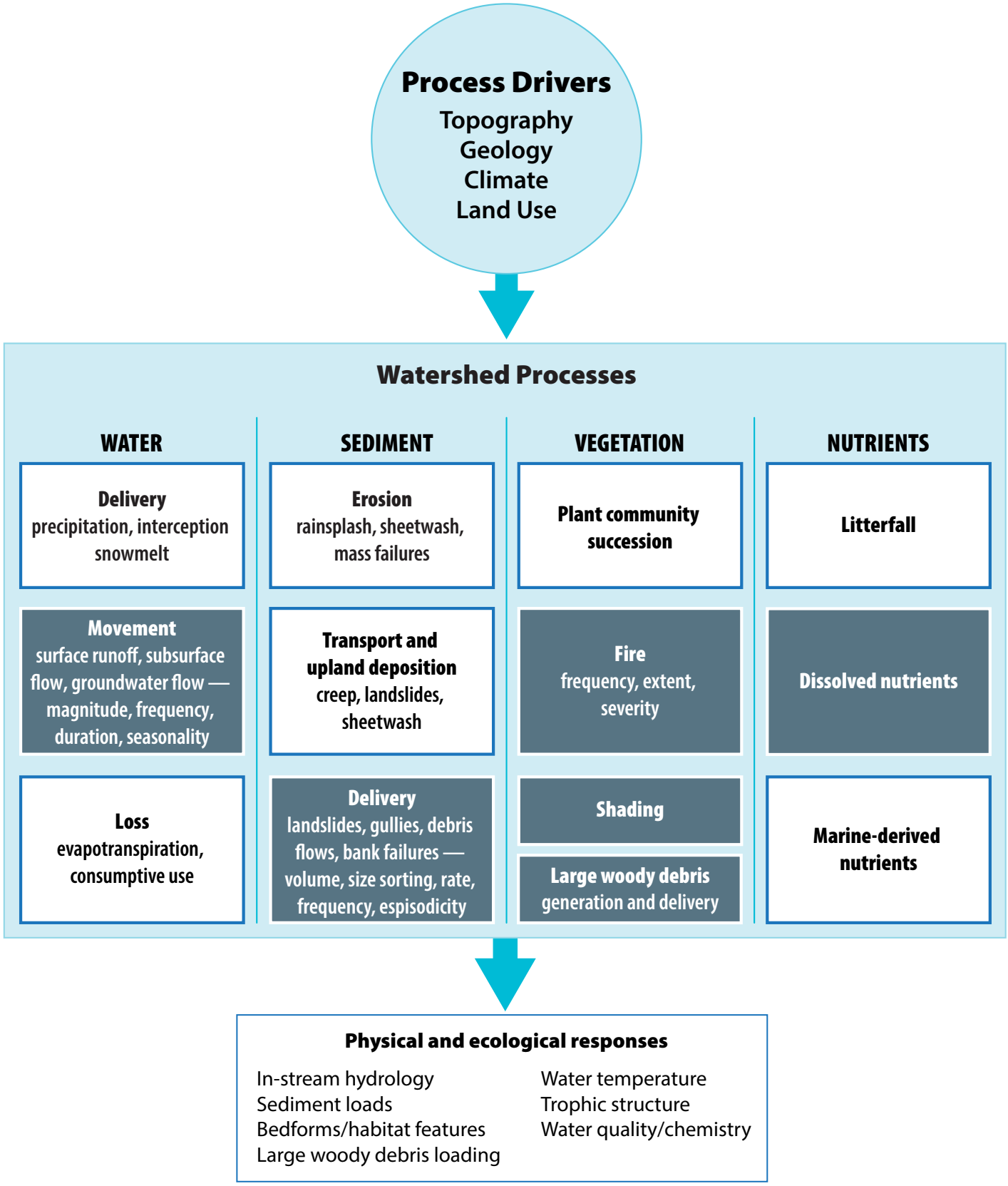


Figure 8.6. The conceptual framework of Figure 8.4, highlighting the subset of watershed processes (dark shaded boxes) that most directly affect instream conditions.



Clearcut harvest in a managed forest landscape/Jane Atha, WDFW

Regardless of our present inability to make reliable predictions of instream conditions from watershed processes, watershed processes do create and maintain instream habitat, and so the determinants of those processes are of indirect, but ultimately critical importance, to the understanding and the management of aquatic resources. Because the nature and intensity of these processes are strongly influenced by prevailing (and past) watershed land use(s), the effects of the dominant land use activities of the Pacific Northwest are discussed individually.

Forestry

The effects of watershed-scale forestry on instream conditions have been a primary focus of scientific research and forest practice regulations for many decades. Most of the attention has been paid to several discrete problems: increased stream temperature from loss of riparian vegetation, the degree to which large-scale loss of forest canopy alters the hydrologic regime, whether the creation of new roads has a discernible impact on both hydrology and sediment delivery to the channel network, and whether forest practices increase the frequency and intensity of debris flows and other forms of mass failure that reach the stream.

The potential for hydrologic alteration in logged watersheds focuses on two major mechanisms: 1) the loss of forest canopy, which should increase total water yield by reducing interception and evapotranspiration, and increase accumulation of snow on canopy-less ground, which increases the total volume of water available during subsequent rain-on-snow events, and 2) more rapid drainage of surface runoff to stream channels from a newly created road network. The review article of Andréassian (2004:12) provides a convenient summary of much of the voluminous literature on this topic, concluding that "deforestation could definitely increase both flood volumes and flood peaks. However, this effect is much more variable than the effect on total flow and may even be inverted in some years or in some

seasons." The underlying causes for such increases are associated not only with the loss of forest canopy but also (and, perhaps, primarily) the consequences of soil compaction and development of the road network.

Increased sediment delivery to streams from watersheds is an anticipated outcome of both the direct and indirect effects of logging. Direct consequences result from the loss of canopy cover, increasing the potential for rainsplash and sheetwash erosion in areas of intrinsically low infiltration capacity, and the eventual loss of soil cohesion in areas of steep slopes. Indirect effects result from the construction of roads, for which inappropriate siting can result in sheetwash erosion and a greater incidence of landslides and debris flows from either concentrated road runoff or failure of the road prism itself. A variety of case studies making use of detailed field mapping, radionuclide tracers, and suspended sediment measurements have implicated various landscape features and erosive processes in post-logging watersheds, such as skid trails and landings, promoting surface runoff and erosion (Wallbrink et al. 2002), enhanced gully erosion (Reid et al. 2010), and road-initiated debris flows (May 2002).

Nutrient dynamics across the watershed are also affected by forest practices, with potential effects throughout the ecosystem (including the channel network and its riparian corridor). Richardson et al. (2005) offered a well-focused and detailed evaluation of the consequences of watershed disturbance, including logging, on the delivery and retention of organic matter in small streams of the Pacific Northwest. He noted that the replacement of coniferous with deciduous trees in recently logged areas can increase the delivery of nutrients, but that more rapid breakdown of delivered material and the accompanying reduction in both large wood and channel complexity, commonly expressed throughout the channel network of logged watersheds, "could produce a substantial reduction in stored organic matter." (Richardson et al. 2005:930).

Agriculture

Cultivated agriculture normally occupies a comparatively narrow range of low-gradient settings in a watershed. Thus, processes associated with steep slopes—particularly landslides and debris flows—found in logged watersheds are nearly absent here. However, the working of the agricultural land surface is far more intensive where it does occur, and a wider range of water-borne contaminants are potentially introduced. As with forestry, hydrology, sediment delivery, and nutrient dynamics are all affected by agricultural land use, but the nature and severity of its impacts on instream resources can be quite different. Runoff from agricultural watersheds, notably its load of nutrients and pesticides, were the historical impetus for the use of riparian buffers under an assumption of surface-runoff filtration (Osborne and Kovacic 1993). Brown et al. (2009) found that the legacy of prior agricultural land use, even in areas presently undergoing urbanization, is one of the strongest determinants of instream conditions in their nine study areas nationwide.

Grazing is a second, broad category of agricultural activities with significant impacts to streams, primarily as a result of direct encroachment into riparian areas and the channel itself. Belsky et al. (1999:2) reviewed dozens of mid- to late-20th century evaluations of grazing throughout arid lands of the American West that evaluated impacts to water quality and temperature, hydrology, channel geomorphology,

Watershed processes help create and maintain instream habitat. Thus the determinants of those processes are indirect but critically important to the understanding and the management of aquatic systems.

wildlife, and instream and riparian-zone vegetation. Their conclusion was that "[n]o positive environmental impacts were found" as a result of grazing, and they advocate complete cessation of grazing as the only sure course for recovery of riparian areas. More recent work (e.g., Agouridis et al. 2005; Raymond and Vondracek 2011) suggest that various strategies of rangeland management may have local success at reducing the magnitude of such impacts; but the large spatial extent over which grazing occurs in certain areas of the Pacific Northwest continues to make this a regionally significant impact to streams and riparian areas.

Urbanization

Urbanization is widely recognized to be the most intensive land use affecting watershed processes. It is also typically the most permanent, insofar as urban developments are rarely returned to anything approaching a natural state, a transition that is not precluded by agriculture and is quite practical in commercially managed forests. As a pervasive, near-total conversion of the land surface, urbanization has the ability to alter each of the dominant watershed processes wherever it occurs: hydrology (both surface and groundwater); the delivery of sediment, nutrients, pollutants, and sunlight; and the interaction of upland/terrestrial biota with the stream channel (Booth et al. 2004; Walsh et al. 2005). Nearly all of these alterations stem from the same fundamental change: the conversation of the land surface, with its vegetative cover and natural soils, to a variety of impervious and near-impervious surfaces. Undisturbed riparian corridors are widely recognized as useful protective measures for streams in urban areas, but all multi-scale evaluations of urban land cover and instream quality affirm the shared importance of not only riparian areas but also upland urbanization in ultimately determining instream conditions (e.g., Wang et al. 2001; Morley and Karr 2002). These watershed-level effects are significant at even low levels of urbanization (e.g., Vietz et al. 2014), and to date they have proven virtually impossible to control under typical riparian-management policies, highlighting the continuing challenge of achieving meaningful aquatic-system protection in an urbanizing watershed.

8.2.3. How Does the Watershed Affect Riparian Areas?

Changes to an upland watershed and watershed processes can also affect the conditions and functions of riparian areas directly (Figure 8.7). Although a riparian area is commonly defined in terms of its relationship to the stream, it also has a relationship to the uplands that surround it. Water from the stream channel will commonly be the riparian area's dominant source of both overland flow (during floods) and groundwater, but adjacent upland water sources can support riparian hydrology during periods of low flow. Much of the sediment that originates from the uplands is transported directly to the streams via channeled flow, but some fraction of that load will deposit before ever reaching the main channel, particularly if the riparian area includes a broad, low-gradient floodplain or if delivery occurs via episodic and channel-overtopping debris flows. Upland vegetation "buffers" riparian areas, providing

More important than simply protecting the habitat itself is protecting the processes that create and sustain that habitat. For this strategy to be successful, however, space in which that habitat can be expressed must also be protected.

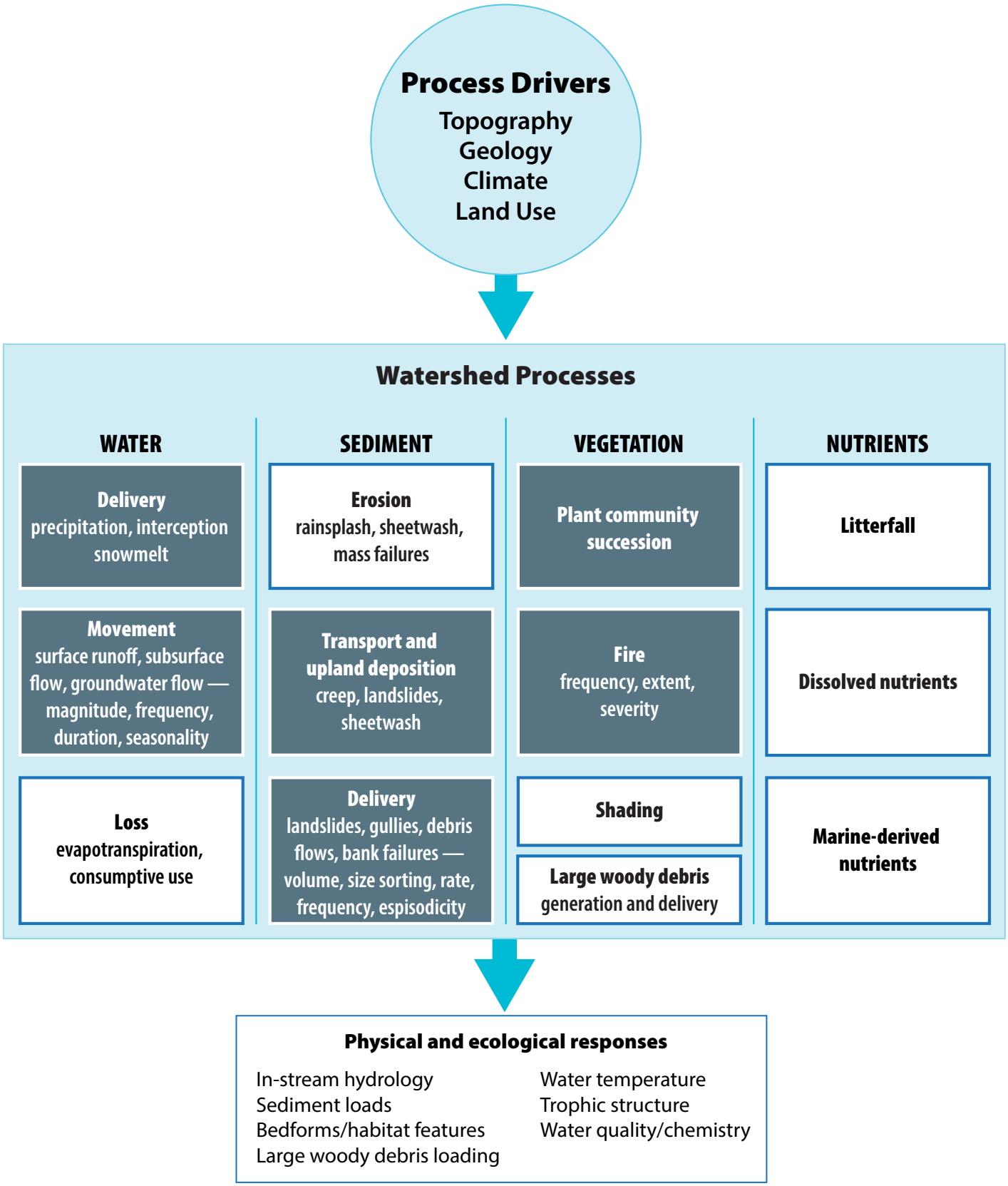


Figure 8.7. The conceptual framework of Figure 8.4, highlighting the subset of watershed processes (dark shaded boxes) that most directly affect conditions in riparian areas.

ecological connectivity between upland plant and animal communities with their riparian counterparts, and providing protection from mechanical disturbances, such as windthrow. Uplands also constitute a broader environment that either supports or suppresses wildfires that may freely cross the upland/riparian boundary.

Various land uses are relatively consistent with respect to their particular impacts to riparian ecosystems. That is, all three of the primary types (forestry, agriculture, urban) physically remove native vegetation, with differences only in the degree of impact. The loss of upland vegetation will consistently affect ecological connectivity and the risks of windthrow and fire regardless of the specific upland land use.

The interactions between uplands, riparian areas, and instream conditions are particularly complex with respect to wildfire. Arkle et al. (2010:299) found that "increasing riparian burn severity and extent were associated with greater year-to-year variation, rather than a perennial increase, in sediment loads, organic debris, large woody debris (LWD) and undercut bank structure." They emphasized a decrease in the stability of physical habitat and high variability in macroinvertebrate communities, which they attributed to annually fluctuating loadings of sediment, large wood and other organic material. They did not recognize any tendency for the macroinvertebrate community to become more like those of relatively undisturbed, reference streams over time, suggesting that changes to wildfire regime can result in permanent changes to stream ecosystems, and that these changes are a result not only of direct influence of burned areas on the stream but also of a permanently altered structure of the riparian corridor. With greater human disturbance, invasive species with high flammability (including those that have begun transforming riparian areas from fire breaks to fire-prone areas of a landscape; Coffman et al. 2010) become more common, as does the greater overall frequency of wildfire in modern human-dominated landscapes (Keeley et al. 2009). Thus this process driver, operating largely independent of typical considerations of riparian area management, can have a profound influence on instream resources (Pausas and Keeley 2014).



Wildfire in Methow River valley, 2018/ Scott Fitkin, WDFW

8.3. The Role and Limitations of Site-Scale Riparian Area Management

Whereas large-scale watershed processes govern the interactions and delivery of water, sediment, organic material, and nutrients to the stream over long distances, the effects of riparian vegetation on physical and ecological processes occur over much shorter distances with complex, direct, time-dependent interactions. These effects are expressed along river corridors "by influencing temperature and light regimes; producing organic detritus (leaf litter, woody debris); by routing water and sediment; by structuring the physical habitat at several scales; by providing a substrate for biological activity and habitat/cover for aquatic, amphibious and terrestrial animals" (Ward et al. 2002:524). For this reason, particular management attention to riparian areas is warranted, insofar as this part of a watershed has a unique, intimate interaction with the stream channel and its biota. Previous chapters explore these specific interactions in detail.

In addition to spatial relationships, temporal interactions are fundamental attributes of aquatic and riparian habitats. These habitats can be created by disturbances and also are episodically affected by them—streams are not static. Just as the influence of process drivers is not uniform across a watershed, so also is the influence of disturbances. In the case of floods, the most common and obvious of disturbances in rivers, this variability is primarily temporal and can be expressed through flood frequency, duration, seasonality (i.e., when in the year they occur), magnitude, and the predictability of occurrence (Lytle and Poff 2004).

The expression of these drivers, their interactions within a watershed and in individual streams, and their variability over time creates and maintains a dynamic mosaic of habitats. These interactions among drivers are complex and intertwined even in the absence of anthropogenic disturbances. Therefore, scientists have had difficulty separating the effects of the different drivers independently and in assessing how any species (even well studied salmon species) respond to this mosaic (Fausch et al. 2002). Adding to this complexity is the fact that habitats are species-specific; what constitutes habitat for one species may be mostly unrelated to what constitutes habitat for another aquatic species in the same river.

Thus, if riparian areas are managed with the objective of maintaining high-quality habitats for aquatic species, managers must ensure that riparian areas contribute what they can (i.e., separate from, but in combination with, watershed processes or drivers) to the long-term maintenance of the temporally variable spatial mosaic of habitat conditions. The mere presence of these habitats, however, is not sufficient: they must exist in configurations that are advantageous to aquatic species, with sufficient variety to support multiple life stages, adequate size and number to support a population, sufficiently proximate to be accessible from one to another, and yet sufficiently distal to not be subject to the same deleterious disturbances.

This, then, defines the fundamental challenge of watershed and riparian ecosystem management: given a system of great diversity and complexity, with attributes that can vary greatly and unpredictably in their influence over time, and biological communities that depend on both the diversity and interconnections between habitats, what fundamental principles should guide management to perpetuate fish and wildlife? We return to this question in the last section of this chapter.

8.4. Integrated Effects of Site-Scale Riparian Areas Management

"Connectivity" is the term most often used to describe whether organisms can move from one habitat to another (Taylor et al. 1993). It comprises two parts: structural connectivity, the physical relationships among habitat patches without regard for the behavior or organisms; and functional connectivity, the degree of movement of organisms through the landscape (Taylor et al. 2006; Kadoya 2009). The two are obviously related in all landscapes, but lotic systems impose some characteristic influences. First, there is a strong (though not universal) downstream bias on functional connectivity, insofar as most organisms and all inert constituents move in the direction of water flow. Second, impediments to flow can impose partial barriers to both structural and functional connectivity, but to very different degrees. For example, a culvert may allow most or all discharges to pass unimpeded but nevertheless present a barrier to migrating salmon (e.g., Davis and Davis 2011).

Concern over longitudinal barriers along a channel network typically focuses on the effects of instream physical barriers, particularly dams, culverts, and road crossings, rather than the consequences of longitudinal disturbances to riparian areas more broadly. Instream connectivity and riparian connectivity are related, however, even if they are not direct surrogates. Some types of discontinuity (e.g., a road running perpendicular to the stream) will affect the longitudinal connectivity (both structural and functional) of both; but others (e.g., an impassible migration barrier in the stream) will affect the movement of aquatic and terrestrial organisms quite differently. Most importantly from the perspective of riparian management, alterations that are limited to riparian areas can nonetheless affect instream (functional) connectivity. For example, loss of shading from riparian area disturbance (Chapter 4) can create unfavorable instream temperatures that impact the movement or outright survival of migrating salmonids (e.g., Thorstad et al. 2008; Martins et al. 2012). Other direct and indirect actions, such as channelization, removal of large wood, or bank failures from vegetation loss can affect connectivity for migratory fish and among other aquatic species, and alter the flow of material and nutrients through the stream network.

These impacts have been explored in a variety of studies at multiple scales. Flitcroft et al. (2012:288) reported that "…[spatial] network variables perform better at explaining juvenile Coho Salmon *Oncorhynchus kisutch* density than instream habitat variables. Moreover, analysis of network distances among seasonal habitats indicates that juvenile Coho Salmon density may be higher where the distance between critical seasonal habitats is short." Perkin and Gido (2012:2183) found lower species richness in fish communities in stream networks fragmented by road crossings across multiple spatial scales. "Our findings support network connectivity as a mediator of ecological processes occurring within complex dendritic ecosystems and promote the need for improved connectivity to enhance conservation of metacommunity dynamics and biodiversity in dendritic ecological networks." Similarly, Favaro et al. (2014:1815) interpreted their findings on the influence of culverts in a channel network to demonstrate that "…fragmentation of habitats and populations acted on a whole stream scale rather than being restricted to within-stream differences that related to position."

These findings speak to the importance of recognizing the channel as part of the riparian ecosystem, that is, they form an interconnected system, both laterally and longitudinally. The degree to which seemingly isolated discontinuities affect either of these elements directly can ultimately impact the entire ecological network. Prescriptive management is challenging, however,



Chum Salmon Oncorhynchus keta *need connected habitat to reach spawning grounds/Alex Biswas, WDFW*

because the ecological functions of any given site or habitat patch along a channel network depend on its context and interconnection with other such sites. Furthermore, not all habitats have the same value for all species:

> ***The relationship between species richness and connectivity is therefore determined by complex relationships among several interacting variables. In addition, species richness maxima for different faunal and floral elements occur at different positions along the connectivity gradient (Tockner et al. 1998). Fish diversity, for example, may peak in highly connected habitats, whereas amphibian diversity tends to be highest in habitats with low connectivity. Other groups attain maximum species richness between these two extremes. The resulting pattern is a series of overlapping species diversity peaks along the connectivity gradient, suggesting that habitats collectively traversing a broad range of connectivity will optimise community diversity in riverine landscapes. [From Ward et al. 2002:535.]***

Although such studies emphasize the importance of connectivity along the channel corridor, they offer little guidance for managing these barriers and discontinuities beyond *less is better.* The impacts of road crossings, in particular, have been evaluated in several studies in Pacific Northwest lowland streams, comparing measures of biological conditions with the frequency of crossings that describe a negative, monotonic relationship (May et al. 1997; McBride and Booth 2005). Unfortunately, these studies do not suggest a consistent, discrete threshold of impacts that might serve as a management objective. For example, the study of McBride and Booth (2005) showed correlations between biological health (as characterized by a multi-metric index of benthic macroinvertebrates) and road crossings with more than three crossings per km, whereas the biological differences reported by Perkin and Gido (2012) occurred on fragmented streams with as few as one road crossing over a stream segment length of one to many kilometers.

The overarching message from these studies is that any given implementation of site-scale riparian area management does not occur in a vacuum: "protecting a site" has ecological meaning only within the context of the entire channel network. Although existing computational tools can characterize the degree of fragmentation from discontinuities or the spatial coherence of a riparian corridor of varying width, the existing literature suggests that we lack clear deterministic linkages between alternative riparian management strategies and the resulting response of instream organisms, particularly the identification of thresholds of disturbance that impact fish mobility. However, any management action that results in frequent interruptions to riparian areas, or riparian corridors where blockage of terrestrial and aquatic organisms is not fully mitigated, is sure to have deleterious impacts to aquatic and terrestrial system health.

8.5. Managing Riparian Areas From a Watershed Perspective

The perspective of riparian area management developed in this chapter has been intentionally expanded, in both space and time, beyond that normally applied (and most feasibly implemented) in the Pacific Northwest. It relies heavily on the active research in the field of landscape ecology, which is organized around a few themes of particular relevance to riparian area management: 1) patches differ in quality, 2) patch boundaries affect flows, 3) patch context matters, 4) connectivity is critical, 5) organisms are important, and 6) scale is important (Wiens 2002:501). We will explore each of these in turn with an eye towards how management of riparian areas might be improved with respect to perpetuating fish and wildlife.

8.5.1. Patches Differ in Quality

Not every location along a stream is equally influential on the physical processes or ecological functions of the riparian-aquatic ecosystem. This generalization is complicated, however, by the fact that different perspectives may not assign the same level of "influence" to every location. For example, bedrock-bound channels have very limited capacity for response (Montgomery and Buffington 1997), despite the potential for highly variable, episodic inputs of water and sediment. Thus, from a geomorphological perspective they might be considered less sensitive and so "less critical" for riparian area protection. However, such channels commonly occupy headwater, high-elevation positions in their watersheds that host potentially critical habitat(s) for a variety of non-fish species. A general treatment of the topic such as this cannot resolve the multiplicity of such complex phenomena across the diversity of landscapes in the Pacific Northwest, but this brief discussion suggests the importance of recognizing the range of riparian functions that must be served, and the improbability that they are all of equivalent importance throughout a channel network.

8.5.2. Patch Boundaries Affect Flows

In general, riparian regulations rarely consider the nature of the transition from riparian to upland (i.e., from regulated to unregulated) areas. This theme provides a reminder that the character of those transitions can affect each of the patches through the flux of material, energy, and organisms across their shared boundary. So, for example, when what was once a part of a forest interior becomes the exposed edge of a buffer strip, adjacent to recently cleared uplands, windthrow can greatly increase (and so compromise the riparian management area itself). Direct adjacency of a riparian area to urban development can invite substantial human intrusion (e.g., invasive species, excess nutrients, pesticides) into the riparian area, reaching all the way to the nominally protected stream because attention is not given to the relationship of upland development to the riparian area, nor to the "porosity" of the boundary between them.

8.5.3. Patch Context Matters

Riparian areas within separate watersheds containing different land uses (e.g., forestry, agricultural, urban) provide very different ecological functions depending on the adjacent land uses. The impacts to a stream from watershed urbanization, for example, span the range

from pervasive hydrologic changes (for which buffers are typically irrelevant) to pesticide-laden run-off (for which the pollutant removal that a buffer provides may be somewhat to highly effective). In a forestry dominated watershed, primary concerns may be the potential for unnaturally high delivery of sediment from increased rates of mass wasting; or potential losses of streambank integrity, habitat complexity, shading, large wood, and allochthonous inputs of organic matter.

According to Hansen et al. (2015:54):

> ***Our review demonstrated that greater widths were required to achieve objectives when adjacent land use intensity was high, or when the objective of management was improving terrestrial biodiversity (particularly fauna). This becomes problematic when intense land use practices occur on small properties, reducing the amount of riparian land that can economically be protected or targeted for management…For example, if we apply the evidence summarized here to a streamside property used for dairying in the lower Hunter River, New South Wales, a riparian zone width of 40 m may achieve ≥75% reduction of nitrogen inputs to the river and reduce streambank erosion, contributing to improved downstream water quality. However, the same investment in riparian set-aside in the upper reaches of the Hunter catchment may provide additional improvements to stream nutrient processing (Lowe and Likens 2005), aquatic biodiversity (Chessman et al. 1997) and bird diversity (Bennett et al. 2014).***

8.5.4. Connectivity is Critical

Connectivity in riparian areas occurs not only parallel to the stream (previous section), but also orthogonally to the channel in a lateral dimension – from the stream through the riparian area into uplands–and the vertical dimension in the hyporheic zone. Typical riparian area regulations are generally successful at maintaining connectivity in the longitudinal dimension at some minimum width, although the consequences of limited interruptions to longitudinal connectivity (e.g., bridges, utility crossings) are commonly dismissed, a consequence of viewing riparian areas only from the perspective of lateral width rather than a recognition of the importance of stream network connectivity.

Longitudinal connectivity is especially important for the movement of sediment, large wood, and other organic matter. Fox (2003), for instance, found that the condition of riparian areas was a reasonable predictor for the quantity of large wood key pieces in adjacent stream channels; however, upstream basin characteristics and processes were likely responsible for most of the large wood in larger channels. Therefore, land managers should not base site-level objectives for in-stream large wood on the condition of adjacent riparian areas alone, but should also manage riparian areas at the watershed scale to provide adequate in-stream large wood throughout a watershed's stream network.



Issaquah Creek is a tributary to Lake Sammamish in King County/ Derek Booth

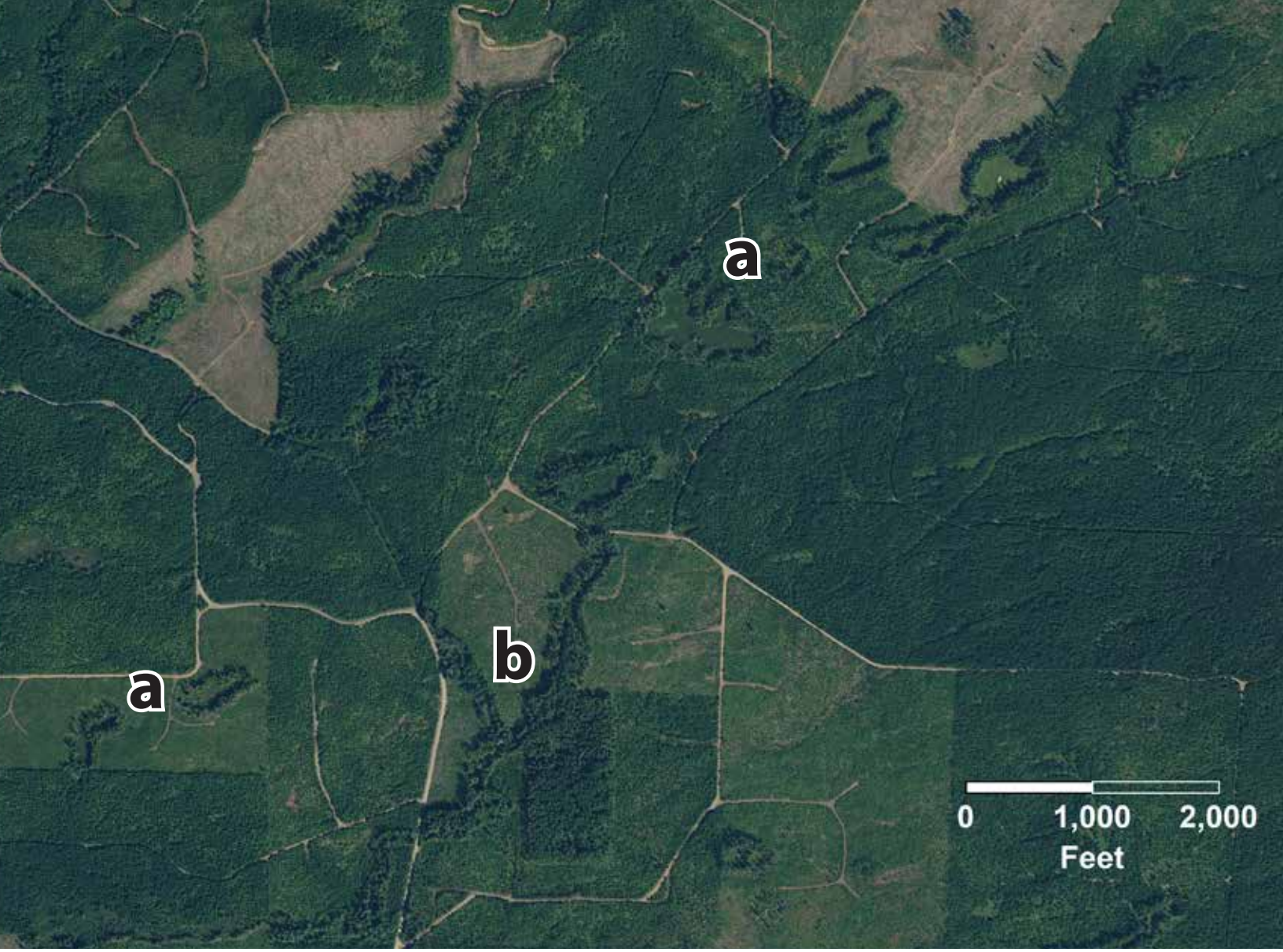


Figure 8.8. View of isolated wetlands (a) and riparian management zones (b) in a commercially logged portion of southwest Washington, providing some degree of local, structural connectivity within each buffer but no functional connectivity between them. Forested buffers in this image are approximately 50 feet (15 meters) wide.

Lateral connectivity, particularly between the riparian area and the adjacent uplands, is a more complex relationship, because improving this connectivity simultaneously enhances ecosystem protection but can also compromise the protection of a stream from upland activities. Continuity of a protected riparian area with uplands that are protected as well provides a range of key habitats for mobile species that depend on both upland and riparian environments for different needs or at different life stages. Separated patches with relatively porous boundaries may achieve only a modest fraction of these benefits, however, and truly isolated riparian–upland patches may be no better than an absence of such habitats altogether (at least for many terrestrial species of concern) (Figure 8.8). Porous boundaries also run the risk of compromising some of the primary goals of a riparian management area, and so the nature of connectivity does not universally result in beneficial outcomes (see 8.5.2 above).

Vertical connectivity occurs at the ecotone between stream water and deeper groundwater. This ecotone, known as the hyporheic zone, is comprised of coarse sediments, and the vertical connectivity occurring there is more commonly referred to as hyporheic exchange (Boultan et al. 1998). Hyporheic exchange includes

water, dissolved solutes, fine sediments, fine organic matter, and small organisms. The size of the hyporheic zone is enlarged by structures such as large wood and boulders that store sediment. Hyporheic exchange is enhanced by structures such as large wood or boulders that redirect flow into the streambed and by undulations in channel morphology (e.g., meanders, pool-riffle beds) that intercept the flow of water.

In summary, the importance of connectivity is broadly recognized:

> ***Restoration of important ecological processes often implies improving connectivity of the stream. For example, longitudinal and lateral connectivity can be enhanced by restoring fluvial dynamics on flood-suppressed rivers and by increasing water availability in rivers subject to water diversion or withdrawal, thereby increasing habitat and species diversity. Restoring links between surface and ground water flow enhances vertical connectivity and communities associated with the hyporheic zone. [From Jansson et al. 2007:589.]***

However, tangible recommendations for how best to manage for this outcome in typical regulatory settings are more elusive.

8.5.5. Organisms are Important

Although not strictly an issue of spatial or temporal relationships between landscape elements, the recognition of organisms as key elements of riverine composition, structure, and functions is a valuable contribution of landscape ecology to watershed management. Some of these influences have been long-appreciated: the importance of large wood to stream structure and salmonid habitat, the role of root strength in mediating bank erosion, and indeed the entire construct of conserving riparian areas of native



Black Bear Ursus Americanus *feeding on grass/Scott Fitkin, WDFW*

vegetation to maintain ecosystem health. However, this perspective has broadened our appreciation of the multiple ways in which biota interact with the physical environment and each other to support the full range of watershed processes and thus the systems that depend on them (Beavers, bears, and marine nutrients, etc.). Management of riparian areas thus must include not only some awareness of the watershed in which that riparian area exists but also the biota that inhabit this environment (and, in some cases, move beyond its boundaries), and the ways in which those biota support the integrity of the aquatic ecosystem (Robinson et al. 2002).

8.5.6. Scale is Important

The goals and application of riparian management actions are generally limited in both space (i.e., the site) and time (i.e., the present). In a system as interconnected and disturbance-prone as a stream channel network, however, the site-scale management of a riparian area is *necessary*, but not *sufficient*, to ensure the desired composition, structure, and functions

of riparian and aquatic habitats. Of all locations on a natural or human-dominated landscape, river channels are probably the least stable in time, experiencing (and depending on) both gradual changes and episodic disturbance that structure their habitats and the organisms that utilize them. They also are subject to a spatial hierarchy of influences, not only those of the immediately adjacent riparian area itself (such as shade) but also those of the upstream watershed (delivering water and sediment to the channel) and the landscape even beyond its drainage boundaries. "Conditions far from stream banks affect the distribution of key instream habitat characteristics. Amount of instream wood, percentage of gravel, and pool frequency, which are essential to healthy salmon habitat, are particularly sensitive to land use" (O'Callaghan 2012:2). At even larger scales, the mobility of large terrestrial animals, the ability of salmon to return to headwater streams from the ocean, and the episodic disturbance from wildfire can exert equivalent (or greater) influences.

8.6. Conclusions

The perspective provided by landscape ecology emphasizes the temporally and spatially varying nature of habitats, and it suggests that achieving genuine habitat protection (and thus species conservation) is crippled by management that is limited to only narrow riparian corridors. To perpetuate fish and wildlife in the long term, three principles need to become integrated into the current paradigm for protecting aquatic ecosystems:

1. More important than simply protecting habitats is protecting the processes that create and sustain habitats. For this strategy to be successful, however, space in which that habitat can be expressed must also be protected. So, for example, instream and riparian area protection is indeed necessary, but it is not sufficient—the watershed and local-scale processes that create habitats within these areas must also be maintained. Current paradigms that focus on site-level management of riparian areas will not successfully support the dynamic processes that maintain diverse, productive fluvial ecosystems.

2. Habitats have not only spatial but also temporal dimensions to their creation and maintenance, and they cannot retain their functions if they remain static. The historical frequencies, durations, and magnitudes of natural disturbances (flood and fire being the most common) need to be better understood and then emulated to the greatest extent that surrounding land uses can tolerate.

3. Spatial connectivity between habitats is critical, particularly for species (such as salmon) with a variety of habitat requirements at different life stages. Isolated key habitats for mobile species are scant improvement over no habitat at all.

Integration of these principles into the management of aquatic systems will be challenging under existing regulatory frameworks. However, even an awareness of their relevance to sustaining healthy ecosystems may reveal opportunities for their application in regulatory and non-regulatory settings alike. The following key points are offered in support of such opportunities:



Decaying salmon carcass/Ned Pitmann, WDFW

8.6.1. Manage the Riverine Landscape

The riverine landscape is the proper construct for understanding and managing aquatic systems. Although riparian areas are disproportionately important for fish and wildlife relative to their area on a landscape, they are not exclusively important. Although riparian areas affect many critical instream conditions, including temperature, nutrient input, bank stability, and large wood, while also filtering sediment and other pollutants from adjacent upland areas, the watershed outside of the riparian area is no less influential on the ultimate state of instream conditions, particularly with respect to its control of hydrology and sediment delivery. From even beyond a watershed's boundaries, influences on the stream can be carried by wind, mobile biota, and wildfire.

8.6.2. Manage at Multiple Scales

Effective and efficient conservation of fish and wildlife habitats requires management at multiple spatial and temporal scales. Just as the influences on streams arise from within and beyond the riparian area, management must find vehicles to embrace these multiple spatial scales as well. Treatments must also embrace the ever-changing temporal patterns of stability and disturbance, which not only result in constantly shifting physical habitats but also create the ecological template necessary for healthy, resilient biological communities (Ryan and Calhoun 2010). This will require approaches that allow sufficient space and for the expression of key habitat-forming processes (Beechie et al. 2010) rather than simply the creation or protection of static habitat features.

8.6.3. Connect Individual Actions

Particularly in rivers, longitudinal connectivity of individual locations is a defining feature of these systems and their biota, and so maintaining this connectivity is an essential consideration of aquatic ecosystem protection. We increase our chances of maintaining connectivity with coordinated actions across all riparian sites, and even more so by considering the entire riverine landscape as the focus of conservation efforts. However, connectivity is only as strong as its weakest link, and so even a single ill-executed action can preclude achieving this goal altogether.

8.6.4. Engage the Challenge of Implementing Effective Management

Adhering to these key points for achieving genuine riparian ecosystem protection, particularly in the face of continued human impacts, may not be presently attainable. Even if specific beneficial actions are neither everywhere known nor universally feasible to implement, our current understanding can support a positive trajectory. "Landscape conditions far from the river's edge may have strong impacts on instream conditions. Understanding the effects of natural processes and human activities across entire drainage basins is key to researching, monitoring, and restoring aquatic resources." (O'Callaghan 2012:5). Progress will require not only an appreciation of the most effective riparian management strategies but also a broadened perspective on the scope of necessary actions, actions that must extend far beyond the river itself and its adjacent riparian ecosystem.

8.7. Literature Cited[1]

Agouridis, C.T., S.R. Workman, R.C. Warner, and G.D. Jennings. 2005. Livestock grazing management impacts on stream water quality: a review. Journal of the American Water Resources Association 41:591-606. (i)

Allan, J.D. 2004. Landscapes and riverscapes: the influence of land use on stream ecosystems. Annual Review of Ecology, Evolution, and Systematics 35:257-284. (i)

Andréassian, V. 2004. Waters and forests: from historical controversy to scientific debate. Journal of Hydrology 291:1-27. (i)

Anlauf, K.J., D.W. Jensen, K.M. Burnett, E.A. Steel, K. Christiansen, J.C. Firman, B.E. Feist, and D.P. Larsen. 2011. Explaining spatial variability in stream habitats using both natural and management-influenced landscape predictors. Aquatic Conservation: Marine and Freshwater Ecosystems 21:704-714. (i)

Arkle, R.S., D.S. Pilliod, and K. Strickler. 2010. Fire, flow and dynamic equilibrium in stream macroinvertebrate communities. Freshwater Biology 55:299-314. (i)

Beechie, T.J., D.A. Sear, J.D. Olden, G.R. Pess, J.M. Buffington, H. Moir, P. Roni, and M.M. Pollock. 2010. Process-based principles for restoring river ecosystems. BioScience 60:209-222. (i)

Belsky, A.J., A. Matzke, and S. Uselman. 1999. Survey of livestock influences on stream and riparian ecosystems in the western United States. Journal of Soil and Water Conservation 54:419-431. (i)

Bennett A.F., D.G. Nimmo, and J.Q. Radford. 2014. Riparian vegetation has disproportionate benefits for landscape-scale conservation of woodland birds in highly modified environments. Journal of Applied Ecology 51:514-523. (i)

Booth, D.B., J.R. Karr, S. Schauman, C.P. Konrad, S.A. Morley, M.G. Larson, and S.J. Burges. 2004. Reviving urban streams: land use, hydrology, biology, and human behavior. Journal of the American Water Resources Association 40:1351-1364. (i)

Boulton, A.J., S. Findlay, P. Marmonier, E.H. Stanley, and H.M. Valett. 1998. The functional significance of the hyporheic zone in streams and rivers. Annual Review of Ecology and Systematics 29:59-81. (i)

Brown, L.R., T.F. Cuffney, J.F. Coles, F. Fitzpatrick, G. McMahon, J. Steuer, A.H. Bell, and J.T. May. 2009. Urban streams across the USA: lessons learned from studies in 9 metropolitan areas. Journal of the North American Benthological Society 28:1051-1069. (i)

Chessman B.C., J.E. Growns, and A.R. Kotlash. 1997. Objective derivation of macroinvertebrate family sensitivity grade numbers for the SIGNAL biotic index: application to the Hunter River system, New South Wales. Marine and Freshwater Research 48:159-172. (i)

Coffman, G.C., R.F. Ambrose, and P.W. Rundel. 2010. Wildfire promotes dominance of invasive Giant Reed (*Arundo donax*) in riparian ecosystems. Biological Invasions 12:2723-2734. (i)

Davis, J.C., and G.A. Davis. 2011. The influence of stream-crossing structures on the distribution of rearing juvenile Pacific salmon. Journal of the North American Benthological Society 30:1117-1128. (i)

Fausch, K.D., C.E. Torgersen, C.V. Baxter, and L.W. Li. 2002. Landscapes to riverscapes: bridging the gap between research and conservation of stream fishes. BioScience 52:483-498. (i)

Favaro, C., J.W. Moore, J.D. Reynolds, and M.P. Beakes. 2014. Potential loss and rehabilitation of stream longitudinal connectivity: fish populations in urban streams with culverts. Canadian Journal of Fisheries and Aquatic Sciences 71:1805-1816. (i)

[1] References are classified according to RCW 34.05.271 (see Appendix 1) denoted by a lower case roman numeral (i – viii) in parentheses at the end of the citation.

Flitcroft, R.L., K.M. Burnett, G.H. Reeves, and L.M. Ganio. 2012. Do network relationships matter? Comparing network and instream habitat variables to explain densities of juvenile Coho Salmon (*Oncorhynchus kisutch*) in mid-coastal Oregon, USA. Aquatic Conservation: Marine and Freshwater Ecosystems 22:288-302. (i)

Fox, M.J. 2003. Spatial organization, position, and source characteristics of large woody debris in natural systems. Doctoral dissertation. University of Washington, Seattle. (i)

Frissell, C.A., W.J. Liss, C.E. Warren, and H.D. Hurley. 1986. A hierarchical framework for stream habitat classification: viewing streams in a watershed context. Environmental Management 10:199-214. (i)

Hansen, B.D., P. Reich, T.R. Cavagnaro, and P.S. Lake. 2015. Challenges in applying scientific evidence to width recommendations for riparian management in agricultural Australia. Ecological Management and Restoration 16:50-57. (i)

Jansson, R., C. Nilsson, and B. Malmqvist. 2007. Restoring freshwater ecosystems in riverine landscapes: the roles of connectivity and recovery processes. Freshwater Biology 52:589-596. (i)

Jellyman, P.G., D.J. Booker, and A.R. Mcintosh. 2013. Quantifying the direct and indirect effects of flow-related disturbance on stream fish assemblages. Freshwater Biology 58:2614-2631. (i)

Kadoya, T. 2009. Assessing functional connectivity using empirical data. Population Ecology 51:5-15. (i)

Keeley J.E., G.H. Aplet, N.L. Christensen, S.G. Conard, E.A. Johnson, P.N. Omi, D.L. Peterson, and T.W. Swetnam. 2009. Ecological foundations for fire management in North American forest and shrubland ecosystems. PNW-GTR-779. U.S. Forest Service, Pacific Northwest Research Station, Portland, Oregon. (viii)

Lake, P.S. 2000. Disturbance, patchiness, and diversity in streams. Journal of the North American Benthological Society 19:573-592. (i)

Lowe, W.H., and G.E. Likens. 2005. Moving headwater streams to the head of the class. BioScience 55:196–197. (i)

Luce, C., P. Morgan, K. Dwire, D. Isaak, Z. Holden, and B. Rieman. 2012. Climate change, forests, fire, water, and fish: building resilient landscapes, streams, and managers. RMRS-GTR-290. U.S. Forest Service, Rocky Mountain Research Station, Fort Collins, Colorado. (viii)

Lytle, D.A., and N.L. Poff. 2004. Adaptation to natural flow regimes. Trends in Ecology and Evolution 19:94-100. (i)

Malanson, G.P. 1995. Riparian landscapes. Cambridge University Press, Cambridge, United Kingdom. (i)

Martins, E.G., S.G. Hinch, D.A. Patterson, M.J. Hague, S.J. Cooke, K.M. Miller, D. Robichaud, K.K. English, and A.P. Farrell. 2012. High river temperature reduces survival of Sockeye Salmon (*Oncorhynchus nerka*) approaching spawning grounds and exacerbates female mortality. Canadian Journal of Fisheries and Aquatic Sciences 69:330-342. (i)

May, C.L. 2002. Debris flows through different forest age classes in the central Oregon Coast Range. Journal of the American Water Resources Association 38:1097-1113. (i)

May, C.W., R.R. Horner, J.R. Karr, B.W. Mar, and E.B. Welch. 1997. Effects of urbanization on small streams in the Puget Sound Lowland Ecoregion. Watershed Protection Techniques 2:483-494. (i)

McBride, M., and D.B. Booth. 2005. Urban impacts on physical stream conditions: effects of spatial scale, connectivity, and longitudinal trends. Journal of the American Water Resources Association 41:565–580. (i)

Montgomery, D.R. 1999. Process domains and the river continuum. Journal of the American Water Resources Association 35:397-410. (i)

Montgomery, D.R., and J.M. Buffington. 1997. Channel-reach morphology in mountain drainage basins Bulletin of the Geological Society of America 109:596-611. (i)

Montgomery, D.R., J.M. Buffington, N.P. Peterson, D. Schuett-Hames, and T.P. Quinn. 1996. Stream-bed scour, egg burial depths, and the influence of salmonid spawning on bed surface mobility and embryo survival. Canadian Journal of Fisheries and Aquatic Sciences 53:1061-1070. (i)

Moore, J.W. 2006. Animal ecosystem engineers in streams. BioScience 56:237-246. (i)

Morley, S.A., and J.R. Karr. 2002. Assessing and restoring the health of urban streams in the Puget Sound Basin. Conservation Biology 16:1498-1509. (i)

O'Callaghan, J. 2012. Thinking big: linking rivers to landscapes. Science Findings, Issue 139. U.S. Forest Service, Pacific Northwest Research Station, Portland, Oregon. (viii)

Osborne, L.L., and D.A. Kovacic. 1993. Riparian vegetated buffer strips in water-quality restoration and stream management. Freshwater Biology 29:243-258. (i)

Pausas, J.G., and J.E. Keeley. 2014. Abrupt climate-independent fire regime changes. Ecosystems 17:1109-1120. (i)

Perkin, J.S., and K.B. Gido. 2012. Fragmentation alters stream fish community structure in dendritic ecological networks. Ecological Applications 22:2176-2187. (i)

Pollock, M.M., M. Heim, and D. Werner. 2003. Hydrologic and geomorphic effects of Beaver dams and their influence on fishes. American Fisheries Society Symposium 37:213-233. (i)

Raymond, K.L., and B. Vondracek. 2011. Relationships among rotational and conventional grazing systems, stream channels, and macroinvertebrates. Hydrobiologia 669:105-117. (i)

Reid, L.M., N.J. Dewey, T.E. Lisle, and S. Hilton. 2010. The incidence and role of gullies after logging in a coastal redwood forest. Geomorphology 117:155-169. (i)

Richardson, J.S., R.E. Bilby, and C.A. Bondar. 2005. Organic matter dynamics in small streams of the Pacific Northwest. Journal of the American Water Resources Association. 41:921-934. (i)

Robinson, C.T., K. Tockner, and J.V. Ward. 2002. The fauna of dynamic riverine landscapes. Freshwater Biology 47:661-677. (i)

Roper, B.B., B. Jarvis, and J.L. Kershner. 2007. The role of natural vegetative disturbance in determining stream reach characteristics in central Idaho and western Montana. Northwest Science 81:224-238. (i)

Ryan, D.F., and J.M. Calhoun. 2010. Riparian adaptive management symposium: a conversation between scientists and management. PNW-GTR-830. U.S. Forest Service, Pacific Northwest Research Station, Portland, Oregon. (viii)

Stanley, S., S. Grigsby, D.B. Booth, D. Hartley, R. Horner, T. Hruby, J. Thomas, P. Bissonnette, R. Fuerstenberg, J. Lee, P. Olson, and G. Wilhere. 2011. Puget Sound characterization. volume 1: the water resources assessments (water flow and water quality). Publication #11-06-016. Washington State Department of Ecology, Olympia. Available: https://fortress.wa.gov/ecy/publications/publications/1106016.pdf. (January 2019). (viii)

Talbot L.M. 1996. The linkage between ecology and conservation policy. Pages 368-378 *in* S.T.A. Pickett, R.S. Ostfeld, M. Shachak, and G.E. Likens, editors. The ecological basis of conservation. Chapman & Hall, New York. (i)

Taylor, P.D., L. Fahrig, K. Henein, and G. Merriam. 1993. Connectivity is a vital element of landscape structure. Oikos 68:571-573. (i)

Taylor P.D., L. Fahrig, and K.A. With. 2006. Landscape connectivity: a return to the basics. Pages 29–43 *in* K. Crooks and M.A. Sanjayan, editors. Connectivity conservation. Cambridge University Press, Cambridge, United Kingdom. (i)

Thorstad, E.B., F. Økland, K. Aarestrup, and T.G. Heggberget. 2008. Factors affecting the within-river spawning migration of Atlantic Salmon, with emphasis on human impacts. Reviews in Fish Biology and Fisheries 18:345-371. (i)

Tockner, K., F. Schiemer, and J.V. Ward. 1998. Conservation by restoration: the management concept for a river-floodplain system on the Danube River in Austria. Aquatic Conservation: Marine and Freshwater Ecosystems 8:71-86. (i)

Vannote, R.L., G.W. Minshall, K.W. Cummins, J.R. Sedell, and C.E. Cushing. 1980. The river continuum concept. Canadian Journal of Fisheries and Aquatic Sciences 37:130-137. (i)

Vietz, G.J., M.J. Sammonds, C.J. Walsh, T.D. Fletcher, I.D. Rutherfurd, and M.J. Stewardson. 2014. Ecologically relevant geomorphic attributes of streams are impaired by even low levels of watershed effective imperviousness. Geomorphology 206:67-78. (i)

Wallbrink, P.J., B.P. Roddy, and J.M. Olley. 2002. A tracer budget quantifying soil redistribution on hillslopes after forest harvesting. Catena 47:179-201. (i)

Walsh, C.J., A.H. Roy, J.W. Feminella, P.D. Cottingham, P.M. Groffman, and R.P. Morgan II. 2005. The urban stream syndrome: current knowledge and the search for a cure. Journal of the North American Benthological Society 24:706-723. (i)

Wang, L., J. Lyons, P. Kanehl, and R. Bannerman. 2001. Impacts of urbanization on stream habitat and fish across multiple spatial scales. Environmental Management 28:255-266. (i)

Ward, J.V., K. Tockner, D.B. Arscott, and C. Claret. 2002. Riverine landscape diversity. Freshwater Biology 47:517-539. (i)

Wiens, J.A. 2002. Riverine landscapes: taking landscape ecology into the water. Freshwater Biology 47:501-515. (i)

Chapter 9. Science Synthesis to Management Implications

By: Timothy Quinn, Kirk L. Krueger, and George F. Wilhere

9.1. Introduction

This chapter summarizes important scientific findings from chapters 1 through 8 and provides a brief discussion of scientific themes that can inform thoughtful approaches to protecting or restoring riparian ecosystems and associated aquatic habitats. The current state of the science, as reviewed in chapters 1 through 8, clearly demonstrates the importance of an intact riparian ecosystem to the proper functioning of aquatic habitats. It also introduces new studies on conservation of watershed-scale processes that directly affect aquatic habitats and that help maximize the ecological benefits of riparian ecosystems.

Riparian ecosystems are a priority habitat because their composition, structure, and functions dramatically affect a multitude of fish, amphibian, reptile, bird, mammal, and invertebrate species (Cummins 1974; Richardson et al. 2005). Although riparian ecosystems are a small portion of the landscape, approximately 85% of Washington's wildlife species use them (Thomas et al. 1979). Protecting or restoring high function to this relatively small portion of the landscape can disproportionally benefit many species and other important ecosystem goods and services (e.g., clean water, fisheries, and flood control) (NRC 2002).

Our definition of riparian ecosystem is integral to the development of management recommendations. Riparian ecosystems are transitional areas (ecotones) between terrestrial and aquatic ecosystems and are distinguished by gradients in biophysical conditions, ecological processes, and biota (NRC 2002). Riparian ecosystems include areas through which surface and subsurface hydrology connect waterbodies with uplands. They include those portions of terrestrial area that significantly influence exchanges of energy and matter with aquatic ecosystems (i.e., a zone of influence). Following Naiman and Bilby (1998), we include active floodplains and the terraces and adjacent uplands that contribute organic matter to active channels or active floodplains as part of the riparian ecosystem.

9.2. Summary of Chapters 2 Through 8

Chapters 2 through 8 discussed five key riparian ecosystem functions including bank stability, stream shading, wood recruitment, litter fall, and pollutant removal, as well as other topics related to the riparian ecosystems including stream channel morphology, nutrient dynamics, dryland riparian areas, and watershed-scale processes. Here we summarize the main points of each chapter.

9.2.1. Stream Channel Morphology (Chapter 2)

The stream morphology chapter explained how the composition, structure, and functions of riparian ecosystems and their associated aquatic habitats

depend on dynamic interactions of water, sediment, wood, and riparian vegetation. Important points from this chapter are:

- Erosion, transport, and deposition of sediment are part of a hierarchy of disturbance processes that continually create, maintain, destroy, and recreate the variety of aquatic habitats.

- Geomorphic processes related to the input of sediments to streams (from local stream bank erosion to mass wasting events) are integral to a watershed's natural disturbance regime and necessary for long-term ecological sustainability. For example, sediments delivered to streams from hillslope mass wasting events are often the predominant source of gravel, which is essential for salmon spawning habitat.

- Bank stability is one of five key ecological functions of riparian areas. Vegetation has mechanical and hydrologic effects on bank stability, and these effects can be stabilizing or destabilizing. However, in general, the net effect of vegetation is stabilizing.

- Simple models suggest that in an old-growth riparian forest, the full contribution of root strength to streambank stability is provided by trees within approximately 33 ft (10 m) of the streambank.

- Over a period of decades to centuries, a river or stream will travel across the entirety of its channel migration zone. Because the riparian ecosystem is defined by proximity to water, as the active channel moves back and forth across the channel migration zone, the riparian ecosystem moves with it.

9.2.2. Wood (Chapter 3)

Chapter 3 focused on the role of wood in aquatic ecosystems, and the recruitment of large wood to aquatic ecosystems. Wood plays a critical role in the composition, structure, and functions of riparian and aquatic ecosystems. In-stream large wood increases hydraulic complexity, i.e., creates a wider range of flow velocities, which causes pool formation, streambed scour, sediment deposition, and channel migration. The net result is a diversity of aquatic habitat types. Main points from the wood chapter include:

- The effects of wood on aquatic ecosystems in the Pacific Northwest are well-understood and ecologists are very confident about the critical role of wood in fish habitats.

- Ecologists are also confident about the role of riparian forests in supplying large wood to aquatic systems.

- Source distances for in-stream wood are a function of tree height in riparian ecosystems. Source distances are longer for riparian forests with taller trees.

- The main uncertainties for management are: the shape of the wood recruitment function, and in particular, the shape under different site-level and watershed conditions; and the potential contributions from recruitment mechanisms outside the riparian forest, such as landslides, debris flows, and extreme channel migration.

- In an unmanaged natural riparian area, 100% of a site's large wood recruitment potential comes from a distance of about 85 to 230 ft (26 to 70 m), depending on site productivity class. This does not account for additional wood recruitment through landslides, debris flows, or extreme channel migration.

9.2.3. Stream Temperature (Chapter 4)

The chapter on stream temperature presented a conceptual model for stream thermal regimes, discussed the effects of water temperature on fish, herpetofauna, and invertebrates; and reviewed the impacts of various land uses on stream thermal regimes. The chapter's key points include:

- Riparian vegetation can strongly affect stream thermal regimes (i.e., the spatial and temporal distribution of temperatures) which affects the survival and productivity of aquatic species. The importance of the thermal regime, not just summer peak temperatures, to aquatic species is increasingly acknowledged, but our ability to manage for suitable thermal regimes is limited.

- Fish and other aquatic organisms use different stream habitats, defined in part by specific water temperature ranges. However, the scientific literature is conclusive about the importance of cool stream temperatures (≤60°F [15.6°C]) for salmonid survival and productivity.

- Shade can substantially reduce the amount of direct solar radiation to the stream, which is one of the main sources of heating, especially in narrow low-order streams.

- Shade from riparian vegetation is affected by vegetation height, canopy density, and stem density. The width of a riparian area affects the amount of shading to the stream.

- A stream's thermal regime is also affected by latitude, elevation, aspect, topographic shading, channel bed shape, and water volume in addition to tributary, groundwater, and hyporheic flows.

- Structures such as large wood can reduce stream temperature by increasing pool depths, causing the development of undercut banks that provide shade, and by enhancing hyporheic exchange through redirecting surface flow to subsurface flow.

9.2.4. Pollution Removal (Chapter 5)

The pollutant removal function is unique in that it only exists in the presence of human activities that generate polluted water, and it is only necessary when nonpoint source runoff from upland activities threaten to degrade water quality. The pollution removal chapter covered the common sources, biological impacts, in situ chemistry, transport pathways, and results of removal efficacy studies for five types of pollutants—sediments, excess nutrients, metals, pesticides and other organic compounds, and pathogens. Key points from the pollution removal chapter include:

- There is overwhelming evidence in the scientific literature that riparian buffers[1] reduce nonpoint source water pollution for a variety of pollutants, and that riparian buffer width is the most important variable explaining removal efficacy.

- Research also indicates that the second most important variable in pollution removal is the vegetative composition and structure in riparian buffers.

[1] Riparian buffer refers to a strip of land adjacent to a stream that helps protect the stream from nonpoint source pollutants originating from upslope areas.

- Riparian buffer width recommendations depend on the particular pollutant to be removed and the desired removal efficacy. Policy makers must choose the desired removal efficacy.

- Models from four separate peer-reviewed meta-analyses show that riparian buffer widths for 95% removal efficacy of sediment range from 56 to 251 ft (17 to 76 m). Meta-analyses for other pollutants exhibit a similar degree of uncertainty with regard to riparian buffer width.

- Due to uncertainty regarding riparian buffer widths needed for a desired removal efficacy, management of riparian areas for the removal of pollutants should be monitored within an adaptive management program.

9.2.5. Nutrient Dynamics (Chapter 6)

The nutrient dynamics chapter explained the many effects of riparian areas on the three primary macro-nutrients: nitrogen, phosphorus, and carbon. Riparian areas can be nutrient sources or sinks, and riparian areas mediate the movements of nutrients between uplands and surface waters. Key points from the nutrient dynamics chapter include:

- Organic matter from riparian areas is an essential source of nutrients and chemical energy for aquatic ecosystems. Nutrients enter streams via plant litter fall or via surface and subsurface water flow.

- Streams in the Pacific Coastal Ecoregion of Washington (Naiman et al. 2000) are generally nutrient-poor and well shaded. Hence, additional nutrients (e.g., salmon carcasses) may enhance aquatic ecosystem productivity. However, aquatic communities may be adversely impacted by excessive anthropogenic nutrients such as nitrogen and phosphorus.

- One study suggests that riparian area widths needed to deliver 95% of annual litter input from mature conifer forests to streams ranges from 39–54% of mean tree height depending on a site's slope and wind exposure.

- Empirical evidence suggests increasing salmon carcasses, and their marine-derived nutrients and energy, to riparian ecosystems could contribute significantly to the recovery of imperiled salmon populations.

- More research is needed on the effects of riparian litter fall on stream productivity and on the relationship between salmon harvest escapement and salmon population productivity.

9.2.6. Riparian Areas of the Columbia Plateau (Chapter 7)

The chapter on riparian areas of the Columbia Plateau covered aspects of riparian ecology that are unique to this semi-arid to arid (i.e., dryland) ecoregion. The chapter clarified the definition of riparian ecosystem in dryland ecoregions, and reviewed the history of human impacts to riparian areas in the Columbia Plateau. It also reviewed the scientific literature on the five key riparian ecosystem functions – bank stability, stream shading, wood recruitment, litter fall, and pollutant removal – and it added a function of particular importance in the Columbia Plateau – alluvial water storage. Other important points include:

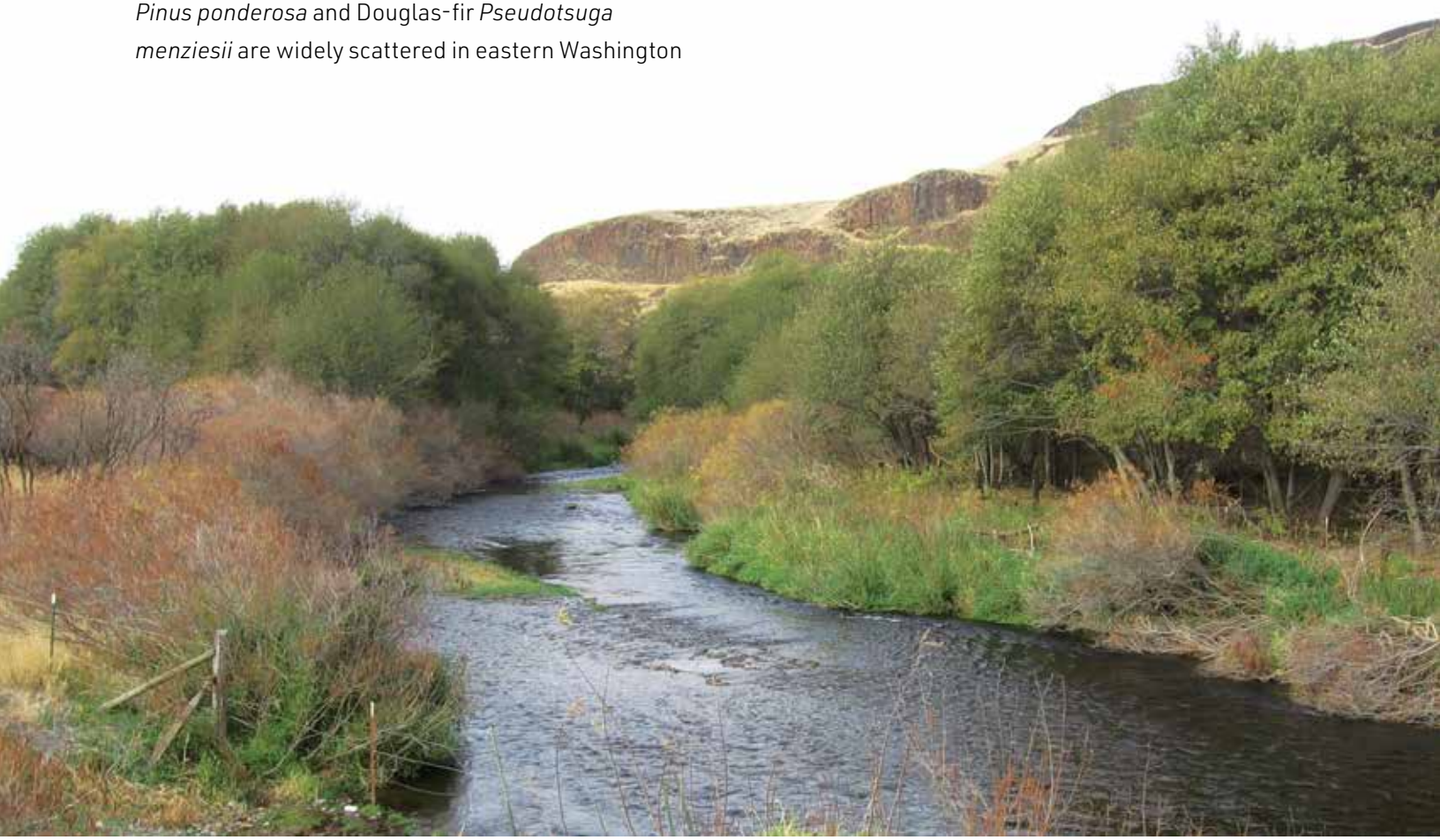
- Vegetation within riparian ecosystems of the Columbia Plateau often exhibits an abrupt demarcation between the riparian zone and the zone of influence. Phreatophytic trees and shrubs and hydrophytic herbaceous plants are confined to moist streamside areas, but the upland zone of influence may consist of sagebrush or bunchgrass communities.

- Nearly all riparian areas in the Columbia Plateau have been significantly impacted by human land use (grazing, intensive agriculture), resource exploitation (Beaver *Castor canadensis* trapping, timber harvest), water management (dams, diversions, reservoirs), or invasive plant species.

- Riparian areas in the Columbia Plateau are inhabited by a variety of deciduous woody plants, with the largest being Black Cottonwood *Populus trichocarpa* and White Alder *Alnus rhombifolia*. Pondersoa Pine *Pinus ponderosa* and Douglas-fir *Pseudotsuga menziesii* are widely scattered in eastern Washington riparian areas and were likely more common historically than at present. Compared to forested ecoregions, large woody debris play a much smaller role in fluvial processes.

- A rudimentary classification system based on overstory conveys obvious differences in stream shading provided by riparian areas: tall tree, short tree, tall shrub, shrub, grass-like, grass, and forb. The obvious implication of these vegetation types is that some stream channels in the Columbia Plateau receive little or no shade from vegetation, even historically. However, the actual historical condition of many riparian areas is unknown.

- Where the riparian zone is narrow (<100 ft [<30 m]) or the zone of influence lacks tall trees (<100 ft), the width of the riparian ecosystem is based on the pollutant removal function.



The Tucannon River flows generally northwest from headwaters in the Blue Mountains of southeastern Washington to the Snake River/Terra Hegy, WDFW

9.2.7. Watersheds (Chapter 8)

The chapter on watershed-scale processes looked beyond the site-level perspective at which riparian ecosystems are normally studied and managed. The chapter presented a conceptual framework that identified the key watershed processes and their primary influences on riparian ecosystems. The key points from the watersheds chapter are:

- Riparian ecosystems occupy perhaps the most dynamic and disturbance-prone area in a watershed. Nevertheless, the relative abundances of various aquatic habitat types in unmanaged, natural watersheds tends to remain constant over long periods (decades to centuries). In other words, at the watershed scale, habitat types appear to be in dynamic equilibrium.

- Riparian areas and surrounding watersheds are complex and dynamic systems comprised of many interacting components. These interactions across the watershed and through time create a mosaic of stream conditions necessary for self-sustaining populations of fish and other aquatic organisms.

- Some animal species have major impacts on the composition and structure of stream networks. Salmon, for example, restructure channel bed substrates during spawning and Beaver restructure the morphology and hydrology of floodplains. These "ecosystem engineers" are vital components of riparian ecosystems.

- Longitudinal, lateral, and vertical connectivity are critical for maintaining or restoring riparian ecological composition, structure, and functions. Studies have shown the importance of connectivity along the riparian corridor, but are often lacking specific guidance for management beyond "more is better."

- The composition, structure, and functions of riparian areas are affected by surrounding land uses (e.g., forestry, agriculture, residential).

- The effectiveness of riparian ecosystems to protect aquatic habitats can be circumvented by anthropogenic changes at the watershed scale. The routing of water from human development to streams via channelized flow, for example, can result in changes to the stream hydrograph, changes in channel morphology, reduced efficacy of the riparian pollutant removal function, and increases in fine sediment inputs to streams.

- More research is needed on practical ways to maintain or emulate natural disturbances in watersheds dominated by human land uses (e.g., agriculture, residential). This includes disturbances such as flooding and landslides that are essential for maintaining aquatic habitats.

9.3. Key Management Implications from Chapters 1 through 8

- Protection and restoration of riparian ecosystems continues to be critically important because: a) they are disproportionately important, relative to area, for aquatic species, e.g., salmon, and terrestrial wildlife, b) they provide ecosystem services such as water purification and fisheries (Naiman and Bilby 2001; NRC 2002; Richardson et al. 2012), and c) by interacting with watershed-scale processes, they contribute to the creation and maintenance of aquatic habitats.

- Stream riparian ecosystems encompass the riparian zone, the active floodplain including riverine wetlands, and the terraces and adjacent uplands that contribute matter and energy to the active channel or active floodplain (Gregory et al. 1991; Naiman and Bilby 1998).



Engineered large wood structure in the north fork of the Lewis River/ Chuck Stambaugh, WDFW

Such terraces and adjacent uplands are called the zone of influence.

- The width of the riparian ecosystem is estimated by one 200-year site-potential tree height (SPTH) measured from the edge of the active channel or active floodplain. Protecting functions within at least one 200-year SPTH is a scientifically supported approach if the goal is to protect and maintain full function of the riparian ecosystem.

- Where the riparian zone is narrow (<100 ft [30 m]) and the zone of influence lacks tall trees (<100 ft), (e.g., in parts of the Columbia Plateau Ecoregion) the pollution removal function may determine the width of the zone of influence.

- The riparian ecosystem begins at the edge of the active channel or active floodplain, whichever is wider. As the active channel moves back and forth across the channel migration zone (CMZ), the riparian ecosystem moves with it. Consequently, there are times when the riparian ecosystem lies adjacent to and immediately outside the CMZ. Hence, to maintain riparian ecosystem functions, management must anticipate and protect future locations of the riparian ecosystems.

- A near consensus of scientific opinion holds that the most effective and reliable means of maintaining viable self-sustaining fish, especially salmon, is to maintain/restore ecosystems to conditions that resemble or emulate their historical range of natural variability (Swanson et al. 1994; Reeves et al. 1995; Bisson et al. 2009). This opinion is based in part on the complexity of processes that affect the expression of habitats over time and space.

- The protection and restoration of watershed-scale processes, especially related to hydrology, water quality, connectivity, and inputs of wood, shade, and sediment are important for aquatic system function, and help maximize the ecological benefits of riparian ecosystem protections.

- Riparian areas and surrounding watersheds are complex and dynamic systems comprised of many interacting components. Natural disturbances (floods, fire, and landslides) across the watershed and through time create the mosaic of conditions necessary for self-sustaining populations of fish, especially salmon, and other aquatic organisms.

- Impending changes to aquatic systems as a result of climate change increase risk to species already threatened by human activities. The effects of climate change on rivers and streams threaten to reduce fish distribution and viability throughout the Pacific Northwest (Beechie et al. 2013).

- The use of the precautionary principle and adaptive management are particularly appropriate when dealing with complex and dynamic systems, and when we have uncertainty related to exactly how management activities affect functioning of watersheds and riparian ecosystems.

9.4. Width of Riparian Ecosystems

The width of the riparian ecosystem is based on the zone of influence, and the zone of influence is based on riparian ecosystem functions (or processes) that affect aquatic habitats. FEMAT's (1993) curves are conceptual models describing how four key riparian ecosystem functions change with distance from the stream channel (Figure 9.1). The four functions are root strength (i.e., streambank stability), stream shading, litter fall (i.e., input of detrital nutrients), and coarse wood debris to

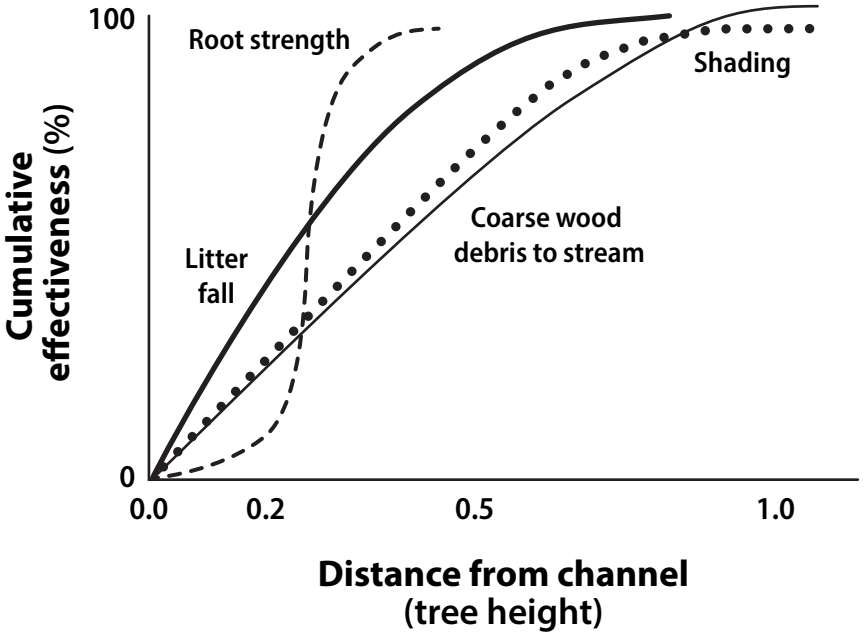


Figure 9.1. The "FEMAT Curves" (FEMAT 1993) are generalized conceptual models describing some riparian ecosystem functions and processes as the distance from a stream channel increases. "Tree height" in this figure is based on the average maximum height of the tallest dominant trees (200 years old or greater) and is referred to as site-potential tree height (SPTH).

stream (i.e., recruitment of large wood). FEMAT (1993) also included the pollution removal function (i.e., water quality) but did not create a curve for it. Originally, the curves were meant to convey two important points: 1) these four riparian ecosystem functions occur within one SPTH, and 2) the marginal return for each function decreases as distance from the stream channel increases. In other words, the FEMAT curves show that areas closer to the stream provide more of each function per unit width than areas farther from the stream.

The FEMAT curves are generalizations that ignore site-specific variability in riparian function among stream reaches. Nevertheless, FEMAT's conceptual models have influenced the width of riparian management zones (RMZs) in a number of important conservation plans such as the Forests and Fish Habitat Conservation Plan (DNR 2005).[2] Protecting natural vegetation within at least one SPTH is a scientifically supported approach if the goal is to protect and maintain ecological functions of riparian areas for the benefit of aquatic species. All else being equal, protecting areas narrower than one SPTH will result in lower levels of ecological function, and generally increase risk to fish and aquatic wildlife.

Although not all riparian functions are strongly associated with tree height (e.g., pollution removal), several key functions are, e.g., large wood recruitment, stream shading, and litter fall. Hence, the FEMAT curves use tree height of the dominant tree species to help estimate the amount of function provided by riparian areas of different widths. Consequently, the area within a site-potential tree height has often been used to define the extent of the "riparian ecosystem." However, FEMAT curves dealt strictly with functions strongly associated with vegetation and thus did not attempt to represent all aspects of the riparian ecosystem, such as other riparian functions or habitats for terrestrial species. For example, FEMAT curves did not explicitly address floodplains and riverine wetlands, sub-surface water movements, nutrient dynamics, pollutant removal, or groundwater recharge.

Given its utility, the height of site-potential trees has been described for a wide variety of tree species and can be readily found in the silvicultural literature. Fox (2003) found that mean heights of dominant trees in riparian old-growth forest of Washington range from 100 to 240 ft (30 to 70 m). The wide range of heights reflects differences in site productivity, i.e., local differences in soil nutrients and moisture, light and temperature regimes, and topography (Avery and Burkhart 1994: 278). Site productivity is described quantitatively through a site index, which is the average height that dominant trees of a particular species are expected to attain at a specified tree age. Tables (e.g., King 1966) have been developed to predict the future average height of dominant trees on a site.

FEMAT (1993:V-34) defined site-potential tree height as "the average maximum height of the tallest dominant trees (200 years or more) for a given site class." The key phrase in this definition is "200 years or more" which refers to the approximate minimum age of old-growth forests (Franklin and Spies 1991). This reflects FEMAT's underlying assumption that old-growth forest conditions are needed for full riparian ecosystem functions. Because Douglas-fir can continue height growth for more than 200 years (Herman and Lavender 1990), site-potential height based on age 200 years is the minimum width for full riparian ecosystem functions according to FEMAT. Moreover, in addition to changes in SPTH with increasing forest age, other riparian forest components (e.g., basal area of live trees, species composition, volume of dead woody material) continue to change after 200 years of age (Fox 2003) resulting in what may be important but relatively unstudied implications for riparian ecosystem functions and values.

[2] However, we note that the Forests and Fish Habitat Conservation Plan (FFHCP) did not adopt the FEMAT (1993) definition of site-potential tree height. The FFHCP defined SPTH as the height of dominant trees at age 100 years.



Quinault River/Wendy Cole, WDFW

9.5. The Condition of Riparian Ecosystems

Many scientific experts (Swanson et al. 1994; Reeves et al. 1995; Bisson et al. 2009) believe that the most likely way to realize viable self-sustaining fish, especially salmon, populations is to maintain/restore ecosystems to conditions that resemble their historical range of natural variability[3] (hereafter historical conditions). The scientific rationale for this opinion is that fish species have over many millennia adapted to particular disturbance regimes and consequent habitat conditions. Therefore, many scientists believe that dramatic deviation from historical conditions reduces the average survival and fecundity of animal populations, and thus puts species at risk of extinction (Swanson et al. 1994).

We define the historical conditions as the dynamic range of ecosystem composition, structure, and functions prior to significant impacts by Euro-American settlement (Swanson et al. 1994). Landres et al. (1999) suggest that the historical conditions provides guidance, context, and benchmarks for management. Understanding changes to historical conditions imposed by past management action (e.g., clearcutting riparian areas) can inform decisions on future management and realistic future objectives, such as desired future condition (DFC). Articulating riparian DFC with awareness of historical conditions provides a meaningful benchmark for assessing potential loss of riparian function and potential risks to fish and wildlife populations (Landres et al. 1999; Morgan et al. 1994). Because historical composition and structure were driven by disturbances, Landres et al. (1999) also suggest that managers should maintain, or at least emulate, the disturbance processes that created historical conditions. In other words, historical conditions describe relationships between species and habitats and thus provide context and guidance for managing ecological systems in the future. Emulating historical conditions could include the appropriate use of engineered solutions (e.g., stormwater basins to reduce peak flows, placing large wood in streams) to protect or restore habitats. Bisson et al. (2009) promote this same concept for conserving freshwater habitats of anadromous salmonids.

Managing a site, reach, or watershed to more closely resemble historical conditions may also effectively serve as a coarse-filter conservation strategy. Coarse filter strategies are based on the idea that managing for a habitat type, perhaps by emulating historical

[3] Also referred to as "historical natural variability," "natural variability," "range of natural variability," "natural range of variability," "historical range of variability," or "reference variability" (Landres et al. 1999).



Riparian ecosystem near Naches/Mary Huff, WDFW

conditions, will more efficiently conserve many species rather than managing for each species separately (Hunter et al. 1988; Swanson et al. 1994). Consistent with Landres et al. (1999), managing riparian areas with a goal of emulating historical conditions may be more cost effective in the long run than other approaches as it should require fewer investments in mitigation for degraded riparian ecosystem functions. In other words, managing for historical conditions is consistent with the idea that avoiding impacts to habitat is less expensive and more scientifically defensible than restoring habitat for each species after impacts.

Emulating an ecosystem's historical conditions poses both empirical and conceptual challenges. Empirical data needed to estimate the historical conditions are seldom available, and when available, the data are usually inadequate for the task of reliably estimating historical variation over time and space (Keane et al. 2009). The biggest conceptual challenge is posed by the ever-changing environment, much of it wrought by humans. While the historical conditions provides the best description of habitats that supported fish and wildlife species in the past, we recognize the challenge of applying that knowledge to watersheds that have been drastically altered by exotic species, fire suppression, intensive land uses, and climate change. Despite these challenges, Keane et al. (2009) still believe that the historical conditions provides an essential perspective for managers.

Historical conditions are the result of natural processes such as frequent floods, landslides, and wildfire – some of catastrophic magnitude – occurring throughout a watershed. Hence, for obvious reasons, managing riparian areas so that they roughly match their historical conditions may be unrealistic, especially in residential or agricultural settings. Furthermore, WDFW acknowledges that other uses of riparian areas as legitimate and worthwhile. Such uses and a wide variety of societal values must also be considered when developing strategies, plans, or rules for riparian areas. Therefore, rather than a goal, the historical conditions may better serve as a guide.

Dynamic mosaics of riparian and aquatic habitats are created, maintained, and altered in predictable (e.g., seasonally) and unpredictable ways (e.g., due to random events like storms, fires, and landslides).

9.6. Other Important Issues

We highlight three important issues that deserve more in-depth discussion: complexity, connectivity, and climate change. We also consider management implications of each issue for riparian areas and watersheds.

9.6.1 Complexity

The ecologist Frank Egler stated, "Ecosystems are not only more complex than we think, but more complex than we can think" (Egler 1977). Riparian ecosystems fit that description – they are dynamic, nonstationary, nonlinear systems comprised of many interacting components. In dynamic systems, conditions continually change over time. Dynamic equilibrium, for instance, means that conditions continually fluctuate about an average state, and the long-term statistics describing that process – mean, variance, fluctuation frequency – remain virtually constant. Nonstationary means that a system's functional relationships are changing over time, and consequently, the long-term statistics describing the process are changing. Some scientists believe that future climate change will lead to more pronounced nonstationarity in aquatic ecosystems (Milly et al. 2008). Nonlinear implies that functional relationships between ecosystem components are complicated. Under certain conditions, some types of nonlinear relationships may exhibit chaotic behavior. Not surprisingly, predicting the effects of management actions on dynamic, nonstationary, nonlinear systems is challenging.

Frissell et al. (1986) helped conceptualize watersheds as hierarchical systems where larger scale components, structures, and processes act primarily in the downstream direction on smaller scale components, structures, and processes. Factors that affect processes



The Nooksack River is located in the northwest part of Washington. It drains an area of the Cascade Range around Mount Baker, and flows through a fertile agricultural area before emptying into Bellingham Bay./Department of Natural Resources

over the longest duration can be considered "drivers" of the conditions and processes at lower levels in the hierarchy. Climate, geology, topography (and land cover) largely determine watershed characteristics and processes (paraphrasing the framework of Montgomery 1999). However, the composition, structure, and functions of streams and riparian ecosystems do not simply arise from these drivers. They are created and modified by continuous and episodic fluxes of materials (particularly water, sediment, and wood) and energy, which are broadly termed watershed processes. Dynamic mosaics of riparian and aquatic habitats are created, maintained, and altered in predictable (e.g., seasonally) and unpredictable ways (e.g., due to random events like storms, fires, and landslides).

These types of nonlinear dynamics are intrinsic properties of all ecosystems and important for the creation and maintenance of habitats that fish and wildlife populations depend on (Fausch et al. 2002; Ward et al. 2002; Wiens 2002), including salmon (Merz et al. 2015). The availability of multiple types of habitat (i.e., habitat heterogeneity) within and among streams may be essential for the persistence of multiple life history strategies in salmon species (Hilborn et al. 2003; Bisson et al. 2009; Waples et al. 2009; Merz et al. 2015) and the coexistence of other aquatic and riparian-dependent species (Bellmore et al. 2015).

The availability of multiple types of habitat within and among streams may be essential for the persistence of multiple life history strategies in salmon species and the coexistence of other aquatic and riparian-dependent species.

How should we approach the management of ecosystem complexity? Because ecosystems are wickedly complex (Ludwig 2001) and exhibit irreducible natural variability at multiple spatial and temporal scales, managers should adopt an attitude of humility. Over-confident managers who approach decisions with resolute certainty may fail to anticipate problems or recognize potential risks. Humility should instill in managers a desire to understand more before acting and a further desire to continually improve one's understanding of the system. The former is a quality of the precautionary principle, and the latter is a philosophical underpinning of adaptive management. Adaptive management is discussed later in this chapter.

9.6.2. Connectivity

Several chapters in this volume introduce the idea of watershed connectivity, in particular, longitudinal, lateral, and vertical connectivity. Connectivity is vital to aquatic ecosystem function and especially important at conferring resiliency to the negative effects of climate change (see section 9.6.3). Streams and their associated riparian ecosystems transport water, wood, sediment, nutrients, and organisms predominantly, but not exclusively in the downstream direction. Longitudinal (upstream to downstream) fragmentation of streams, for example by road crossings that block passage of fish, can reduce habitat capacity for individual species and change aquatic community composition by impeding movements of fish and other animals. Dams and undersized culverts also reduce the transport of large wood and sediment from upstream areas, which can adversely impact habitat composition and structure. Loss of lateral connectivity between streams and their floodplains due to levees, dams, or channel incision can reduce development of off-channel aquatic habitats, alter riparian plant communities, and impact processes such as water storage and nutrient cycling. Reduction of vertical connectivity, i.e., exchanges between stream water and deeper groundwater in the

hyporheic zone, can increase stream water temperatures, alter stream chemistry, and impact macroinvertebrate populations.

The importance of connectivity is also supported by our understanding of the extents at which aquatic species, especially fish, use stream habitat (Fausch et al. 2002). Movement of individuals among reaches and watersheds to locate specific habitat conditions (e.g., suitable water temperatures) is increasingly acknowledged as important to fish population persistence, particularly in light of climate change.



Bull trout in Deep Creek, Yakima County/Eric Anderson, WDFW

Maintaining connectivity in aquatic ecosystems likely requires management at site and watershed-scales. Management to protect or restore salmon and other aquatic species should ensure that all parts of a stream network that could be accessible to fish are in fact accessible to fish. That is, artificial structures should not impede fish movement. This requires watershed-scale stream network inventories and site-scale correction of artificial barriers. Additionally, barriers to the longitudinal or lateral transport of sediment and wood should be corrected, and hyporheic exchange should be enhanced by restoring the processes that supply in-stream large wood and coarse sediments. Where practical, management should ensure that the flows of water, sediment, and wood continue to flow as they did historically.

9.6.3. Climate Change

Climate change is expected to directly affect aquatic ecosystems by increasing air and water temperatures, altering stream hydrology, and impacting sediment yields throughout Washington. Indirect effects are too numerous to mention here but are likely to include changes to riparian plant communities, changes in fire regime, introduction of new diseases, exotic pests, and competitors with salmon. Because water temperature is widely recognized as one of the most important environmental factors influencing the geographic distribution, growth, and survival of fish (Regier et al. 1990; Armour 1991; McCullough 1999), the warming effects of climate change on rivers and streams threaten to reduce fish distribution and population viability (Beechie et al. 2013). The Pacific Northwest experienced a significant warming trend in summer stream temperatures of approximately 0.40°F/decade (0.22°C/decade) between 1980 and 2009 (Isaak et al. 2012). In the future, August stream temperatures are expected to increase an average of 5.1°F (2.8°C) by the 2080s (Isaak et al. 2015), and stream temperatures are expected to increase in all seasons of the year. The effects of climate change on surface water temperatures are compounded by other anthropogenic increases of water temperature caused by removal of riparian vegetation, water withdrawals, and channelization of streams (Poole and Berman 2001; Moore et al. 2005).

Climate change is projected to cause major changes in hydrology across Washington. Scientists have already detected negative trends in glacier volume and snowpack (Granshaw and Fountain 2006, Sitts et al. 2010, Stoelinga et al. 2010) and earlier peak streamflow in many rivers (Stewart et al. 2005). These trends are expected to continue in the future, along with increasing flood magnitudes, declining summer minimum flows, and rising stream temperatures (Elsner et al. 2010, Mantua et al. 2010). In Washington State, projected changes in future annual total precipitation are generally small compared to year-to-year fluctuations in seasonal and annual rainfall. Nonetheless, hydrological projections for the mid to late 21st century show a shift in flood frequencies that results in larger peak flows at all recurrence intervals , e.g., 2-year, 5-year, 10 year, etc. in some watersheds (Salathè et al. 2014). Changes are projected to be most pronounced in middle elevation basins, where a substantial proportion of the basin is located near the snowline (i.e., the "mixed rain and snow" zone). In these watersheds, warming will cause more precipitation to fall as rain instead of snow, which will decrease snow accumulation, hasten melt, and increase runoff (Hamlet et al. 2007).

Changes in stream flow are expected to alter sediment transport and channel morphology, however, published research analyzing the potential impact of future climate change on fluvial processes is limited. Praskievicz (2015) modeled the effects of future climate on geomorphic responses in three snow-dominated river basins of Idaho and eastern Washington. The results from the first site on the Tucannon River indicate that net sediment deposition is likely to occur, with increasing mid-channel bars. The second study site on the Coeur d'Alene River projects net erosion, and results for the third site forecast minimal changes on the Red River. These varying results indicate that the impacts of climate on sediment movement also depend on local context, i.e., how reach traits, such as substrate size or riparian vegetation, affect a stream channel's morphological stability or lateral mobility.

Management to minimize direct detrimental effects of climate change on aquatic habitat includes: 1) increasing shade to streams by protecting or restoring riparian forests, 2) decreasing thermal sensitivity of surface waters by increasing summer low flows, 3) maintaining longitudinal, lateral, and vertical connectivity within watersheds, 4) monitoring and mitigating stream temperatures, especially when management actions are known to cause stream temperature increases, and 5) developing contingency plans for responding to climate related changes to water temperature, hydrology, or channel morphology. Because riparian areas can provide longitudinal habitat connectivity, link aquatic and terrestrial ecosystems, and create thermal refugia for wildlife, climate change makes the restoration of riparian areas especially important (Seavy et al. 2009).

9.7. Uncertainty and Management

Chapters 2 through 8 demonstrate that management of riparian ecosystems often involves substantial and unavoidable uncertainty, despite the fact that many riparian ecosystem functions are well understood. We include a discussion on uncertainty in management because effective use of scientific knowledge requires an understanding of its uncertainty (Fischhoff and Davis 2014) and because addressing uncertainty can lead to better long-term outcomes (Steel et al. 2009) for all stakeholders.

Some uncertainty is due to limited knowledge. For instance, the historical composition and structure of native riparian vegetation in the Columbia Plateau remains relatively unknown (see Chapter 7). Research can improve knowledge and reduce this type of uncertainty. A less well-appreciated type of uncertainty is associated with stochastic environmental variability, which introduces irreducible uncertainty or "unavoidable unpredictability" (sensu Spielgelhalter and

Riesch 2011) into the expected effects of management decisions. In other words, the longer one's time horizon for management decisions, the more likely that less expected, or even unexpected effects are going to occur. This type of uncertainty can be quantified through research, but never reduced. For example, large floods may unexpectedly alter channel form (e.g., widen a channel) and as a result change a stream's thermal regime. This in turn can decrease the effectiveness of management aimed at maintaining stream temperature based on pre-flood riparian conditions (see Chapter 4). This concept is important because conditions created by some land management actions are ubiquitous and long-lived (e.g., young forests after timber harvest), thus creating a situation where less expected effects due to environmental variability are virtually guaranteed.

Using stream temperatures to discuss uncertainty is instructive because our understanding of riparian effects on stream temperatures is arguably the best developed of any riparian function (see Chapter 4). We know for instance how certain ecosystem composition, structures, and functions (predictor variables) affect stream temperatures, so we could accurately predict the effects of common management actions with high certainty. Unfortunately, logistical or economic constraints of collecting predictor variable data usually preclude the development and use of such models. Instead, we often employ simpler, statistical models or correlations to inform management. For instance, we can generally predict changes to water temperatures based on changes to shade from riparian vegetation because changes in shade are often strongly correlated with changes in water temperatures (Cristea and Janisch 2007).

Figure 9.2 shows the results of several studies relating changes in summer stream temperatures to changes in riparian buffer width. Stream temperatures were measured before and after reducing the widths of forested riparian buffers, which decreased shading of streams. The results of such studies are often assumed to predict the effects of shade reduction on stream temperatures in other locations. However, because each stream is unique (e.g., differences in stream widths, topographic shade, groundwater flows, etc.), changes in water temperature based solely on shade are relatively uncertain. For example, Jackson et al. (2001) found that 30-ft wide forested buffers caused summer stream temperatures to increase by an average of 4.2°F (2.4°C), but the 95% confidence interval for the average was -0.1° to 8.6°F (0.0 to 4.8°C). At one site, temperatures decreased, likely due to unmeasured effects on groundwater flow (Janisch et al. 2012). Such uncertainty is common. Additional studies of this type might narrow confidence intervals and more accurately estimate the average response, but predictions of stream temperature based on buffer width alone will remain highly uncertain despite our knowledge that shade can strongly affect water temperature.

Similarly, empirical data describe wood recruitment from riparian areas as increasing with distance from the channel (i.e., riparian area width), but this relation varies widely among streams (Figure 9.3). Other potential predictor variables might include the wood recruitment mechanism, topography, fire regime, and forest age. However, we are unaware of other recruitment models that include variables that would allow us to predict the effects of management actions on wood recruitment with high certainty.

Currently, most riparian ecosystem functions described in this volume are best described with statistical models or correlations that often reliably predict the direction or sign (+ or -) of the correlation and some of the variability around the central tendency. Many such models rely on data from few sites that poorly describe the average or range of relations. For example, sample sizes for studies in Figure 9.2 are small, i.e., $N = 6, 3, 5,$ and 5. Additional studies with larger sample sizes could better describe responses to shade reduction but are unlikely to substantially reduce uncertainty if they do not consider other important predictors in addition to buffer width.

Even as we conduct studies that reduce uncertainty associated with a lack of knowledge, we are continually challenged to make sound decisions into the future by irreducible uncertainty due to stochastic events, such as natural disturbances, and non-stationary processes like climate change. As riparian ecosystems change through time, whether due to future wildfire, floods, or climate change, we must ensure that our management strategies meet their intended goals. Uncertainty about the future effects of current management actions is perhaps the biggest challenge faced by managers because those effects of management often persist over long periods or may be practically irreversible (e.g., loss of riparian areas due to residential development). With this uncertainty comes the risk that the unpredictable may convert current and successful regulatory policies or management practices into future failures.

We can never eliminate uncertainty, but we can make management decisions that are appropriate given our current level of uncertainty. We recommend reducing risk to riparian ecosystems by: 1) reducing uncertainty through new research, 2) explicitly acknowledging and directly addressing uncertainty in policy and management decisions that affect fish and wildlife habitats, 3) considering the application of the precautionary principle to reduce unacceptable risk (O'Riordan and Jordan 1995; Gullet 1997). That is, erring on the side of caution, particularly when dealing with environmental impacts that are difficult to undo (irreversible damage or long recovery times), and 4) practicing adaptive management.

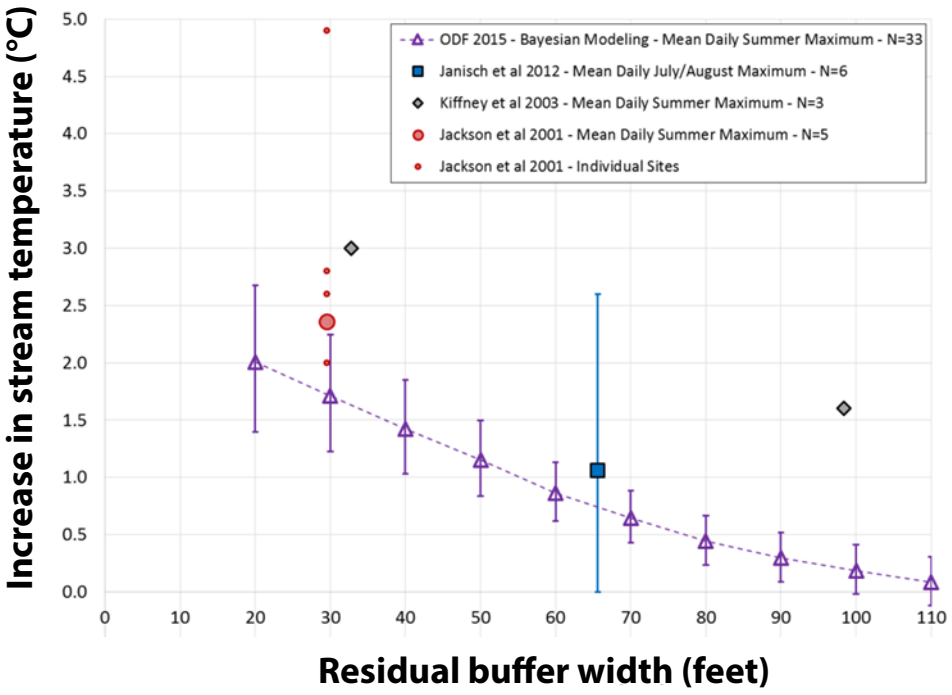


Figure 9.2. Observed temperature response associated with "no-cut" riparian buffers with adjacent clearcut harvest. Only studies that employed a Before-After-Control-Impact design and conducted in Pacific Northwest forests are included. Bayesian modeling results (and 90% credible intervals) were derived from data collected as part of Groom et al. (2011). A change of 1°C is equivalent to a 1.8°F change. Analyses provided by P. Leinenbach, USEPA Region 10 (See Chapter 4 for a more complete description of this figure).

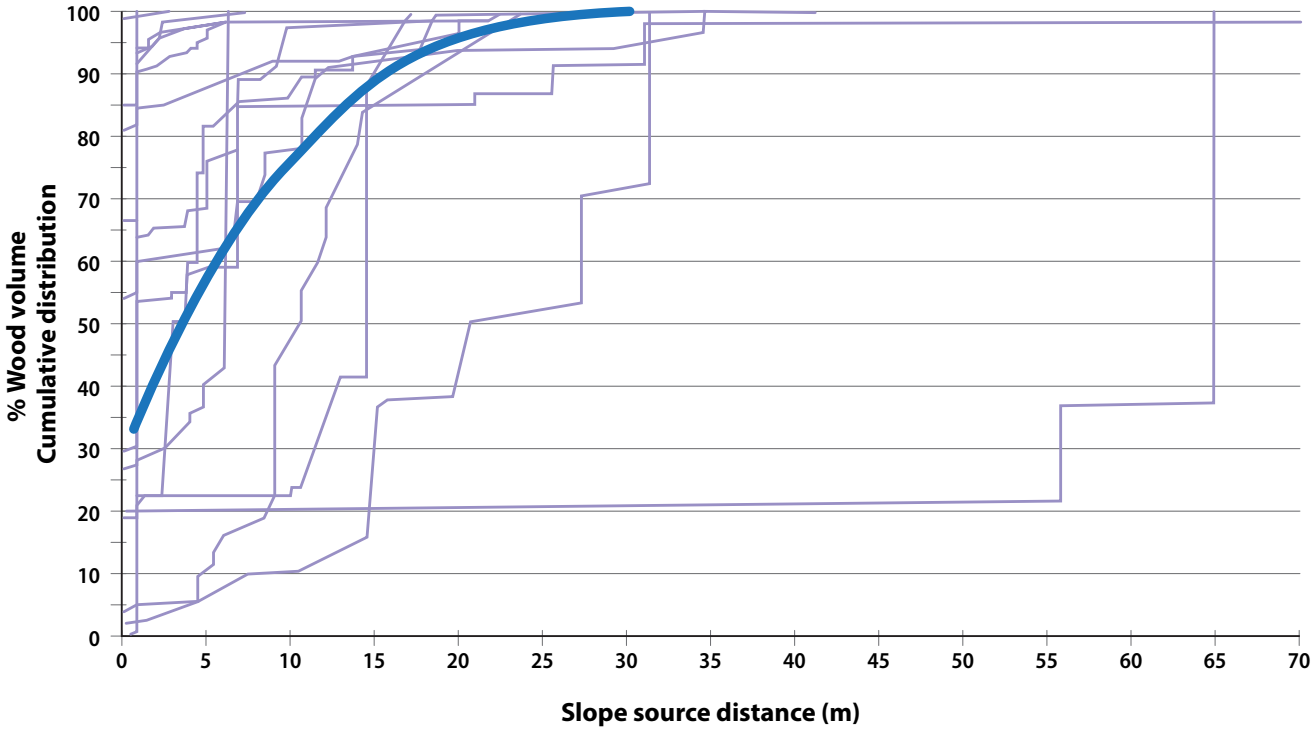


Figure 9.3. Sixteen large wood recruitment curves for second-growth redwood forest on 16 sites in northern California (from Benda et al. 2002). The theoretical prediction curve (thick line) is based on mortality recruitment only using random 360° fall trajectories. Curves to the left of the theoretical curve are sites where bank erosion is a major recruitment mechanism. Curves to the right of the theoretical curve are sites where landsliding is a major recruitment mechanism. (See Chapter 3 for a more complete description of this figure).

9.8. Adaptive Management

Despite new insights into ecosystems dynamics and better understanding of the effects of management actions on species and their habitats, natural resource management decisions will always struggle with some level of uncertainty. Adaptive management is widely recognized as a sensible, if not essential, approach to the management of natural resources under uncertainty. As originally conceived, adaptive management can be defined as the systematic acquisition and application of reliable information to improve management over time (Wilhere 2002). Reliable information is acquired through statistically-valid research and monitoring. Furthermore, adaptive management can facilitate a way forward when levels of uncertainty become high enough to threaten stakeholder agreement about environmental policies (Wilhere and Quinn 2018).

The adaptive management process is a continual cycle consisting of planning, action, monitoring, evaluation, and adjustment (Bormann et al. 1994, Wilhere 2002) (Figure 9.4). Monitoring and evaluation form a feedback loop that provides information for management decisions. However, feedback alone cannot fulfill the goal of adaptive management, that is, the continual improvement of management. Ideally, an "adaptive management plan" integrates every phase of management with monitoring, and considers how information collected through monitoring will lead to future changes in management. Developing an adaptive management plan should be a collective endeavor of policy makers, managers, field staff, and scientists.

Successful adaptive management requires an understanding of all stakeholder perspectives. Hence, developing an adaptive management plan should begin with discussions amongst stakeholders about their concerns regarding uncertainty and risk. The plan should be developed through a negotiated process, and it should explain how specific risks will be addressed through a program of systematic learning (e.g., management experiments, focused monitoring, targeted literature reviews, etc.). Importantly, the best adaptive management plans have agreements about the specific information necessary to change policy or management and what those changes might be.

Adaptive management programs can fall victim to the widespread confusion between the roles of values and science in management decisions (Wilhere and Quinn 2018). Maintaining a clear distinction between values (cultural, social, and economic) and science, and between the roles of policy makers and scientists, is critical to success. That said, WDFW recognizes that natural resource management or land use policies must often balance competing ecological, economic, and social values. In fact, one of WDFW's conservation principles is that management decisions should integrate ecological, economic, and social perspectives. This volume addresses only the ecology of riparian area management; it does not cover economic and social aspects. Determining an acceptable balance requires a political process involving stakeholders, local governments, tribes, and state agencies. We hope this volume can help to inform that process.

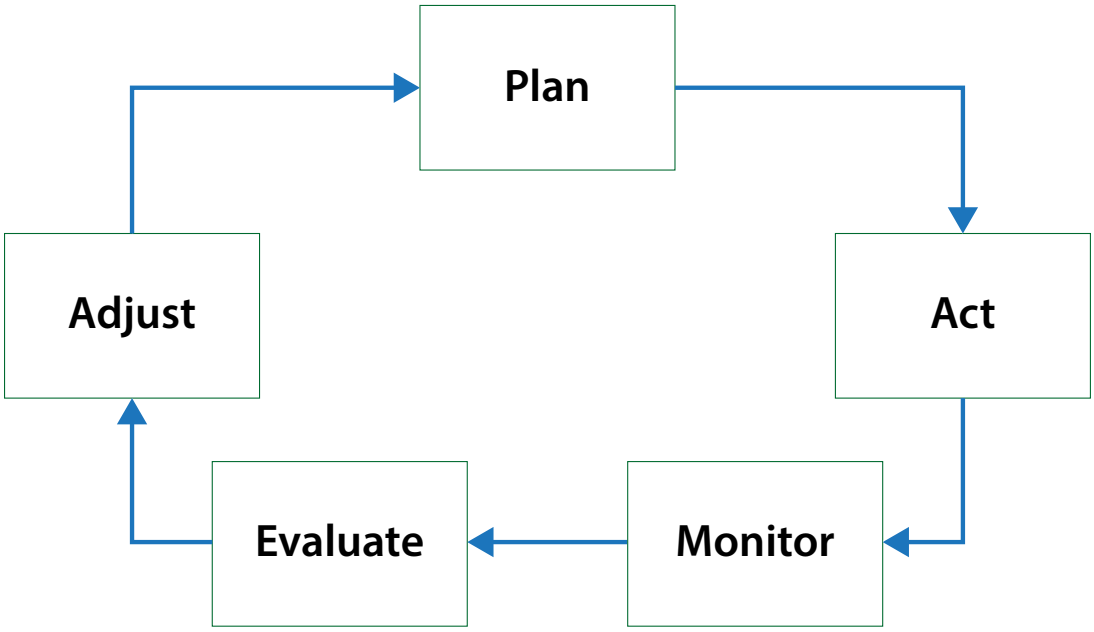


Figure 9.4. The adaptive management cycle (modified from Bormann et al. 1994).

9.9. Literature Cited[4]

Armour, C. 1991. Guidance for evaluating and recommending temperature regimes to protect fish. Biological Report 90(22). Fish and Wildlife Service, Washington, D.C. (viii)

Avery, T.E., and H.E. Burkhart. 1994. Forest measurements. McGraw-Hill, New York. (i)

Beechie, T.J., H. Imaki, J. Greene, A. Wade, H. Wu, G. Pess, P. Roni, J. Kimball, J. Stanford, P. Kiffney, and N. Mantua. 2013. Restoring salmon habitat for a changing climate. River Research and Applications 29:939–960. (i)

Bellmore, J.R., C.V. Baxter, and P.J. Connolly. 2015. Spatial complexity reduces interaction strengths in the meta-food web of a river floodplain. Ecology 96:274-283. (i)

Benda, L.E., P. Bigelow, and T.M. Worsley. 2002. Recruitment of wood to streams in old-growth and second-growth redwood forests, northern California, U.S.A. Canadian Journal of Forest Research 32:1460-1477. (i)

Bisson, P.A., J.B. Dunham, and G.H. Reeves. 2009. Freshwater ecosystems and resilience of Pacific salmon: habitat management based on natural variability. Ecology and Society 14(1):45. (i)

Bormann, B.T., P.G. Cunningham, M.H. Brookes, V.W. Manning, and M.W. Collopy. 1994. Adaptive ecosystem management in the Pacific Northwest. PNW-GTR-341. U.S. Forest Service, Pacific Northwest Research Station, Portland, Oregon. (viii)

Cristea, N., and J. Janisch. 2007. Modeling the effects of riparian buffer width on effective shade and stream temperature. Washington Department of Ecology, Olympia. (viii)

Cummins, K.W. 1974. Structure and function of streams ecosystems. BioScience 24:631-641. (i)

DNR (Washington Department of Natural Resources). 1999. Forests and fish report. Forest Practices Division, Olympia, Washington. (viii)

DNR (Washington Department of Natural Resources). 2005. Final forest practices habitat conservation plan. Forest Practices Division, Olympia, Washington. (viii)

Egler, F.E. 1977. The nature of vegetation: its management and mismanagement. Aton Forest, Norfolk, Connecticut. (viii)

Elsner, M.M., L. Cuo, N. Voisin, J.S. Deems , A.F. Hamlet, J.A. Vano , K.E.B. Mickelson, S.Y. Lee, and D.P. Lettenmaier. 2010. Implications of 21st century climate change for the hydrology of Washington State. Climatic Change 102:225–260. (i)

Fausch, K.D., C.E. Torgersen, C.V. Baxter, and H.W. Li. 2002. Landscapes to riverscapes: bridging the gap between research and conservation of stream fishes. BioScience 52:483-498. (i)

FEMAT (Forest Ecosystem Management Assessment Team). 1993. Forest ecosystem management: an ecological, economic and social assessment. U.S. Department of Agriculture and U.S. Department of the Interior, Portland, Oregon. (viii)

Fischhoff, B., and A.L. Davis. 2014. Communicating scientific uncertainty. Proceedings of the National Academy of Science 111(Supplement 4): 13664-13671. (i)

Fox, M.J. 2003. Spatial organization, position, and source characteristics of large woody debris in natural systems. Doctoral dissertation. University of Washington, Seattle. (i)

Franklin, J.F., and T.A. Spies. 1991. Composition, function, and structure of old-growth Douglas-fir forests. Pages 71-82 *in* L.F. Ruggerio, K.B. Aubry, A.B. Carey, and M.H. Huff, technical coordinators. Wildlife and vegetation of unmanaged Douglas-fir forests. PNW-GTR-285. U.S. Forest Service, Pacific, Northwest Research Station, Portland, Oregon. (viii)

Frissell, C.A., W.J. Liss, C.E. Warren, and M.D. Hurley. 1986. A hierarchical framework for stream classification: viewing streams in a watershed context. Environmental Management 10:199-214. (i)

4 References are classified according to RCW 34.05.271 (see Appendix 1) denoted by a lower case roman numeral (i – viii) in parentheses at the end of the citation.

Granshaw, F.D., and A.G. Fountain. 2006. Glacier change (1958–1998) in the North Cascades National Park Complex, Washington, USA. Journal of Glaciology 52:251-256. (i)

Gregory, S.V., F.J. Swanson, W.A. McKee, and K.W. Cummins. 1991. An ecosystem perspective of riparian zones: focus on links between land and water. Bioscience 41:540-551. (i)

Groom, J.D., L. Dent, and J. Madsen. 2011. Stream temperature change detection for state and private forests in the Oregon Coast Range. Water Resources Research 47:1-12. (i)

Gullet, W. 1997. Environmental protection and the "precautionary principle": a response to scientific uncertainty in environmental management. Environmental Planning and Law Journal 14:52-69. (i)

Hamlet, A. F., P.W. Mote, M.P. Clark, and D.P. Lettenmaier. 2007. Twentieth-century trends in runoff, evapotranspiration, and soil moisture in the western United States. Journal of Climate 20:1468-1486. (i)

Herman, R.K., and D.P. Lavender. 1990. *Pseudotsuga menziesii*. Pages 527-540 *in* R.M. Burns and B.H. Honkala, technical coordinators. Silvics of North America volume 1: conifers. Agriculture Handbook 654. U.S. Forest Service, Washington, D.C. (viii)

Hilborn, R. 1987. Living with uncertainty in resource management. North American Journal of Fisheries Management 7:1-5. (i)

Hilborn, R., T.P. Quinn, D.E. Schindler, and D.E. Rogers. 2003. Biocomplexity and fisheries sustainability. Proceedings of the National Academy of Sciences 100:6564-6568. (i)

Hunter, M.L. Jr., G.L Jacobson Jr., and T. Web III. 1988. Paleoecology and the coarse filter approach to maintaining biological diversity. Conservation Biology 2:375-385. (i)

Independent Scientific Group. 1999. Scientific issues in the restoration of salmonid fishes in the Columbia River. Fisheries 24:210-219. (i)

Isaak, D., S. Wenger, E. Peterson, J. Ver Hoef, C. Luce, S. Hostetler, J. Dunham, J. Kershner, B. Roper, D. Nagel, D. Horan, G. Chandler, S. Parkes, and S. Wollrab. 2015. Development and application of NorWeST stream temperature climate scenarios for the Pacific Northwest. Webinar, January 27. North Pacific Landscape Conservation. Cooperative, Lacey, Washington. (viii)

Isaak, D.J., S. Wollrab, D. Horan, and G. Chandler. 2012. Climate change effects on stream and river temperatures across the northwest U.S. from 1980 - 2009 and implications for salmonid fishes. Climate Change 113:499-524. (i)

Jackson, C.R., C.A. Sturm, and J.M. Ward. 2001. Timber harvest impacts on small headwater stream channels in the coast ranges of Washington. Journal of the American Water Resources Association 37:1533–1549. (i)

Janisch, J.E., S.M. Wondzell, and W.J. Ehinger. 2012. Headwater stream temperature: interpreting response after logging, with and without riparian buffers, Washington, USA. Forest Ecology and Management 270:302-313. (i)

Keane, R.E., P.F. Hessburg, P.B. Landres, and F.J. Swanson. 2009. The use of historical range and variability (HRV) in landscape management. Forest Ecology and Management 258:1025-1037. (i)

Kiffney, P.M., J.S. Richardson, and J.P. Bull. 2003. Responses of periphyton and insect consumers to experimental manipulation of riparian buffer width along headwater streams. Journal of the American Water Resources Association 40:1060-1076. (i)

King, J.E. 1966. Site index curves for Douglas-fir in the Pacific Northwest. Weyerhaeuser Forestry Paper No. 8. Forestry Research Center, Weyerhaeuser Company, Centralia, Washington. (viii)

Landres, P.B., P. Morgan, and F.J. Swanson. 1999. Overview of the use of natural variability concepts in managing ecological systems. Ecological Applications 9:1179-1188. (i)

Ludwig, D. 2001. The era of management is over. Ecosystems 4:758–764. (i)

Mantua, N., I. Tohver, and A. Hamlet. 2010. Climate change impacts on streamflow extremes and summertime stream temperature and their possible consequences for freshwater salmon habitat in Washington State. Climatic Change 102:187-223. (i)

McCullough, D.A. 1999. A review and synthesis of effects of alterations to the water temperature regime on freshwater life stages of salmonids, with special reference to Chinook salmon. EPA 910-R-99e010. U.S. Environmental Protection Agency, Region 10, Seattle, Washington. (viii)

Merz, J.E., D.G. Delaney, J.D. Setka, and M.L. Workman. 2015. Seasonal rearing habitat in a large Mediterranean-climate river: management implications at the southern extent of Pacific salmon (*Oncorhynchus* spp.). River Research and Applications 32:1220-1231. (i)

Milly, P.C.D., J. Betancourt, M. Falkenmark, R.M. Hirsch, Z.W. Kundzewicz, D.P. Lettenmaier, and R.J. Stouffer. 2008. Stationarity is dead: whither water management? Science 319: 573-574. (i)

Montgomery, D.R. 1999. Process domains and the river continuum. Journal of the American Water Resources Association 35:397-410. (i)

Moore, R.D., D.L. Spittlehouse, and A. Story. 2005. Riparian microclimate and stream temperature response to forest harvesting: a review. Journal of the American Water Resource Association 41:813-834. (i)

Morgan, P., G.H. Aplet, J.B. Haufler, H.C. Humphries, M.M. Moore, and W.D. Wilson. 1994. Historical range of variability: a useful tool for evaluating ecosystem change. Journal of Sustainable Forestry 2:87-111. (i)

Naiman, R.J., and R.E. Bilby, editors. 1998. River ecology and management: lessons from the Pacific Coastal Ecoregion. Springer-Verlag, New York. (i)

Naiman, R.J., R.E. Bilby, and P.A. Bisson. 2000. Riparian ecology and management in the Pacific Coastal Rain Forest. BioScience 50:996-1011.

NRC (National Research Council). 2002. Riparian areas: functions and strategies for management. National Academy Press. Washington, D.C. (i)

O'Riordan, T., and A. Jordan. 1995. The precautionary principle in contemporary environmental politics. Environmental Values 4:191-212. (i)

Poole, G.C., and C.H. Berman. 2001. An ecological perspective on in-stream temperature: natural heat dynamics and mechanisms of human-caused thermal degradation. Environmental Management 27:787-802. (i)

Praskievicz, S. 2015. A coupled hierarchical modeling approach to simulating the geomorphic response of river systems to anthropogenic climate change. Earth Surface Processes and Landforms 40:1616-1630. (i)

Reeves, G.H., L.E. Benda, K.M. Burnett, P.A. Bisson, and J.R. Sedell. 1995. A disturbance-based ecosystem approach to maintaining and restoring freshwater habitats of evolutionary significant units of anadromous salmonids in the Pacific Northwest. American Fisheries Society Symposium 17:334-349. (i)

Regier, H.A., J.A. Holmes, and D. Pauly. 1990. Influence of temperature changes on aquatic ecosystems: an interpretation of empirical data. Transactions of the American Fisheries Society 119:374-389. (i)

Richardson, J.S., R.J. Naiman, F.J. Swanson, and D.E. Hibbs. 2005. Riparian communities associated with Pacific Northwest headwater streams: assemblages, processes, and uniqueness. Journal of the American Water Resources Association 41:935-947. (i)

Salathé Jr., E.P., A.F. Hamlet, C.F. Mass, S.-Y. Lee, M. Stumbaugh, and R. Steed. 2014. Estimates of twenty-first-century flood risk in the Pacific Northwest based on regional climate model simulations. Journal of Hydrometeorology 15:1881-1899. (i)

Seavy, N.E., T. Gardali, G.H. Golet, F.T. Griggs, C.A. Howell, R. Kelsey, S.L. Small, J.H. Viers, and J.F. Weigand. 2009. Why climate change makes riparian restoration more important than ever: recommendations for practice and research. Ecological Restoration 27:330-338. (i)

Sitts D., A.G. Fountain, and M. Hoffman. 2010. Twentieth century glacier change on Mount Adams, Washington, USA. Northwest Science 84:378-385. (i)

Spiegelhalter, D.J., and H. Reisch. 2011. Don't know, can't know: embracing deeper uncertainties when analysing risks. Philosophical Transactions of the Royal Society A 369:4730–4750. (i)

Stanford, J.A., J.V. Ward, W.J. Lis, C.A. Frissell, R.N. Williams, J.A. Lichatowich, and C.C. Coutant. 1996. A general protocol for restoration of regulated rivers. Regulated Rivers: Research & Management 12:391-414. (i)

Steel, E.A., T.J. Beechie, M.H. Ruckelshaus, A.H. Fullerton, P. McElhany, and P. Roni. 2009. Mind the gap: uncertainty and model communication between mangers and scientists. American Fisheries Society Symposium 71:357–372. (i)

Stewart, I.T., D.R. Cayan, and M.D. Dettinger. 2005. Changes toward earlier streamflow timing across western North America. Journal of Climate 18:1136-1155. (i)

Stirling, A., and D. Gee. 2003. Science, precaution, and practice. Public Health Reports 117:521-533. (i)

Stoelinga, M.T., M.D. Albright, and C.F. Mass. 2010. A new look at snowpack trends in the Cascade Mountains. Journal of Climate 23:2473-2491. (i)

Suter, G.W., L.W. Barnthouse, and R.V. O'Neill. 1987. Treatment of risk in environmental impact assessment. Environmental Management 11:295-303. (i)

Swanson, F.J., J.A. Jones, D.O. Wallin, and J.H. Cissel. 1994. Natural variability-implications for ecosystem management. Pages 80-94 *in* M.E. Jensen and P.S. Bourgeron, technical coordinators. Volume II: ecosystem management: principles and applications. PNW-GTR-318. U.S. Forest Service, Pacific Northwest Research Station, Portland, Oregon. (viii)

Thomas, J.W., technical editor. 1979. Wildlife habitats in managed forests the Blue Mountains of Oregon and Washington. Agriculture Handbook No. 553. U.S. Forest Service, Washington, D.C. (viii)

Walker, B., C.S. Holling, S.R. Carpenter, and A. Kinzig. 2004. Resilience, adaptability and transformability in social–ecological systems. Ecology and Society 9(2):5. Available: http://www.ecologyandsociety.org/vol9/iss2/art5. (January 2019) (i)

Waples, R.S., T. Beechie, and G.R. Pess. 2009. Evolutionary history, habitat disturbance regimes, and anthropogenic changes: what do these mean for resilience of Pacific salmon populations? Ecology and Society 14(1):3. Available: http://www.ecologyandsociety.org/vol14/iss1/art3/. (January 2019) (i)

Ward, J.V., K. Tockner, D.B. Barscott, and C. Claret. 2002. Riverine landscape diversity. Freshwater Biology 47:517–539. (i)

Wiens, J.A. 2002. Riverine landscapes: taking landscape ecology into the water. Freshwater Biology 47:501-515. (i)

Wilhere, G.F. 2002. Adaptive management in habitat conservation plans. Conservation Biology 16:20-29. (i)

Wilhere, G.F., and T. Quinn. 2018. How wide is wide enough?: values, science, and law in riparian habitat conservation. Natural Resources Journal 58:279-318. (i)

Wohl, E. 2005. Compromised rivers: understanding historical human impacts on rivers in the context of restoration. Ecology and Society 10(2):2. Available: http://www.ecologyandsociety.org/vol10/iss2/art2. (January 2019) (i)

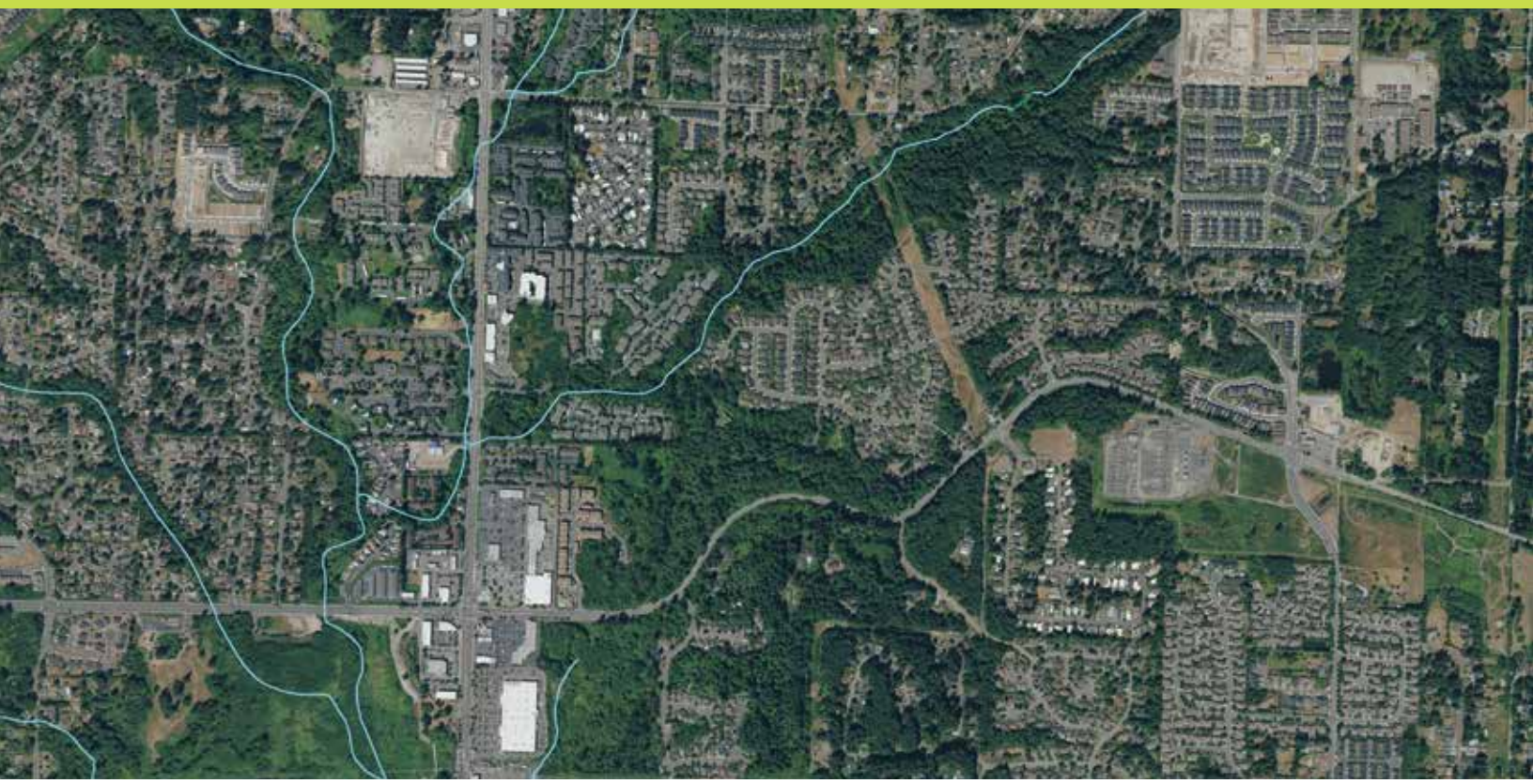
Wynne, B. 1992. Uncertainty and environmental learning: reconceiving science and policy in the preventive paradigm. Global environmental change 2:111-127. (i)

Zar, J.H. 1996. Biostatistical analysis. Prentice-Hall, Upper Saddle, New Jersey. (viii)



Grande Ronde River/Alan Bauer

Appendix 1: Glossary



Riparian areas along streams (blue lines) in north King County/Terry Johnson, WDFW

Active channel

The portion of a stream channel defined by the lower limit of continuous riparian vegetation, and it may be delineated by absence of both moss on rocks and rooted vegetation. The upper most elevation of the active channel is sometimes equated with the ordinary high water mark.

Active floodplain

A portion of floodplain that is located between the active channel and adjacent terrace or hillslopes. Depending on the watershed, the flood return interval of the active floodplain varies between 1 and 10 years.

Adaptive management

The systematic acquisition and application of reliable information to improve management over time. Ideally, adaptive management treats management decisions as experiments in order to address critical uncertainties and learn more quickly from experience. It involves setting targets, monitoring outcomes, and adjusting management decisions based on results. Hallmarks of a well conceived adaptive management program include: 1) adequate funding for research, 2) a willingness to change course when pre-established triggers are reached, and 3) a commitment to monitor and evaluate conditions at appropriate spatial and temporal scales. See Ecosystem-based management.

Anthropogenic

Caused by human activity.

Channel confinement

A description of how much a channel can laterally move within its valley determined by the ratio of valley width (distance between toe of hillslopes on both sides of a

valley) to active channel width. Typically, a segment is considered confined when the ratio is less than two and unconfined when greater than four.

Channel migration zone
The area within which a river channel is likely to move laterally over a specified period (e.g., 100 years).

Channel morphology
A stream channel's shape, which changes over time due to the interplay of water, sediments, vegetation, and certain animals, e.g., Beaver *Castor canadensis* and salmon.

Channel reach (stream)
A continuous segment of a channel that has similar physical features, such as gradient and confinement.

Channel slope or gradient
The average steepness of a stream segment measured as its change in elevation divided by its length. Typically, a segment's gradient is considered low if less than 2%, moderate between 2% and 4%, and high if greater than 4%.

Composition: See *Ecological composition*.

Disturbance regime
The frequency, magnitude, and duration of disturbance events.

Disturbance
A disturbance is any relatively discrete event in time that disrupts the composition, structure, or functions of ecosystems, communities, or populations.

Dynamic equilibrium
An ecological system's long-term state of relative stability that is maintained through opposing processes. Understanding an ecosystem's equilibrium, is a goal of ecosystem-based management.

Ecological (biological) integrity
Capacity of an ecological system to maintain a community of organisms that has species composition, diversity, and functional organization comparable to those of natural habitats within a region. An ecological system has integrity when its dominant ecological characteristics (e.g., composition, structure, function) occur within their historical ranges of natural variation.

Ecological composition
A term encompassing all parts of an ecosystem that include both living (biotic) and nonliving (abiotic) parts. Ecosystem composition is an important consideration in conservation.

Ecological function(ing)
1) The process or cause-effect relationships between two or more interacting ecosystem components; 2) the sum of processes that sustain the system; or 3) the capacity of natural processes to provide goods and services that satisfy human needs, either directly or indirectly.

Ecological process
Interactions among components of an ecosystem, both biotic (living organisms) and abiotic (chemical and physical) components. Many processes involve the transfer, conversion, or storage of matter and energy. This term is synonymous with the first definition of *ecological function.*

Ecological structure
The arrangement of and relations among the parts or components of an ecosystem.

Ecosystem
A spatially explicit unit of the Earth that includes all of the organisms, along with all components of the abiotic environment. Ecosystems have *composition, structure,* and *functions.*

Ecosystem-based management (EBM)
An integrated management approach that recognizes the full array of interactions within an ecosystem, including humans, rather than considering single issues, species, or ecosystem services in isolation. EBM often involves balancing ecological, economic, and social trade-offs within the context of existing laws and policies.

Erosion
The loosening and transport of soil particles and other sediment by water. Terrestrial erosion includes raindrop splash erosion, overland flow sheet erosion, surface flow rill (shallow) and gully (deeper) erosion. Channel erosion includes streambank erosion and channel incision. Rill and gully erosion diminishes the capacity of riparian areas to trap sediment and pollutants and often can be avoided with intact riparian vegetation.

FEMAT curve
A conceptual model that describes the relationship between various riparian *ecosystem functions* and distance from channel. The model consists of generalized curves that show the cumulative effectiveness of litter fall, root strength, shading, and coarse wood debris recruitment to stream as a function of distance from channel.

Flow regime
The distribution of stream discharges through space and time. Flow regimes can be described by their magnitude (e.g., mean annual, hourly maximum), timing, frequency or return periodicity, duration, spatial distribution, and rate of change. The pathways that water takes to reach a stream (e.g., surface runoff) exert a strong influence on the flow regime.

Function
Physical, chemical, or biological processes that occur within an ecosystem. See *ecological function(ing)* and *ecological process.*

Historical conditions: See *Range of natural variability.*

Hot moments
Periods of elevated denitrification rates. Hot moments can occur during a rainfall event. Also see *hot spots.*

Hot spots
Areas that exhibit high denitrification rates. Hot spots often occur in floodplains and other riparian areas with oscillating groundwater levels and/or higher hyporheic flows. Locations of hot spots can vary through time.

Hydrology
Study of the occurrence, distribution, movement, and properties of the water and their relationship with land.

Hyporheic zone
The area beneath the bed of a river or stream that is saturated with water.

Impervious surface
Ground surfaces that resist or prevent water infiltration, e.g., roofs of houses and roadways.

Incision
The process of downcutting into a stream channel leading to a decrease in the channel bed elevation. Incision is often caused by a decrease in sediment supply or an increase in stream flows capable of transporting (scouring) sediment.

Infiltration
The rate or process by which water on the ground surface enters the soil.

Macroinvertebrates
Animals, including insects, mollusks, crustaceans, and worms, that do not have a backbone, and are large enough to be seen without a microscope. Aquatic macroinvertebrates are commonly used as an indicator of habitat and water quality.

Mass wasting
The down slope movement of soil, sediments, and rock due to gravity (rather than water, wind, or ice, for example).

Nutrient cycling
The movement, uptake, transformation, storage, and release of nutrients, especially carbon, nitrogen, and phosphorus. Riparian characteristics that affect nutrient cycling include flow path, vegetation composition and structure, topography, groundwater level, and soil type.

Nutrient spiraling length
The distance nutrients move downstream during a complete cycle; a measure of nutrient utilization to nutrient supply. Long spiraling lengths indicate that the system is saturated with nutrients and organisms can no longer use the incoming nutrient loads. Streams in Washington forests typically have relatively short nutrient spiraling lengths.

Ordinary high water mark
This mark occurs along stream channels where the presence and action of waters are so common and usual, and so long continued in all ordinary years, as to mark upon the soil a character distinct from that of the abutting upland.

Precautionary principle
Erring on the side of causing no negative impact to natural resources when faced with uncertainty, especially for harm that is essentially irreversible. The precautionary approach involves: 1) taking preventive action (avoiding impacts), 2) shifting the burden of proof to the project proponents, 3) exploring a wide range of potential alternatives, and/or, 4) including multiple stakeholders and disciplines in decision making.

Process: See *Ecological process.*

Range of natural variability (or historical range of natural variability)
Refers to the range of ecological conditions (composition, structure, and functions) in a time period before widespread anthropogenic changes.

Riparian
An adjective meaning adjacent to a water body: stream, river, lake, pond, bay, sea, ocean. Riparian areas are sometimes referred to by different names: riparian ecosystems, riparian habitats, riparian corridors, or riparian zones. Depending on the context, these different terms may have somewhat different meanings.

Riparian buffer
Buffer refers to its purpose, which is to reduce or prevent adverse impacts to water quality, fisheries, and aquatic biodiversity from human activities occurring upslope of the buffer. Riparian buffers may also be called a riparian management zone. Riparian buffers managed specifically for pollutant removal may also be called a vegetated filter strip.

Riparian ecosystem
Riparian ecosystems are transitional between terrestrial and aquatic ecosystems and are distinguished by gradients in biophysical conditions, ecological processes, and biota. They are areas through which surface and subsurface hydrology connect waterbodies with their adjacent uplands. They include those portions of terrestrial ecosystems that significantly influence exchanges of energy and matter with aquatic ecosystems (i.e., a zone of influence). Our definition of riparian ecosystem does not include adjacent waters (i.e., river or streams, but does include riverine wetlands) and recognizes the riparian zone as a distinctive area within riparian ecosystems.

Riparian management zone
Riparian management zone is often synonymous with riparian buffer. See *Riparian buffer.*

Riparian zone
A distinctive area within riparian ecosystems. The riparian zone contains wet or moist soils and plants adapted to growing conditions associated with periodically saturated soils.

Riverscape
A landscape organized around a river system that includes the river network and contributing watershed along with other components that are not organized by watershed boundaries such as wildfire, mobile organisms, and wind-borne seeds. Distinct from uplands, it is primarily organized in a downstream direction (e.g., movement of water, sediment, and wood) but also contains lateral elements (e.g., floodplain interaction), vertical elements (e.g., interaction of surface and hyporheic flow), and upstream elements (e.g., migrating salmon).

Salmonid
A family of fish comprised of salmon, trout, and whitefish. Native salmonid species in Washington State include: Chinook Salmon *Oncorhynchus tshawytscha,* Chum Salmon *O. keta,* Coho Salmon *O. kisutch,* Pink Salmon *O. gorbuscha,* Sockeye Salmon/Kokanee *O. nerka*, Steelhead/Rainbow Trout *O. mykiss,* Cutthroat Trout *O. clarki,* Bull Trout *Salvelinus confluentus,* Dolly Varden *Salvelinus malma,* Pygmy Whitefish *Prosopium coulteri,* and Mountain Whitefish *P. williamsoni.* This list does not include names of subspecies.

Site class
The classification of a site's productivity based on the growth of the dominant tree species. Site classes vary based on local differences in soil nutrients and moisture, light and temperature regimes, and topography. Site classes are typically described as most productive (I) through least productive (V).

Site-potential tree height
The average maximum height of the tallest dominant trees for a given age and site class.

Stochastic process
An event involving chance or probability (e.g., landslide, flood). Stochastic processes may have patterns that can be analyzed statistically but cannot be precisely predicted.

Stream order
A hierarchical stream classification system in which headwater tributaries are classified as first order; when two first order tributaries meet they form a second order tributary, when two second order tributaries meet they form a third order tributary, and so on. Low order (1st-3rd) streams make up ~88% of the state's stream miles. Below its confluence with the Snake and Yakima rivers, the Columbia River is a 10th order river.

Structure: See *Ecological structure*.

Thermal loading potential
The potential amount of solar radiation (sunlight) available at a given location. Primary factors include shading (topographic and vegetative), latitude, elevation, and date.

Thermal regime (stream)
The distribution of stream temperatures through space and time. Thermal regimes can be described by their magnitude (e.g., monthly mean, hourly maximum), timing, frequency, duration, spatial distribution, and rate of change.

Thermal sensitivity (stream reach)
The susceptibility of a stream reach to changes in temperature. Thermal sensitivity typically increases with less stream flow, less groundwater input, and a wider channel to depth ratio.

Uncertainty (scientific)
The absence of information about something. Sources of uncertainty include, but are not limited to: natural variation (i.e., because ecosystems vary in unpredictable ways through time and space), model

uncertainty (e.g., we do not understand a process), systematic error (e.g., poorly designed experiments), or measurement error.

Vegetative filter strips

A riparian buffer designed to capture nutrients, contaminant compounds, and sediment transported by run-off. Filter strips are sometimes synonymous with riparian buffers.

Water quality

Physical, chemical, and biological characteristics of water that describe its suitability to meet human needs or habitat requirements for fish and wildlife.

Watershed processes

The fluxes of energy (e.g., chemical, sunlight, wildfire) and materials (particularly water and sediment) that interact with biota (e.g., vegetation, salmon, Beavers, soil microbes) to form a watershed's physical features and characteristics, which give rise to its instream physical and ecological conditions. These processes occur within a context that reflects the watershed's climate, geology, topography, and existing human land use. Also see *Ecosystem process*.

Watershed

An area of land that drains to a common waterbody.

Wood recruitment

The process of wood moving from a riparian area to the stream channel. Sources of recruitment include bank erosion, windthrow, landslides, debris flows, snow avalanches, ice storms, Beaver, and tree mortality due to fire, insects, or disease.



Northwestern salamander/WDFW

Appendix 2: Categorization of Information Sources

Legal Requirement: RCW 34.05.271

The Revised Code of Washington (RCW) 34.05.271 requires the Washington Department of Fish and Wildlife (WDFW) to categorize sources of information used to inform technical documents that directly support implementation of a state rule or statute. Because WDFW Priority Habitat and Species documents—such as this one—are referenced in regulations for the Growth Management Act [e.g., WAC 365-190-130(4)] and Shoreline Management Act [e.g., WAC 173-26-221(5)(b)], we classify all references in the literature cited sections of Volume 1 into the following RCW 34.05.271 categories:

(i) Independent peer review: Review is overseen by an independent third party;
(ii) Internal peer review: Review by staff internal to the department of fish and wildlife;
(iii) External peer review: Review by persons that are external to and selected by the department of fish and wildlife;
(iv) Open review: Documented open public review process that is not limited to invited organizations or individuals;
(v) Legal and policy document: Documents related to the legal framework for the significant agency action including but not limited to:
(A) Federal and state statutes;
(B) Court and hearings board decisions;
(C) Federal and state administrative rules and regulations; and
(D) Policy and regulatory documents adopted by local governments;
(vi) Data from primary research, monitoring activities, or other sources, but that has not been incorporated as part of documents reviewed under the processes described in (i), (ii), (iii), and (iv) of this subsection;
(vii) Records of the best professional judgment of department of fish and wildlife employees or other individuals; or
(viii) Other: Sources of information that do not fit into categories i - vii.

Meeting the Intent of RCW 34.05.271

Assigning references to categories requires judgement where methods of peer-review are not clearly defined. We assigned all scientific journal articles, science related books by independent science book publishers, universities, the National Research Council (NRC), and the National Academy of Engineering; symposia volumes sponsored by professional organizations (e.g., American Fisheries Society); and graduate theses and dissertations to category i –*independent peer review.* Government agency documents including those published by the Fish and Wildlife Service (USFWS), Environmental Protection Agency (EPA), Geologic Survey (USGS), Forest Service (USFS), and the Canadian Wildlife Service were assigned to category *viii*. Others references were assigned as described above.



Headwater wetland that flows north to Stavis Creek and south to Tahuya River/Keith Folkerts, WDFW













Washington Department of FISH and WILDLIFE

Riparian Ecosystems, Volume 2: Management Recommendations



A Priority Habitats and Species Document of the Washington Department of Fish and Wildlife

Washington Department of FISH and WILDLIFE

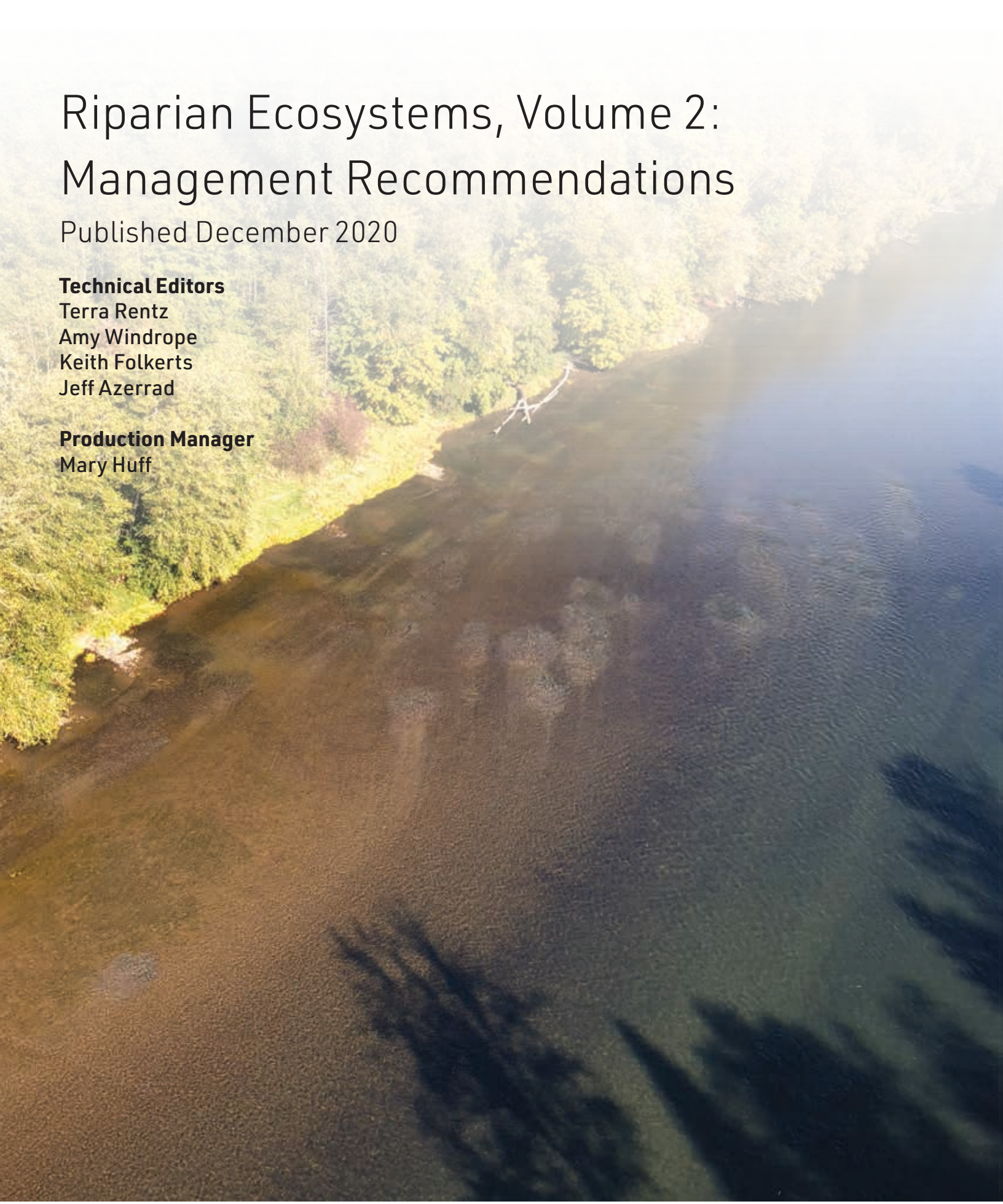
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Salmon redds along the Cowlitz River, Lewis County/George Fornes, WDFW

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The Washington State Academy of Sciences, with coordination by Dr. Robert Bates, provided an independent peer review that improved the scientific rigor of Volume 1.

Federal (EPA and NOAA Fisheries) and tribal entities (individual tribes, the Northwest Indian Fisheries Commission, Columbia River Inter-Tribal Fish Commission, and Upper Columbia United Tribes) as well as numerous state agencies (Washington State departments of Ecology, Natural Resources, and Commerce; Recreation and Conservation Office; Washington State Conservation Commission; and Puget Sound Partnership) reviewed draft versions of this document. During the summer 2018 public comment period, local governments and members of the public provided valuable feedback that led to a more concise and user-friendly final version of Volume 2.

Within WDFW, Keith Folkerts led coordination, contract planning and budgeting for this work. Tim Quinn and George Wilhere were integral in ensuring a strong relationship with information in Volume 1 and provided additional valuable feedback on multiple drafts. Terry Johnson developed the Site-Potential Tree Height mapping tool and wrote the associated user guide information in the Appendix to this Volume 2. Alison Hart produced final graphics and ensured consistent formatting and stylistic usage throughout. Mary Huff provided editorial support, improved the document's organization, and (in late 2020) took it across the finish line.

WDFW recognizes and appreciates the significant role that tribes, local governments, conservation organizations, and others play in accomplishing our agency's mission. Indeed, we are certain that without these concerted efforts to designate and protect the riparian ecosystems that are essential for most of the state's fish and wildlife species, WDFW would be unable to fulfill its mandate on behalf of all of Washington's residents.

While we acknowledge and have deep appreciation for all the review and comments provided, WDFW bears sole responsibility for this document and any errors contained herein.

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This document is available in alternative formats upon request. Please contact WDFW's ADA Program Manager at 360-902-2349, TTY (711), or ADAProgram@dfw.wa.gov.

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Acronyms for Volume 2

CAO	Critical Areas Ordinance
CMZ	Channel Migration Zone
CREP	Conservation Reserve Enhancement Program
DFC	Desired Future Condition
DNR	Department of Natural Resources (Washington State)
EBM	Ecosystem Based Management
EPA	Environmental Protection Agency (U.S.)
ESA	Endangered Species Act
FEMA	Federal Emergency Management Agency
FEMAT	Forest Ecosystem Management Assessment Team
FPA	Forest Practices Act
FWHCA	Fish and Wildlife Habitat Conservation Area
GIS	Geographic Information System
GMA	Growth Management Act
HMP	Habitat Management Plan
HRCD	High Resolution Change Detection
LID	Low Impact Development
NHD	National Hydrography Dataset
NOAA	National Oceanographic and Atmospheric Administration
NRCS	Natural Resources Conservation Service
OHWM	Ordinary High-Water Mark
OSS	On-site Sewage Systems
PHS	Priority Habitats and Species
RCO	Recreation and Conservation Office (Washington State)
RCW	Revised Code of Washington
RMZ	Riparian Management Zone
RZ	Riparian Zone
SMA	Shoreline Management Act
SMP	Shoreline Master Program
SPTH	Site-Potential Tree Height
$SPTH_{200}$	Site-Potential Tree Height (at age 200 years)
USFS	United States Forest Service
USFWS	United States Fish and Wildlife Service



Watershed lesson/Brittany Gordon, WDFW

UWCIG	University of Washington Climate Impacts Group
VSP	Voluntary Stewardship Program
WAC	Washington Administrative Code
WDFW	Washington Department of Fish and Wildlife
WFPB	Washington Forest Practices Board
WRIA	Water Resource Inventory Area
WSCC	Washington State Conservation Commission
WWRP	Washington Wildlife and Recreation Program

Chapter 1. Overview

1.1. Our Role as Washington's Conservation Agency

The mission of the Washington Department of Fish and Wildlife (WDFW) is to preserve, protect, and perpetuate the state's fish, wildlife, and ecosystems while providing sustainable fish and wildlife recreational and commercial opportunities. We offer the following science-based guidance to further that mission through the preservation, protection, and–where possible–restoration of healthy, intact, and fully functioning riparian ecosystems statewide. As described throughout this volume, we believe that protection *and* restoration[1] of Washington's riparian ecosystems is a foundational conservation action; considering a growing population and changing climate, it is also an urgent one.

Within the State of Washington's land use decision-making framework, WDFW's role is that of advisor. We provide information relative to our mission about the habitat needs of fish and wildlife, and the likely implications of various land use decisions on those resources over time. Through the Priority Habitats and Species (PHS) Program, we work cooperatively with land use decision makers and landowners to facilitate solutions that accommodate their needs and the needs of fish and wildlife. We provide this PHS document, *Riparian Ecosystems Volume 2: Management Recommendations* in support of that effort.

Priority Habitats are places that warrant special consideration for protection when land use decisions are made and should also be prioritized for restoration or enhancement wherever possible. To qualify as a "Priority Habitat" in WDFW's PHS program, an ecosystem or habitat component must provide unique or significant value to many species. Specifically, it must have one or more of the following attributes (WDFW 2008):

- Comparatively high fish and wildlife density
- Comparatively high fish and wildlife species diversity
- Important fish or wildlife breeding habitat
- Important fish or wildlife seasonal ranges
- Important fish or wildlife movement corridors
- Limited availability
- High vulnerability to habitat alteration
- Unique or dependent species

Riparian areas (comprised of riparian ecosystems, active floodplains, and riverine wetlands) meet all these criteria, and were among the first Priority Habitats described by WDFW. Riparian areas provide important ecological functions that help create and maintain aquatic habitats in addition to supporting terrestrial wildlife. Riparian areas alongside

[1] Restoration of riparian ecosystems is critically important because legacy of environmental impacts resulting from the ways land use has affected riparian areas over the past 200 years. In other words, what remains available for protection is not enough to provide the full functions and values Washington's fish and wildlife need.



Hundreds of fish and widlife species, like this female Wood Duck, depend on or use the state's riparian areas. This includes over 150 species of birds, mammals, amphibians, reptiles, and invertebrates designated as Species of Greatest Conservation Need in the 2015 State Wildlife Action Plan./Jeanne Hannah

rivers and streams are the focus of this document, however much of the science reviewed in Volume 1 and the recommendations in this Volume 2 are relevant for lakes, ponds, and marine shorelines as well.

As previously mentioned, one role of WDFW in land use decision making is that of advisor. In that role, recommendations like those contained in this document and in complementary PHS documents (available at https://wdfw.wa.gov/species-habitats/at-risk/phs/recommendations) provide critical information for the protection (and where necessary, recovery) of Washington's fish and wildlife. We recognize landowners and land managers most often face situations where various human needs must also be met; and thus, considerations other than fish and wildlife will be incorporated into land use decision making.

The information presented in this management recommendation document is not, in and of itself, science. Rather, it consists of policy recommendations which are informed by the best available science

WDFW's Mission

To preserve, protect, and perpetuate Washington's fish, wildlife, and ecosystems while providing sustainable fish and wildlife recreational and commercial opportunities.

WDFW'S Riparian Values

We value the protection and restoration of healthy, intact, and fully functioning riparian ecosystems statewide.

WDFW'S Recommendation

Within the context of wise watershed management, preserve, protect, and–where possible–restore the full extent of riparian ecosystems.

Ecosystem Based Management & WDFW's Conservation Principles

In 2013, WDFW adopted ecosystem-based management principles into policy (WDFW Policy 5004). Ecosystem-based management is an integrated, science-based approach to natural resource management that aims to sustain the ability of ecosystems to provide goods and services upon which humans and other species depend. Importantly, ecosystem-based management recognizes the magnitude of humans as change agents in the ecosystem, and the role of social, economic, and ecological factors in managing complex and dynamic systems.

We believe that conservation is best achieved through employing the following ecosystem-based management principles:

1. **We practice conservation by managing, protecting, and restoring ecosystems for the long-term benefit of people, and for fish wildlife and their habitats.**

2. **We work across disciplines to solve problems because of their connections among organisms, species and habitats.**

3. **We integrate ecological, social, economic, and institutional perspectives into our decision-making.**

4. **We embrace new knowledge and apply best science to address changing conditions through adaptive management.**

5. **We collaborate with our co-managers and conservation and community partners to help us achieve our shared goals.**

summarized in Volume 1[2] and which reflect WDFW's mission and legislative mandate. To that end, these recommendations represent WDFW's guidance for the protection and restoration of healthy, intact, and fully functioning riparian ecosystems and for how land managers and land use regulators can utilize best available science to protect these ecosystems within the scope of their authority and/or ability.

For example, local governments are encouraged to use information provided through PHS to guide critical area ordinance (CAO) updates and other land use policies, plans, or regulations. More specifically, WDFW advises using the information in this PHS Riparian Volume 2 for designating riparian areas as Fish and Wildlife Habitat Conservation Areas (FWHCAs) and protecting them for their inherent value, rather than just as buffers for rivers and streams. This is because riparian areas are so important for helping sustain endangered, threatened, and sensitive species; providing habitat connectivity for both aquatic and terrestrial wildlife; and for their critical role in protecting salmonid habitat (WAC 365-190-130).

In short, Volumes 1 and 2 focus on the science and management, respectively, of riparian ecosystems to support fish and aquatic wildlife species. Volume 1 characterizes riparian ecosystem functions and essential processes, while Volume 2 provides management guidance for riparian ecosystems in the context of watershed processes. To be clear, these two volumes do not provide a summary of science or recommendations regarding the contribution of riparian ecosystems for the protection of terrestrial wildlife species. However, our first generation PHS Riparian-specific document, *Management Recommendations for Washington's Priority Habitats: Riparian* (Knutson and Naef 1997) does provide terrestrial species information related to riparian areas. Further, PHS has separate, species-specific management recommendations that address the needs of many terrestrial Priority Species.

This document provides recommendations applicable across the State of Washington but does not address unusual, site-scale environmental conditions or issues specific to particular ecological communities. We strongly encourage addressing such matters at a local level with the assistance of WDFW regional habitat biologists, and other technical experts and stakeholders such as tribal biologists and conservation organizations.

2 The original manuscript of *Riparian Ecosystems, Volume 1: Science Synthesis and Management Implications* was publicly released in May 2018. In 2020, the format of the document was professionally designed, which included making limited updates to content focused on copyediting and improving usability. In accordance with standard citation practice, Volume 1 is now cited as having a 2020 publication date, but substantively, the current document is equivalent to the original 2018 version.

1.2. Purpose and Applicability of Volume 2

The purpose of this document is to provide guidance to protect and–where possible–restore healthy, intact, and fully functioning riparian ecosystems, which are fundamental for clean water, healthy salmon populations, and climate resilient watersheds.

Volume 2 provides information to:

- Protect existing and restore degraded riparian ecosystem functions in support of aquatic and terrestrial species recovery;
- Assist local governments with their responsibilities to protect priority fish and wildlife and their habitats;
- Assist landowners and local groups in implementing voluntary restoration actions on and off working lands; and
- Incorporate monitoring and adaptive management to understand how well regulatory and non-regulatory efforts are protecting riparian functions and values.

This guidance is applicable to riparian ecosystems statewide. We offer a specific focus on lands within the purview of the Growth Management Act (GMA) and Shoreline Management Act (SMA), although a broader application by local governments and other users is also appropriate.

While many other federal, state, and tribal government programs and policies pertain to riparian ecosystems, they are not specifically addressed in this document. For instance, we do not discuss holistic protection of floodplains, nor do we discuss specific Endangered Species Act (ESA) requirements relative to listed salmonids and other species. Also, we do not address commercial forestlands that fall under the jurisdiction of the Forest Practices Act (FPA), or the Department of Ecology's clean water regulations. These other programs and policies were developed with specific goals and objectives that may be different from the goals of this document, and as such may differ with guidance provided herein.

1.3. Science Synthesis and Management Implications (Volume 1) Summary

As stated above, Volume 1 (Quinn et al. 2020; see footnote 2) provides important information integral to the development of these management recommendations. It includes both overarching as well as specific considerations important to all efforts, large and small, to protect rivers and streams for the benefit of the aquatic species associated with them. Volume 1 focuses on the science of riparian ecosystems–specifically, how riparian areas interact with large-scale drivers (e.g., topography, geology, climate, and land use) and watershed processes to create and maintain riparian and aquatic habitat in support of fish and wildlife. Thus, we provide here an explicit definition of riparian ecosystems from Volume 1 that combines a variety of conceptual riparian descriptions from the scientific literature:

> Riparian ecosystems are transitional between terrestrial and aquatic ecosystems, distinguished by gradients in biophysical conditions, ecological processes, and biota. They are areas through which surface and subsurface




Many adult flying insects, such as the blue damselfly (above, left) spend their larval stage as freshwater macroinvertebrates. During this early period, some of those species, like the stonefly nymph (above, right) help fallen leaf litter to decompose by shredding it while feeding. At both life stages, these animals provide important food for fish and other aquatic and terrestrial widlife./Jim Cummins and Taylor Cotten, WDFW

hydrology connect waterbodies with adjacent uplands. They include those portions of terrestrial ecosystems (i.e., *a zone of influence*) that significantly influence exchanges of energy and matter with aquatic ecosystems and the portion of the ecosystem characterized by moist soils and plants adapted to periodically saturated soils – the *riparian zone* (RZ). The width of the riparian ecosystem is typically defined by the outer edge of the zone of influence, which, in forested regions, is based on site-potential tree height (SPTH) measured from the edge of the active channel. While our definition of riparian ecosystem does not include the water in river or streams, it does include riverine wetlands and recognizes the riparian zone as a distinctive area within riparian ecosystems.

To assist managers in understanding important implications of the science synthesized in Volume 1, we reiterate the ten overarching findings of that document below. These findings are also discussed in more detail in later chapters.

1. Protection and restoration of riparian ecosystems continues to be critically important because: (a) they are disproportionately important, relative to area, for aquatic species (e.g., salmon) and terrestrial wildlife; (b) they provide ecosystem services such as water purification and fisheries (Naiman and Bilby 2001, NRC 2002, Richardson et al. 2005); and (c) by interacting with watershed-scale processes, they contribute to the creation and maintenance of aquatic habitats.

2. Stream riparian ecosystems encompass the riparian zone; the active floodplain, including riverine wetlands and the terraces; and adjacent uplands that contribute matter and energy to the active channel or active floodplain (Gregory et al. 1991, Naiman and Bilby 1998). Such terraces and adjacent uplands are called the zone of influence.

3. The width of the riparian ecosystem is estimated by one 200-year SPTH measured from the edge of the active channel or active floodplain. Protecting functions within at least one 200-year SPTH is a scientifically supported approach if the goal is to protect and maintain full function of the riparian ecosystem.

4. Where the riparian zone is narrow (<100 ft [30 m]) and the zone of influence lacks tall trees (<100 ft), (e.g., in parts of the Columbia Plateau Ecoregion), the pollution removal function may determine the width of the zone of influence.

5. The riparian ecosystem begins at the edge of the active channel or active floodplain, whichever is wider. As the active channel moves back and forth across the channel migration zone (CMZ), the riparian ecosystem moves with it. Consequently, there are times when the riparian ecosystem lies adjacent to or overlaps the CMZ (see Figure 2.3). Hence, to maintain riparian ecosystem functions, management must anticipate and protect future locations of the riparian ecosystem.

6. A near consensus of scientific opinion holds that the most effective and reliable means of maintaining viable self-sustaining fish, especially salmon, and wildlife populations is to maintain/restore ecosystems to conditions that resemble or emulate their historical range of natural variability (Swanson et al. 1994, Reeves et al. 1995, Bisson et al. 2009). This opinion is based in part on the complexity of processes that affect the expression of habitats over time and space.

7. The protection and restoration of watershed-scale processes, especially related to hydrology, water quality, connectivity, and inputs of wood, shade, and sediment are important for aquatic system function, and help maximize the ecological benefits of riparian ecosystem protections.

8. Riparian areas and surrounding watersheds are complex and dynamic systems comprised of many interacting components. Natural disturbances (flood, fire, and landslides) across the watershed and through time create the mosaic of conditions necessary for self-sustaining populations of fish, especially salmon, and other aquatic organisms.

9. Impending changes to aquatic systems as a result of climate change increase risk to species already threatened by human activities. The effects of climate change on rivers and streams threaten to reduce fish distribution and viability throughout the Pacific Northwest (Beechie et al. 2013).

10. The use of the precautionary principle and adaptive management are particularly appropriate when dealing with complex and dynamic systems, and when we have uncertainty related to exactly how management activities affect functioning of watersheds and riparian ecosystems.

1.4. Key Findings and Recommendations

WDFW recognizes that there is a significant amount of work currently being done throughout the state to protect and restore riparian areas. This focus is longstanding and has ranged from regulatory protections that guide Washington's growing population to voluntary conservation on our working lands. Below, we highlight what we believe—based on best available science and our agency's mission—are the most important recommendations to ensure healthy, intact, and fully functioning riparian ecosystems that provide for the preservation, protection and perpetuation of Washington's fish and wildlife:



A tributary stream (lower left of photo) contributes sediment to a side channel of the Stillaguamish River as precipitation levels rise in autumn. Snohomish County/Mary Huff, WDFW

1. **Designate riparian ecosystems as critical areas:** WDFW recognizes riparian ecosystems as a Priority Habitat for fish and wildlife and recommends that local jurisdictions designate those ecosystems as Fish and Wildlife Habitat Conservation Areas (FWHCAs), a type of critical area. We define the bounds of the riparian ecosystem as the riparian management zone (RMZ), and this RMZ should be designated as the location where protection and restoration of riparian ecosystem functions and values are addressed. RMZs provide a framework for delineating, evaluating, planning, and managing functions and values. In this volume, we provide a process for RMZ delineation (Chapter 2).

2. **Include watershed–scale management considerations:** Watershed-scale management is critical to realizing the full benefits of riparian ecosystem protection and restoration. Certain types of anthropogenic changes at the watershed scale can dramatically reduce the effectiveness of riparian ecosystems to protect aquatic habitat. For example, unmitigated delivery of stormwater from impervious surfaces like roads, parking lots, and rooftops to streams, for example, dramatically increases peak stream flows, alters channel form, and short-circuits the capacity of riparian areas to remove pollutants from runoff. Similarly, road-crossing culverts that are impassible to fish can reduce stream-network connectivity and dramatically reduce amounts of otherwise suitable habitat.

3. **Use reference points to locate the inner edge of the RMZ:**

    - For streams without Channel Migration Zones (CMZs), the inner edge of the RMZ should be delineated starting at theouter edge of active floodplain, if this has or can be determined; otherwise, from the active channel, as delineated by the Ordinary High-Water Mark (OHWM)[3].

    - For streams with CMZs, the unpredictable nature of channel migration should be accommodated through delineation of an RMZ that encompasses both the entire CMZ and future locations of the riparian ecosystem. In these instances, the inner edge of the RMZ should be located at the outer edge of the CMZ.

Whether or not a stream has a CMZ, the distance from the inner edge of the RMZ to the outer edge of the RMZ should be one $SPTH_{200}$.

4. **Include CMZs in delineation of the RMZ:** CMZs are important to protect for maintaining riparian functions and values, and so are included in the delineation of RMZs. Over time, a riparian ecosystem will occupy different parts of the CMZ and uplands outside the CMZ. Lateral channel migration and related streambank erosion processes can pose risks to homes and communities located near rivers; however, when channels are constrained from moving, aquatic and riparian ecosystems may degrade over time. To maintain riparian ecosystem functions, land managers must anticipate and protect future locations of the riparian ecosystem and thus delineate the RMZ accordingly.

5. **Establish RMZ widths based on site-specific conditions:** From the perspective of those riparian ecosystem functions affecting aquatic systems, the width of the riparian ecosystem varies with ecological conditions. The most efficient way to protect riparian functions is to adopt protections that recognize these differences, rather than uniform-width (i.e., one-size-fits-all) RMZs, as these may result in over-protection in some places and under-protection in others.

3 Active floodplain delineations are rarely available, and we currently lack a repeatable, well-vetted, and widely accepted method for the delineation of active floodplains. Therefore, until such a process is developed, we recommend delineating the RMZ's inner edge using the OHWM for streams without CMZs.



Dryland ecoregion riparian area, Whitman County/Michael Townsend



Forested ecoregion riparian area, Chelan County/George Wilhere, WDFW

a. **In forested ecoregions, start with SPTH$_{200}$**: At most riparian areas in forested ecoregions, SPTH$_{200}$ is 100 feet or greater, and so the RMZ is delineated using one SPTH$_{200}$. If SPTH$_{200}$ is less than 100 feet, the RMZ is delineated by the pollution removal function (see below).In highly altered areas where soil data are not available, it may be necessary to estimate SPTH$_{200}$ values based on nearby soils.

b. **In dryland ecoregions, start with SPTH$_{200}$** (if available), or the width of the riparian vegetation community: If site conditions do not support tree species or SPTH$_{200}$ is less than 100 feet, then RMZ width is determined by the full extent of all riparian vegetation (the riparian zone) or by the pollution removal function–see below.

c. **For both forested and dryland ecoregions, use the pollution removal function when appropriate:** Where the SPTH$_{200}$ and/or the width of the riparian vegetative community is less than 100 feet, we recommend that RMZ width be delineated at a minimum of 100 feet, as this provides the width necessary for 95% pollution removal target for most pollutants (approximately 85% for surface nitrogen.)[4]

To aid with site-specific RMZ delineation, WDFW created an internet-based mapping tool that reports recommended widths for RMZs (Appendix 1) statewide based on SPTH$_{200}$. The tool also notes instances where a 100-foot RMZ should be applied to support the pollution removal function.

6. **Apply the recommended RMZ delineation steps to all streams, whether or not they are fish-bearing:** In 1997, WDFW recommended a lower level of protection for non-fish bearing streams than fish-bearing streams. In reviewing the current science literature for Volume 1, we found no evidence that full riparian ecosystem functions

[4] See Chapter 2, Section 2.3.5 for more information about surface nitrogen removal and other site-specific characteristics that may require RMZ distances greater than 100 feet in order to ensure an adequate pollution removal function.



Deer tracks and fallen leaves near Scatter Creek, Thurston County/Janet Anthony, WDFW

along non-fish-bearing streams are less important to aquatic ecosystems than full riparian ecosystem functions along fish-bearing streams. This recommendation is based on four additional considerations. Non-fish-bearing streams:

- Support a unique community of aquatic and riparian-obligate wildlife;
- Provide movement corridors for wildlife, particularly in the face of changing climate conditions;
- Provision fish-bearing streams with matter and energy; and
- Provide cool water to downstream reaches. Washington State has already experienced increased stream
- temperatures due to climate change and expect further increases, which have direct implications for the persistence of fish.

7. **Establish monitoring and adaptive management frameworks:** We believe it is critical to understand if riparian ecosystems protections are working as intended, and if not, to adjust them accordingly. We recommend the establishment of monitoring and adaptive management designed to improve (where necessary) local permit implementation and compliance, and to increase effectiveness of actions intended to protect aquatic species.

8. **Consider needs of relevant terrestrial species:** As stated earlier, a review of new literature related to the needs of terrestrial Priority Species was not a focus of Volume 1. Nonetheless, riparian areas provide important functions for threatened, endangered, and sensitive terrestrial wildlife that require consideration by landowners and land managers. WDFW regional habitat biologists, tribal biologists and/or other local habitat experts can assist in identification of site-specific terrestrial species needs. Because riparian protections benefit both aquatic and many terrestrial wildlife species, concentrating protections around riparian areas may also be an efficient use of resources.

1.5. Relationship with Washington's Development Laws and Regulations

1.5.1. Relationship with the Growth Management Act (GMA)

The GMA requires local jurisdictions to designate and protect critical areas, and in so doing, use best available science and give special consideration to anadromous species[5]. The GMA also encourages state agencies to provide technical assistance to counties and cities in the review of their critical areas ordinances (CAOs), comprehensive plans, and development regulations [RCW 36.70A.130(6)(g)]. While the Washington State Department of Commerce (Commerce) administers the GMA, WDFW is the lead state agency for advising local governments on matters related to one type of critical area: Fish and Wildlife Habitat Conservation Areas (FWHCAs), and we produce PHS Management Recommendations like this Volume 2 in support of that role.

This document provides guidance that is consistent with the GMA, under which local governments exercise their land use responsibilities: specifically, protection of the functions and values of critical areas. It also reflects the legal and policy framework within which WDFW and the PHS program operate, which includes among other things providing a source of best available science necessary to support local governments in distinguishing and delineating those critical areas (e.g., FWHCAs).

WAC 365-190-130
FISH AND WILDLIFE HABITAT CONSERVATION AREAS

(1) "Fish and wildlife habitat conservation" means land managed for maintaining populations of species in suitable habitats within their natural geographic distribution, so that the habitat is sufficient to support viable populations over the long term and isolated subpopulations are not created. This does not mean maintaining all individuals of all species at all times, but it does mean not degrading or reducing populations or habitats so that they are no longer viable over the long term. Counties and cities should engage in cooperative planning and coordination to help assure population viability.

Fish and wildlife habitat conservation areas contribute to the state's biodiversity and occur on both publicly- and privately-owned lands. Designating these areas is an important part of land use planning for appropriate development densities, urban growth area boundaries, open space corridors, and incentive-based land conservation and stewardship programs."

WDFW understands that local jurisdictions have existing critical area regulations that have been approved by elected officials and in many cases have been found to be compliant with GMA through the Growth Management Hearings Board and courts. We acknowledge that revising a critical area regulation can be a lengthy, expensive, and contentious process, and so jurisdictions frequently do not make updates to their CAOs more frequently than required by law or rule. In this volume, we aim to be more precise about where recent science has improved our certainty around the need for riparian protections, as well as for specific practices; and how to incorporate best available science and WDFW's management recommendations.

WDFW also recommends local jurisdictions continue considering PHS best available science (e.g., Volume 1; PHS maps), incorporating PHS Management Recommendations, and seeking technical assistance from WDFW's regional habitat biologists not just when updating and implementing critical area policies and regulations, but in all land use planning efforts.

5 RCW 36.70A.172(1): "In designating and protecting critical areas under this chapter, counties and cities shall include the best available science in developing policies and development regulations to protect the functions and values of critical areas. In addition, counties and cities shall give special consideration to conservation or protection measures necessary to preserve or enhance anadromous fisheries."

1.5.2. Relationship with the Shoreline Management Act (SMA)

As with GMA, WDFW plays a role of technical advisor under SMA, working directly through locally led development processes, with the goal of addressing needs for fish and wildlife. Under SMA, the Department of Ecology (Ecology) has a role approving Shoreline Master Program (SMP) updates when they are deemed consistent with all statutory and regulatory requirements. Ecology also has a direct role in implementation of SMPs, including issuing the final decision to approve, deny, or put conditions on locally issued conditional use permits and variances. [Under GMA, Commerce does not approve comprehensive plan updates or CAOs.]

The goal of SMA is "to prevent the inherent harm in an uncoordinated and piecemeal development of the state's shorelines" (RCW 90.58.020). To achieve that end, WDFW recommends local jurisdictions designate riparian areas and provide the same levels of protection for them within the SMA jurisdiction areas as they do under GMA. While the SMA does not apply to streams with 20 cubic feet per second (cfs) or less mean annual flow, we recommend the application of the guidelines in this Volume 2 to all rivers and streams, regardless of size.

WAC 173-26-186 GOVERNING PRINCIPLES OF THE [SMP] GUIDELINES

(8) "Through numerous references to and emphasis on the maintenance, protection, restoration, and preservation of "fragile" shoreline "natural resources," "public health," "the land and its vegetation and wildlife," "the waters and their aquatic life," "ecology," and "environment," the act makes protection of the shoreline environment an essential statewide policy goal consistent with other policy goals of the act. It is recognized that shoreline ecological functions may be imparted not only by shoreline development subject to the substantial development permit requirements of the act but also by past actions, unregulated activities, and development that is exempt from the act's permit requirements. The principle regarding protecting shoreline ecological systems is accomplished by these guidelines in several ways, and in the context of related principles."



The Shoreline Management Act includes a goal to balance multiple uses, including protecting natural resources and providing public access to waters of the state./ Andy Walgamott






Riparian areas provide habitat for many types of birds at one or more life stages, especially during breeding season and for food year round. Photo credits: Sandpiper chicks in nest/Laura Rogers; Northern Harrier foraging low over marshy vegetation/Brad Collins; male Belted Kingfisher watching for fish from fallen tree limb/Anna Owen; Purple Martin pair resting on piling above their nest-box/Kim Eggleston

1.6. Organization of Volume 2

Chapter 1 aims to establish Volume 2's purpose and intent; articulate WDFW's values; and provide policy context regarding protection and designation of riparian ecosystems.

In Chapter 2, we define the RMZ based on $SPTH_{200}$ with special considerations for urban and dryland landscapes; and provide a stepwise process for identifying and delineating the RMZ both for requiring riparian protections and for classifying RMZs as a FWHCA under GMA.

Chapter 3 articulates policies, plans, and practices that protect riparian ecosystems. WDFW recognizes that counties and cities have a long history of providing such protections, and the responsibility to include best available science when updating CAOs. The protection recommendations described in this chapter are intended to help counties and cities moving forward with reviewing and updating their CAOs and other relevant policies and plans.

Chapter 4 explains the importance of restoration in riparian management, which is necessary for recovery of the degraded riparian functions present in many locations and is critical to recover salmon stocks and preserve Washington's riparian-dependent Priority Species. To that end, we outline voluntary approaches to improve riparian functions. Although Volume 2 is not a restoration guide, it is applicable to restoration practitioners in that it describes management actions that enhance riparian functions and values. We do not address restoration project design or standards but provide links within this chapter to resources that do.

Chapter 5 will assist with developing monitoring programs in support of adaptive management, designed to ensure transparent programs that consistently deliver sufficient protection of riparian functions. Careful monitoring and adaptive management are particularly important when a land use may harm a critical area and scientific information about the likely severity of harm is lacking. Although specific to local governments, this chapter provides valuable resources for any land manager interested in engaging in adaptive management.

Finally, this volume includes an appendix that contains a "how-to" process for utilizing WDFW's SPTH mapping tool to help determine recommended minimum RMZ widths around the state. The tool itself is available at wdfw.maps.arcgis.com/apps/MapSeries/index.html?appid=919ea98204eb4f5fa70eca99cd5b0de1.

Chapter 2. Riparian Management Zone Delineation

2.1. Introduction

We define the extent of the riparian ecosystem as the area that provides full ecological function for bank stability, shade, pollution removal, contributions of detrital nutrients, and recruitment of large woody debris. For the purposes of management or regulatory protection, the riparian management zone (RMZ) encompasses the riparian ecosystem, and–when present–the channel migration zone (CMZ) to account for lateral movement of the riparian ecosystem over time. RMZs can also provide habitat for many terrestrial wildlife species including movement corridors. WDFW categorizes the riparian ecosystem as a Priority Habitat, and thus recommends local jurisdictions designate all riparian areas as critical areas: specifically, Fish and Wildlife Habitat Conservation Areas (FWHCAs), as mentioned in Chapter 1.

The RMZ provide an initial framework for delineating, assessing, planning, and managing riparian ecosystems. The RMZ as defined here is not necessarily the same as setbacks or buffers. Setbacks are areas meant to protect an important feature (e.g., a stream or wetland) from certain types of adjacent activities, e.g., the area separating a building from the bank of a river. Setbacks are not typically designed to provide ecological function. On the other hand, buffers, which also protect important features, are commonly undeveloped, naturally vegetated areas that can contribute habitat and in the case of a stream, to riparian functions. In this document, we reserve the use of the term RMZ to mean the area capable of providing full function and managed to that end.

2.2. Foundational Concepts in RMZ Determinations

2.2.1. Desired Future Condition

A major goal in fulfilling WDFW's mission to preserve, protect, and perpetuate Washington's fish, wildlife, and ecosystems is the protection and restoration of healthy, intact, and fully functioning riparian areas. More specifically, the goal will be achieved through management strategies that result in ecosystem composition and structure that provides the five key ecological functions associated with riparian ecosystems. A useful benchmark for this goal is desired future condition (DFC) for riparian areas. DFC describes what land managers are attempting to achieve, often in terms of composition and structure (e.g., vegetation or land-use), over a period of time in a given geographic area. The DFC we recommend results in fully functioning riparian ecosystems as measured by the five key ecological functions (bank stability, shade, pollution removal, contributions of detrital nutrients, and recruitment of large woody debris) in western

Washington. The DFC for composition and structure is old, structurally complex conifer-dominant forest. Such forests exhibit large diameter trees, contain numerous large snags and logs, and have multi-layered canopies and canopy gaps, which promote understory plant diversity.

Throughout the Columbia Plateau, differences in hydrology and geomorphology manifest substantial site-level differences in composition and structure of riparian vegetation, and hence, the DFC for composition and structure is more site-dependent in the Columbia Plateau than in western Washington. Nonetheless, the DFC in the Columbia Plateau is based on the same concepts of ecosystem composition and structure that support the same five key ecological functions in forested regions; specifically, biologically diverse vegetation communities consisting of native trees, shrubs, grasses and forbs. In addition, the DFC for the upland portion of the riparian ecosystem which serves as the zone of influence and contributes to the pollution removal function in the Columbia Plateau is often intact native shrub-steppe or prairie vegetation.

2.2.2. Site-Potential Tree Height (SPTH) Background

A fundamental component of our recommendation is the use of site-potential tree height (SPTH). In this section, we provide background information on its origin, applicability, and usefulness (see also Volume 1, Chapter 9).

In 1993, a group of experts (Forest Ecosystem Management Assessment Team [FEMAT]) was convened to develop a conceptual model to determine how to protect riparian areas in forested landscapes. This model has come to be known as the FEMAT curves (FEMAT 1993). Though this model is over 25 years old, it continues to be one of the most useful conceptual models informing riparian management.

The FEMAT curves provide a conceptual model of important riparian functions and how those functions change with increased distance from the stream channel (Figure 2.1). The model conveys two important points: (1) four of the five riparian ecosystem functions or processes occur within one 200-year SPTH; and (2) the marginal return for each function or process decreases as distance from the stream channel increases. Thus, designating a riparian area based on at least one $SPTH_{200}$ is a scientifically supported approach if the goal is to protect and maintain full function of the riparian ecosystem for aquatic habitat and species, including salmon.

The FEMAT curves and SPTH have been used to describe the lateral extent of riparian ecosystems, and accordingly, the width of the RMZ needed to provide full riparian ecosystem function.

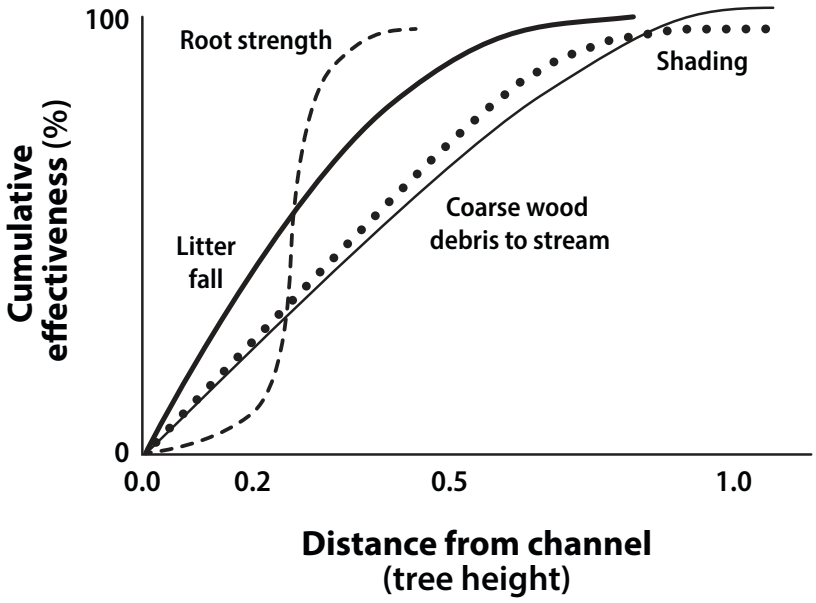


Figure 2.1. The "FEMAT Curves" (FEMAT 1993): a generalized conceptual model describing contributions of key riparian ecosystem functions to aquatic ecosystems as the distance from a stream channel increases. "Tree height" refers to average height of the tallest dominant tree (200 years old or greater); referred to as site-potential tree height (SPTH).

FEMAT (1993, p. V-34) defined SPTH as "the average maximum height of the tallest dominant trees (200 years or more) for a given site class." The key phrase in this definition is "200 years or more" which refers to the approximate minimum age of old-growth forests. This reflects FEMAT's underlying assumption that old-growth forest conditions are needed for full riparian ecosystem functions. WDFW uses SPTH at 200 years (abbreviated $SPTH_{200}$) in our recommendations in this Volume 2.

FEMAT defined Site potential tree height (SPTH) as "the average maximum height of the tallest dominant trees (200 years or more) for a given site class."

"200 years or more" is the approximate minimum age of old-growth forests which are thought to be necessary for full riparian ecosystem functions.

Given its utility, the height of site-potential trees has been described for a variety of tree species and can be readily found in silvicultural literature. Mean heights of dominant trees in riparian old-growth forest of Washington range from 100 to 240 feet (Fox 2003). The wide range of heights reflects differences in site productivity, i.e., local differences in soil nutrients and moisture, light and temperature regimes, and topography. Site productivity is described quantitatively through a site index, which is the average height that dominant trees of a species are expected to obtain at a specified tree age at a given location.

2.2.3. The Importance of Channel Migration Zones (CMZs)

Not all streams have CMZs, but where CMZs are present, it is necessary to map the CMZ in order to establish an RMZ. The Washington Forest Practices Board Manual (DNR 2004) provides a useful definition of the CMZ as "the area where the active channel of a stream is prone to move and this results in a potential near-term loss of riparian function and associated habitat adjacent to the stream, except as modified by a permanent levee or dike" (DNR 2004, Section M2).

Protecting the CMZ from incompatible land uses (e.g., development) is important for providing riparian ecosystem functions. Human alterations to river channels that limit channel migration and bank erosion can degrade aquatic and riparian habitats. For these reasons, geomorphologists have developed protocols for delineating CMZs. Further, RMZ delineation along streams with CMZs ensures that riparian functions do not degrade as a channel moves. Proper delineation also helps landowners avoid siting homes and infrastructure in CMZs that coincide with geologically hazardous critical areas and floodplains (**WAC 365-190-120[6f]**).

2.2.4. Relationship of CMZs and Floodplains

This document does not include guidance on the integration of floodplains into RMZ delineation (see footnote 4 for a brief explanation about the active floodplain). However, a general understanding of floodplains and their relationship to CMZs is valuable, as the two often overlap.



Beavers are considered to be ecosystem engineers. The dams they build, the resulting ponds created, and the surrounding areas from which they fell trees all provide habitat for many other animals./Liz Bocksteigel, WDFW

Both federal and state regulations establish floodplain protections. Floodplain data and **maps** (typically 100-year floodplains) are readily available through the Federal Emergency Management Agency's National Flood Insurance Management Program. Ecology is the state's authority as lead on floodplain management and we support their recommendations for management of **Frequently Flooded Areas** (another type of critical area specified in GMA) and the use of the **Floodplains by Design** grant program to reduce hazards and restore natural functions. Proper floodplain delineation and protection helps landowners and land managers avoid placing homes and infrastructure in areas at high-risk of flooding.

The Bureau of Land Management provides common clues to help determine the presence of an active floodplain (BLM 2015) such as visual evidence of frequent inundation, which may include but is not limited to:

- Fresh deposits of fine sediment;
- Floodplain vegetation matted down or lying flat on floodplain from overbank flow or by deposition or overbank sediment;
- Debris piled on the upstream side of tree trunks; or
- High water marks seen on rocks, trees, or other stationary objects; and ice-rafted deposits on the floodplain.

However, BLM advises caution when relying on these visual clues. Furthermore, looking for signs that an active floodplain is present is only the first step toward delineating the outer edge of an active floodplain. We recommend reviewing BLM's technical reference titled *Proper Functioning Condition Assessment for Lotic Areas* (BLM 2015) and to consult Ecology for assistance regarding floodplain delineation and protections.

Good floodplain management is not only beneficial for human communities, it is also good for fish and wildlife. Although we do not describe use of the 100-year floodplain to measure the RMZ in Volume 2, we recommend that landowners and land use decision makers treat floodplains similarly to RMZs due to their importance to instream health, as habitat, and for their ecological services.

2.3. Procedures for RMZ Delineation

To conserve riparian habitat, one must first establish the lateral extent (i.e., width) of the RMZ. In Chapter 1, we noted that an RMZ encompasses the riparian zone and zone of influence (Figure 2.2), and, where present, considers the CMZ (Figure 2.3). In this section, we outline general steps for collecting site-specific information essential to map an RMZ. These steps will help you identify a site's proximity to streams as well as essential site characteristics. With this information, we then explain how to delineate an RMZ.

In the rest of this section, we explain how to:

- Identify the ecoregion in which the riparian ecosystem is located (e.g., forested or dryland);
- Verify the presence of a stream;
- Identify the inner edge of the RMZ; and finally
- Determine the RMZ width.

2.3.1. Determining Ecosystem Location

We have identified two distinct types of ecoregions statewide, each with a slightly different RMZ delineation procedure: (1) Forested, and (2) Dryland. In general, forested ecoregions dominate western Washington, northeastern Washington, and portions of southeast, north central, and eastern Cascades. Dryland ecosystems are more readily contained in the Columbia Plateau Ecoregion east of the Cascade Range.

Landowners and land use planners should utilize the SPTH mapping tool, described in Appendix 1, to determine the ecoregion where the river or stream lies. Appendix 1 also provides instructions for using this tool to determine the 200-year site-potential tree height ($SPTH_{200}$) at a given location.



Site visits are important because small streams are often unmapped, including in GIS tools commonly used for planning and permitting. Shaner Creek, Thurston County/Janet Anthony, WDFW

2.3.2. Verifying the Presence of a Stream

Once you have identified which ecoregion you are in (e.g., Columbia Plateau), a qualified professional[6] should visit the site to verify the stream's location on or near the project area. It is very important not to rely solely on "stream maps" (e.g., DNR stream layer, National Hydrography Dataset) in place of a site visit (which is also important for mapping RMZs) because existing mapped stream layers often have errors, including streams whose locations are mapped inaccurately on the landscape, and streams actually present on the landscape that are missing from maps. Instead, use the site visit to validate existing stream maps.

[6] Qualified professionals can be entities and individuals identified by the jurisdiction, WDFW regional habitat biologists, tribal biologists, Ecology staff, and/or other individuals familiar with stream verification and who have local expertise (e.g., Conservation District staff, Stream Teams, etc.).

2.3.3. Identifying the Inner Edge of the RMZ

Once you have verified a stream's location, proceed to locate the inner edge of the RMZ. Accurate RMZ delineation is dependent on using the correct starting point. In this section, we describe how to determine the location of the RMZ's inner edge using either the Channel Migration Zone (CMZ), if one is present; or the Ordinary High-Water Mark (OHWM). Ecology, as the state's water quality lead, provides extensive guidance and resources associated with OHWM or CMZ, and those resources are referenced here forward.

2.3.3 (A). Identifying Ordinary High-Water Mark (OHWM)

Delineate the RMZ's inner edge by identifying the OHWM along both sides of the stream following the procedure in Chapter 3 of Ecology's **OHWM delineation manual** (Anderson et al. 2016).

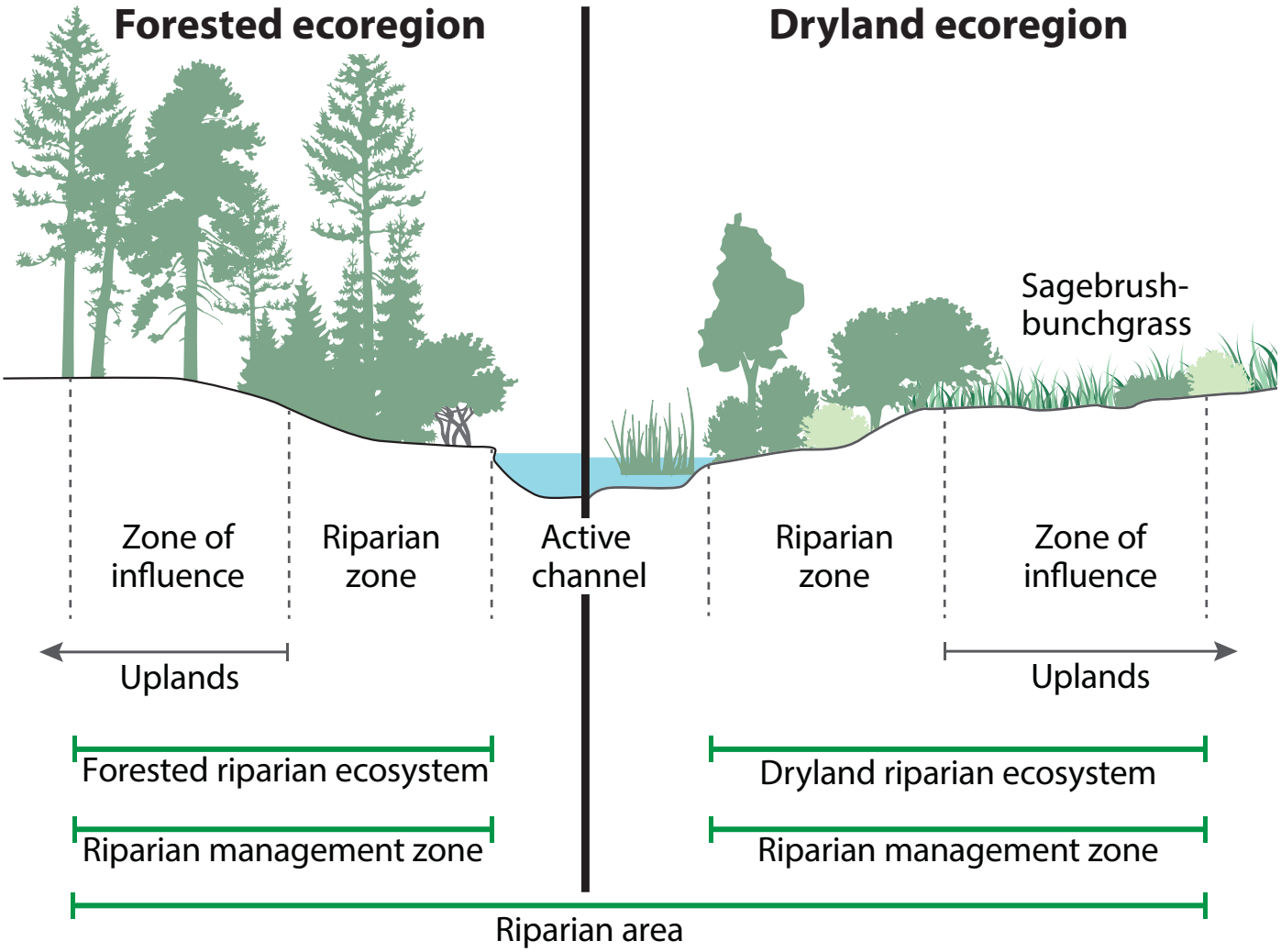


Figure 2.2. The diagram depicts the riparian management zone (RMZ) for both forested (left) and dryland (right) ecoregions. The RMZ is coincident with the riparian ecosystem, *which consists of the* riparian zone *(riparian vegetative community) and the* zone of influence. *The* riparian zone *extends from the edge of the active channel towards the uplands and it includes areas where vegetation is influenced at least periodically by flowing waters. The* zone of influence *includes areas where ecological processes significantly influence the stream, at least periodically.*



A drone photo showing an area of the Nooksack River in Whatcom County. Taken during summertime low flows, the existence of multiple braided channels is evident./Ross Zimmerman, Department of Natural Resources

2.3.3 (B). Identifying the Channel Migration Zone

Delineate the RMZ's inner edge by identifying the edge of the CMZ. Information about CMZs is available for certain streams in the state. For example:

- **SMA-Covered Shorelines** – During Shoreline Master Program comprehensive updates, many jurisdictions map the general location of CMZs associated with shorelines that fall under the jurisdiction of SMA (RCW 36.70A.480). Note that even smaller streams not subject to SMA jurisdiction can have CMZs. In these cases, we recommend jurisdictions still identify and analyze CMZs to protect riparian ecosystems and public health and safety.
- **Puget Sound Streams** – The federal Endangered Species Act may require CMZ delineation in Puget Sound basin streams under the FEMA National Flood Insurance Program Biological Opinion for Puget Sound.
- **Other Local Examples** – Check with your jurisdiction to see if they have more detailed CMZ maps.

Ecology provides the following resources which can help landowners and land managers assess the presence and extent of CMZs where maps and data on CMZs do not currently exist:

- CMZ Home Page provides a high-level look at CMZ identification, and references useful documents;
- Channel Migration Processes and Patterns in Western Washington (Legg and Olson 2014) describes the general channel migration processes that occur in western Washington;
- A Methodology for Delineating Planning-Level Channel Migration Zones (Olson et al. 2014) provides a process for delineating "planning-level" CMZs and gives a few good examples in the appendices;
- A Framework for Delineating Channel Migration Zones (Rapp and Abbe 2003) is a more in-depth guide on how to develop "detailed" CMZs; and
- Screening Tools for Identifying Migrating Stream Channels in Western Washington (Legg and Olson 2015) outlines the "CHAMP" (channel migration potential) GIS layer with guidance on using it to identify high-risk CMZs.

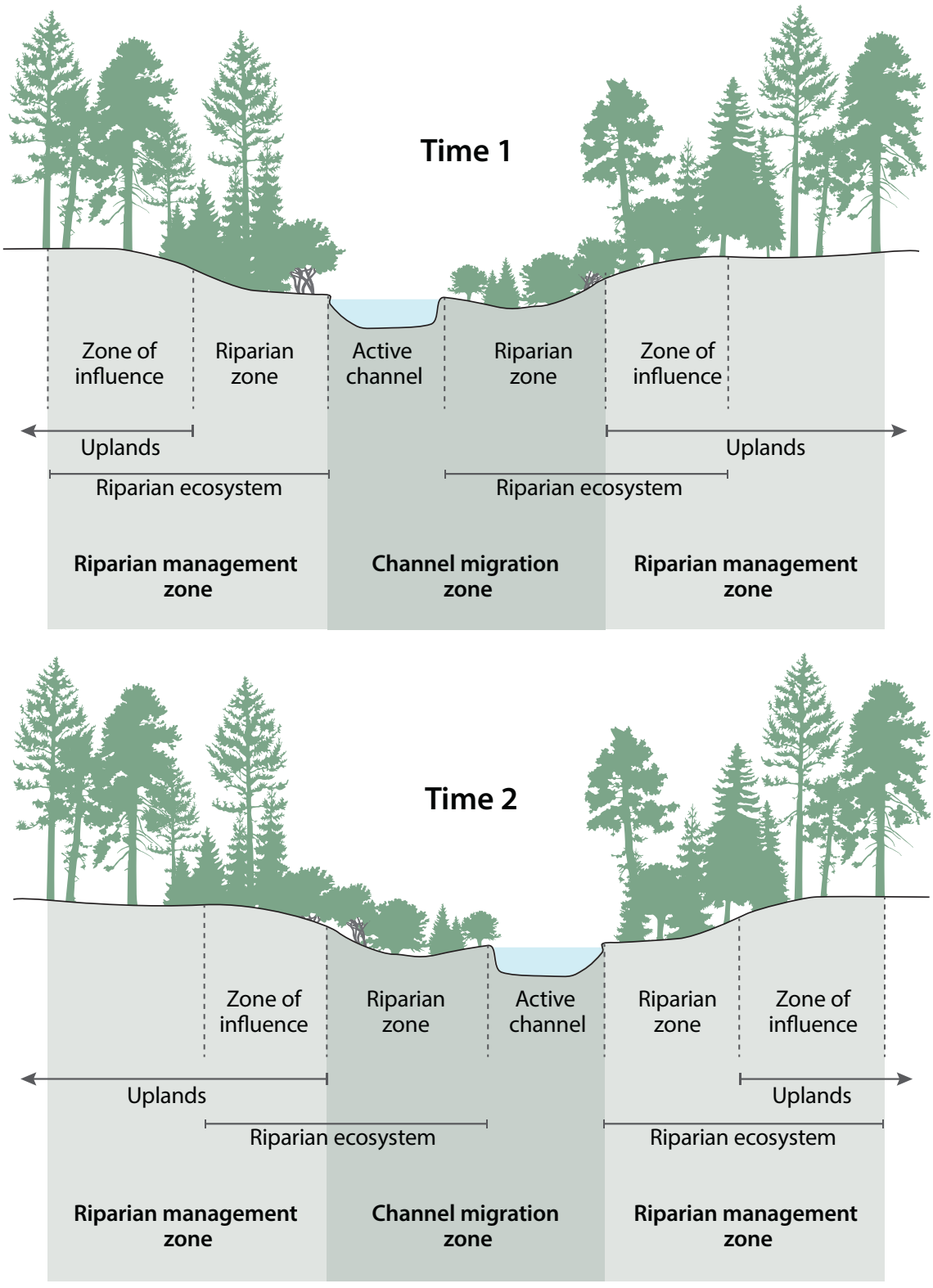


Figure 2.3. This diagram depicts the spatial relationship between the riparian management zone (RMZ) and channel migration zone (CMZ) over time. As the active channel moves laterally within the CMZ, the riparian ecosystem moves with it. As a result, when considering the establishment of an RMZ, delineation should occur at the edge of the CMZ to account for the full extent of both the present day and future riparian ecosystems. Time 1 and Time 2 could be separated by days or centuries. This depiction of a forested system is one representation of a CMZ, which are also present in dryland systems: both should be managed for accordingly.

2.3.4. Determining RMZ Width

Once you have determined the location of the RMZ's inner edge, you then establish the width of the RMZ. The following stepwise process aims to establish recommended minimum delineation distances based on $SPTH_{200}$, vegetation composition, and pollution removal function (Figure 2.4). We say "recommended minimum" because upland adjacent land uses may require further adjustment of the RMZ to provide adequate pollution removal functions. Landowners and land use regulators should also consider additional actions to support wildlife connectivity and/or to protect riparian adjacent Priority Habitats.

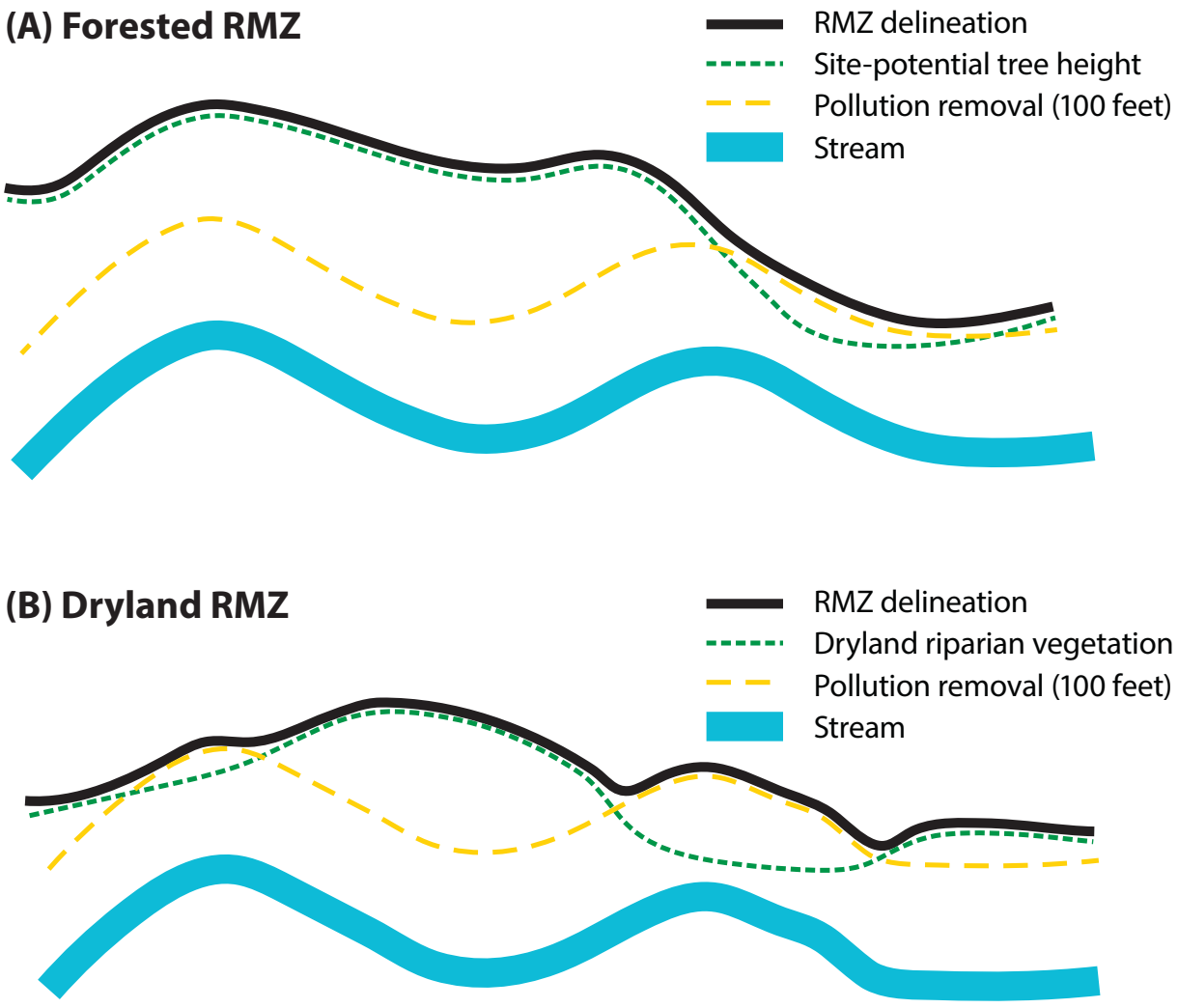


Figure 2.4. Aerial view of variable width RMZ delineation process for forested (A) and dryland (B) systems.

- *Step 1: Identify the SPTH or full extent of the riparian vegetative community (green);*
- *Step 2: Overlay a 100-foot pollution removal distance (yellow);*
- *Step 3: Delineate the RMZ (black) as the greater of the two distances.*

We tailor the following guidance based on two types of ecoregion: (1) Forested and (2) Dryland.

2.3.4 (A). Forested Ecoregions

Forested ecoregions are well-suited for using $SPTH_{200}$ consistently to establish RMZ widths, and so for these areas, landowners and land managers can rely on the $SPTH_{200}$ information provided in the SPTH mapping tool (see Appendix 1). The tool provides the derived average height attained by the dominant tree species at age 200 years ($SPTH_{200}$) using the U.S. Natural Resource Conservation Service (NRCS) forest productivity site index values, which we recommend for delineation of RMZs (see Sec 9.3 in Volume 1 for background on the origin and use of $SPTH_{200}$). In forested ecoregions, contributions of large wood as a riparian ecosystem function often define the farthest lateral extent of the RMZ.

Occasionally, the $SPTH_{200}$ may be less than 100 feet, in which case the pollution removal function (described in more detail in Section 2.3.5 below) defines the lateral extent of the RMZ.

In Washington, $STPH_{200}$ can be as large as 260 feet: therefore, be sure to evaluate each soil polygon within 260 feet of the stream channel to ensure that RMZ delineation is in fact being driven by the largest dominant tree species.

2.3.4 (B). Dryland Ecoregion

Riparian ecosystems in arid and semi-arid regions of North America (also referred to as the dryland ecoregion) make up less than 1 to 3 percent of the landscape (Patten 1998). Dryland riparian ecosystems are hydrologically linked to and influenced by adjacent surface waters; as a result, surface waters sustain riparian vegetation that is clearly distinct from upland vegetation.

Riparian ecosystems in dryland environments are highly variable due to various site-level conditions. While these ecosystems may support large trees in low gradient floodplains, tree presence in riparian ecosystems throughout the dryland ecoregion is much more varied than in forested ecoregions, and so in many cases, the contribution of large wood no longer serves as the outermost ecological function for RMZ delineation. Further, riparian vegetation may be minimal or even non-existent, particularly along degraded, incised streams. In dryland ecoregions, the outermost of

Protecting Columbia Plateau's Priority Habitats Supports Riparian Health

Native shrub-steppe vegetation and other drought-tolerant plant communities dominate Washington's dryland environments. Approximately 450 plant community associations occur in this region, with over 20% of these associations considered vulnerable (WDFW 2005, p. 523). Among the most imperiled ecosystems in North America, historical shrub-steppe has been greatly reduced due to conversion to other land uses (Vander Haegen 2007).

Riparian areas are critical to most animal species using shrub-steppe. Biodiversity in these vegetative communities increases dramatically where surface water occurs, and riparian areas directly support numerous species found only in or near water (Rogers et al. 1988, Johnson and O'Neil 2001). Linking and protecting upland adjacent Priority Habitat(s) not only aims to support Washington's wildlife and their associated habitat conservation goals, but also works to protect and maintain riparian ecosystem integrity.

three factors drives delineation of the RMZ: (1) $SPTH_{200}$ (if trees are present); (2) riparian vegetative community; or (3) pollution removal function.

2.3.4 (C). Considerations in Highly Modified and Urban Systems

In some locations, riparian systems have been substantially modified, and current site-specific conditions may not provide adequate indication of where riparian vegetation would naturally occur. On the whole, this is particularly true of riparian systems in dryland ecoregions. In these instances, we recommend considering nearby sites with unaltered vegetation or selecting a representative site with similar bank height and gradient conditions to identify adequate riparian vegetation delineation for both protection and restoration.



A modified riparian area within an agricultural landscape in Kittitas County. The stream channel was likely straightened decades ago. More recently, small bridges were built across the stream for pivot sprinklers to move back and forth. To allow ease of sprinkler movement, no woody vegetation is allowed to grow./Jennifer Nelson, WDFW

Similarly, four major urban areas (Seattle, Spokane, Tacoma, and Bellingham) in forested ecoregions lack NRCS soils data. For these areas, WDFW identified nearby NRCS soils polygons and calculated weighted averages as estimates reflective of the surrounding environment ("imputed $SPTH_{200}$"). Much like in forested areas where $SPTH_{200}$ data are available, we recommend using the imputed $SPTH_{200}$ values specified for each of these urban areas to delineate RMZs within them.

2.3.5. Width delineation steps

Step 1: Use $SPTH_{200}$ if it is at least 100 feet.

In **forested ecoregions,** WDFW recommends full protection within one $SPTH_{200}$, identified with the use of our SPTH mapping tool (https://arcg.is/1ueq0a). The mean $SPTH_{200}$ in western Washington ranges from 100 to 240 feet (Fox 2003). Some soil polygons have $SPTH_{200}$ information for multiple tree species; therefore, each soil polygon within one $SPTH_{200}$ should be evaluated to ensure RMZ delineation is driven by the largest dominant tree species. Occasionally the $SPTH_{200}$ in forested ecoregions is less than 100 feet; for example, red alder is a fairly common riparian tree species, yet the $SPTH_{200}$ for this species does not always exceed 100 feet. If red alder is the only species for which $SPTH_{200}$ information is available for a certain location, and it is less than 100 feet, then skip to Step 3.

In **dryland ecoregions,** it is less common, but still possible to find riparian vegetation which includes–and may even be dominated by–large trees. Examples of large tree species in these areas are black cottonwood (*Populus trichocarpa*) and ponderosa pine (*Pinus ponderosa*). If $SPTH_{200}$ in dryland ecoregions exceeds 100 feet, then it should be used for the RMZ width.

Step 2: In dryland ecoregions, if $SPTH_{200}$ is less than 100 feet or if no large trees are present, identify the extent of the riparian vegetative community.

In **dryland ecoregions,** the riparian vegetative community is often comprised of shrubs, sedges, grasses, and forbs that are distinct from upland communities. For example, in the Columbia Plateau, vegetation within riparian ecosystems often exhibits an abrupt demarcation between the riparian zone and zone of influence. Phreatophytic[7] trees and shrubs and hydrophytic[8] herbaceous plants are confined to moist streamside areas, but the upland zone of influence may consist of sagebrush or bunchgrass communities [for more information, see Volume 1, Chapter 7 (Section 7.1.1)]. Where trees are not present or consist only of small species (less than 100 feet tall), WDFW recommends full protection of the entire riparian vegetative community. In some places the community may only be a few feet wide but in others it may extend up to several hundred feet, particularly when associated with a wetland or floodplain (Bermingham et al. 2013). Where the riparian vegetative community is less than 100 feet wide, go to step 3.

Step 3: Overlay 100-foot pollution removal delineation

The following applies to both **forested and dryland ecoregions.**

Our recommendation to protect full riparian function recognizes the importance of the pollution removal function of riparian ecosystems. Because pollution removal depends on multiple factors, including slope, soils, plant community composition, and upland uses, establishing a standard RMZ width for 100% pollution removal even at the site scale was impractical.

Where neither $SPTH_{200}$ nor the extent of the riparian vegetative community is at least 100 feet, we recommend RMZ delineation of a *minimum* distance of 100 feet, because this distance will achieve 95% or more removal efficacy of phosphorous, sediment, and most pesticides. To be clear, we value a similar removal efficacy for nitrogen, and at a 100-foot width, an RMZ would achieve only 80% removal efficacy for surface runoff containing excess nitrogen. However, the literature reflects that both the actual risk posed by excess nitrogen, as well as the efficacy of its removal, are very site-specific. In recognition of this, we strongly recommend that, where upland uses contribute nitrogen, the 100-foot minimum pollution removal distance be extended accordingly when determining the appropriate RMZ width.

Further, if RMZ widths are being based on a minimum pollution removal function at locations with steep slopes or poorly drained soils, distances greater than 100 feet should also be considered: this applies for all pollutants. Additionally, WDFW recommends cities and counties identify high intensity land uses that may be located adjacent to riparian areas within their jurisdiction and establish wider RMZs to enhance the pollution removal function in these locations as well, following guidance from Ecology.

When dealing with variables such as those outlined above, it may be necessary to seek expert assistance in determining the appropriate adjustments to RMZ widths based on the pollution removal function.

7 A phreatopyhtic plant is a species that obtains water from the subsurface zone of saturation either directly or through the capillary fringe (Thomas 2014).
8 Hydrophytic plants are those that are adapted to growing conditions associated with periodically saturated soils. They include obligate wetland plants that almost always occur in wetlands under natural conditions, facultative wetland plants that usually occur in wetlands but are occasionally found in non-wetlands, and facultative plants that equally likely to occur in wetlands or non-wetlands (Lichvar et al. 2012).

Chapter 3. Riparian Regulatory Protections

3.1. Introduction

This chapter gives guidance to help local governments review, develop, and implement regulatory tools to protect riparian ecosystems as critical areas, i.e., Fish and Wildlife Habitat Conservation Areas (FWHCAs). We describe key steps toward creating effective programs to protect riparian ecosystems consistent with the goals of the Growth Management Act (GMA), Shoreline Management Act (SMA), and Voluntary Stewardship Program (VSP). More specifically, this chapter describes recommendations for carrying out common land use activities and provides steps for developing Habitat Management Plans (HMPs). The riparian management zone (RMZ) should serve as the focal area to apply our recommendations.

Parcel-scale regulations are foundational to Washington's traditional land use regulatory approaches for protecting rivers and streams and their adjacent riparian ecosystem. However, sole reliance upon a regulatory approach at this site scale may result in loss of aquatic system function over the long term (see Volume 1). Thus, we believe that site-scale regulations must work in coordination with watershed-scale planning (Chapter 4) and that both should be monitored and adaptively managed (Chapter 5). In this chapter, we present considerations and recommendations for managing and protecting riparian ecosystems at both site- and watershed-scales.

3.2. Recommendations to Local Jurisdictions

Protection of watersheds commonly falls under the purview of agencies other than WDFW. Nonetheless, we encourage local jurisdictions (and their long-range planners in particular) to consider how land use patterns at all scales collectively affect fish and wildlife and other important ecosystem services.

The scientific literature review (see Volume 1) informs WDFW's position that protecting the area within one $SPTH_{200}$ from the edge of a stream channel maintains full riparian ecosystem functions for all aquatic species, including salmon, and promotes healthy, intact riparian ecosystems. This recommendation provides the greatest level of certainty that land use activities do not impair functions and values of riparian ecosystems. We recommend the use of monitoring and adaptive management (see Chapter 5) to inform regulations and evaluate the complement of both regulatory and voluntary conservation measures in achieving outcomes.

Land use decision makers should ensure all programs that can affect riparian habitat (e.g., CAOs; SMPs; and ordinances for clearing and grading, fire hazard reduction, and tree protection) are coordinated to optimize the ability of local policies, rules, and management activities to protect those habitats. Further, jurisdictions should look for gaps

such as inconsistencies, exemptions and loopholes, or inefficient practices (e.g., inspection and monitoring protocols) that could impede protection of or cause harm to riparian ecosystems.

To that end, we provide important questions to consider when reviewing CAOs, Comprehensive Plans, or other plans that can affect riparian ecosystems:



The Coweeman River Joint Wetland and Conservation Bank in Cowlitz County includes riparian areas as a focus for both restoration and preservation./Chuck Stambaugh-Bowey, WDFW

1. Conservation Strategies:

- What external strategies exist (e.g., salmon recovery plans, reach-scale assessments, and incentive-based plans) to maintain, protect and restore riparian areas?
- Which of these strategies (if any) currently inform your regulatory, planning, and/or voluntary processes or programs?
- If these strategies are not in your current programs, could they be incorporated to provide additional benefits to riparian ecosystems? Are there other strategies that could also (or instead) benefit riparian ecosystems?
- Which of these strategies may help your jurisdiction satisfy mitigation obligations?
- How are riparian restoration and/or enhancement programs informed by these strategies?

2. Regulatory Buffers:

- Does your jurisdiction rely on $SPTH_{200}$ for delineating regulatory riparian buffers?
- If your jurisdiction does not rely on $SPTH_{200}$ for delineating those buffers, does your jurisdiction currently have regulatory buffers for riparian areas that are equal to or greater than the distance equal to $SPTH_{200}$?
- Are there buffer exemptions? If so, how do those affect riparian function across your jurisdiction?
- Do your buffers consider the CMZ?
- Do your buffers consider adjacent wetlands and appropriate wetland delineation methodology as prescribed by Ecology?
- If your jurisdiction's CAO or SMP buffers are less than $SPTH_{200}$, can you use the RMZ to identify areas to do mitigation or areas impacted that will require mitigation?

3. Restoration and Adaptive Management (see also Chapter 5):

- Can your jurisdiction use the RMZ to identify areas for incentive-based restoration?
- Do you have a monitoring and adaptive management program for improving permit implementation?

- Is your jurisdiction collecting information on effectiveness of protecting riparian areas?
- If you collect effectiveness information, what programs (e.g., incentives, regulations) could you improve to increase riparian conservation?

4. Other Programs and Regulations

- What other regulations separate from CAOs, may inadvertently affect riparian areas (e.g., clearing and grading ordinance that lack safeguards for riparian protection)?
- Are there opportunities to connect riparian areas with other protected areas (e.g., frequently flooded areas, geologically hazardous areas, green belts, parks, wetlands, and aquifer recharge areas)?

3.2.1. Recommendations for Common Activities in the RMZ

Local governments should regulate all land use activities that are likely to impact functions of a riparian ecosystem found within the RMZ to ensure, at a minimum, that the existing functions and values are protected from development actions. For the purposes of meeting requirements under GMA, SMA, and VSP, we describe the RMZ as the area in which functions and values are contributed to the riparian ecosystem: providing a delineated space not just for protection, but also for mitigation and management. We also recommend prioritizing the RMZ as the space for restoration[9]. We provide specific information and recommendations for the following ten common activities: (Note that neither the list of activities nor the recommendations themselves are exhaustive; for more information, contact your WDFW regional habitat biologist.)

1. On-site Sewage Systems (OSS)
2. Bank hardening
3. Clearing, grading, and placement of fill
4. Removal of noxious weeds
5. Forest practices and conversions
6. Firewise and wildfire hazard reduction
7. Removal of hazard trees
8. Non-compensatory restoration and enhancement
9. Emergency activities
10. Educational or Recreational Areas

1. **On-site Sewage Systems (OSS)** – Historically, developers sited OSS at lower elevations bordering streams, lakes and wetlands in order to use passive gravity flow. The disadvantage of these systems is that when drain fields are located near water features, they can more easily contaminate water with high loads of nutrients and toxic pollutants, causing significant impacts to flora, fauna and water quality. The State Department of Health adopted rules establishing public health standards for location, design, installation, operation, maintenance, and monitoring of OSS, including requiring setbacks from waterbodies (WAC 246-272A) which modern OSS systems, using pump systems, can support. Some OSS may meet public health standards even if located within RMZs; nevertheless, jurisdictions should exercise authority to require HMPs to ensure project proponents protect habitat functions of riparian critical areas.

[9] As explained previously, many riparian areas had already experienced a substantial degree of degradation before laws like GMA, SMA, and VSP were passed, so while protecting what level of riparian functions and values remain is essential, protection alone will not be sufficient for meeting the needs of the state's fish and wildlife species.

2. **Bank Hardening** – We recommend jurisdictions avoid allowing new development that requires bank protection now or is likely to in the future (consider channel migration, wind and wave action, and climate change), unless it addresses an imminent threat as an emergency activity (*see* Emergency Activities in this section below). Always look to alternative places to site a project so that no bank protection measures are needed. If measures cannot be avoided, require that a project proponent evaluate the effectiveness of bioengineering alternatives (also known as soft armoring) prior to proposing hard armoring. Follow bank protection recommendations in the Washington State Integrated Streambank Protection Guidelines (Cramer et al. 2002) when bank protection is unavoidable.

3. **Clearing, Grading, and Filling** – We recommend jurisdictions acknowledge impacts of clearing, grading, and filling on riparian areas in their CAOs by limiting these activities to areas outside the RMZ (unless directly related to restoration) as they can negatively affect riparian areas. If a clearing, grading, or filling project must encroach in an RMZ, limit disturbance and minimize effects to the greatest extent possible. Require that a qualified professional prepare an HMP describing how the project proponent will follow the mitigation sequence.

   Jurisdictions that exempt small areas from filling or grading ordinances in riparian ecosystems should calculate cumulative impacts from these exemptions. They should also mitigate impacts and subsequently establish monitoring to ensure that mitigation measures are effectively negating potential losses to habitat function.

4. **Invasive and/or Noxious Plant Removal** – Many CAOs do not require a permit for control and removal of invasive and/or noxious weeds within riparian ecosystem. We support this when weed control efforts (1) employ hand weeding with light equipment; (2) use only Ecology-approved aquatic herbicides and adjuvants (a substance added to herbicides to improve application); avoid use of hazardous substances; and (3) do not result in soil compaction. Local governments should retain some oversight authority for more extensive invasive and/or noxious plant control projects to ensure adequate protections of riparian functions, especially water quality. Most communities issue an exemption letter or permit, which should include conditions to ensure impacts to fish, wildlife, and habitat are minimal. It is important to note that even plants native to the region can, in certain circumstances, be detrimental to riparian areas. An example is in Puget Sound Prairies, where in the absence of periodic fire events (typically prescribed fire), common western Washington conifer species like Douglas fir outcompete native deciduous species (primarily Oregon white oak). In these circumstances, conifer removal and re-establishment of historical riparian conditions (oak and prairie vegetation) should occur under an approved HMP. WDFW regional habitat biologists can assist in preparing, reviewing, and implementing such a plan.

5. **Forest Practices and Conversions** – The state's Forest Practices Act (RCW 76.09 and WAC 222) regulates forest practice activities on forestland. We recommend that the proponent always contact DNR prior to conducting forest practice activities and seek technical assistance from a WDFW regional habitat biologist to ensure protections for Priority Habitats and Species. When conducting commercial forest practice activities, the forest practice rules—not the CAO—apply for protection of resources on site. Lands converted from forestry to another use require a special forest practice permit, and when converting land, local CAOs are applied. If conversion occurs, WDFW recommends timber harvests not be allowed within $SPTH_{200}$.

6. **Wildfire Hazard Reduction** – Wildfire is a concern in Washington, though the threat varies across the state. Local regulations to reduce wildfire hazards should be coordinated with a Firewise program in order to require landowners to consult with a Firewise professional (http://www.dnr.wa.gov/firewise) before removing trees or

manipulating vegetation in an RMZ. Understanding the composition of historical forest stands and shrub-steppe can help ensure retention of riparian functions when carrying out wildfire hazard reduction activities. When fuel (vegetation) reduction efforts involve the removal of merchantable trees, the proponent should check with the local jurisdiction and DNR, which may require a permit for tree removal.

7. **Removing Hazard Trees** – Tree trimming or removal in RMZs is sometimes necessary to address public safety concerns but should be balanced with the potential impacts to riparian ecosystem function. Jurisdictions should define a "hazard tree" (sometimes referred to as a "danger tree") as a threat to life, property or public safety, and require that the method of tree removal not adversely affect riparian ecosystem functions if possible. Specifically, we recommend that any removal of hazard trees involve an avoidance and minimization of damage to remaining trees and vegetation within the RMZ. We further recommend that local governments require a qualified arborist to evaluate requests for hazard tree removal.

   The qualified arborist should be able to establish when a tree presents an imminent threat to life, property or public safety. It is important to note that snags (dead trees) are a Priority Habitat feature for wildlife, and so should be preserved if not hazardous.



Like many dead and dying trees, this snag along the Chehalis River shows evidence of woodpecker activity. Grays Harbor County/Mary Huff, WDFW

   Some local governments use Forest Practice Rules (WAC 222-21-010[4]), which define a hazard tree as "any qualifying timber reasonably perceived to pose an imminent danger to life or improved property." This applies to any tree within 1.5 tree-lengths of the structure. A DNR forester can verify during a site visit that a tree is a hazard based on this definition, and thus removing the hazard would not be subject to the Forest Practice jurisdiction or require a Forest Practice Application.

8. **Restoration and Enhancement** – We encourage local governments to include in their CAOs allowances for restoration and/or enhancement of the riparian ecosystem, including in-channel or streamside work, especially on lands set aside for conservation. To the extent possible, jurisdictions should promote incentives and set up a streamlined review process for restoration or enhancement projects to help facilitate project proponents not just meeting the minimum requirements of the local CAO, but instead going "above and beyond". Significant resources are available to jurisdictions that address limiting factors in riparian areas or undertake high priority restoration activities that benefit salmon or other listed species (see Chapter 4 for information on restoration).

9. **Emergency Activities** – Local codes typically have provisions for emergency activities (e.g., bank stabilization to address imminent threats to homes) that provide relief from time delays related to procedural code requirements.

Local regulations should distinguish the immediate need to permit an emergency activity from the need to compensate for its impacts after-the-fact.

10. **Educational or Recreational Areas** – Public access to shorelines is a priority use under the SMA and providing educational and/or recreational developments such as trails, viewing platforms, or similar facilities may also enhance the public's understanding and appreciation of riparian areas, streams, and habitats. Thus, some focused use of the RMZ for educational and recreational activities may be desirable, if it does not create significant disturbances. Most CAOs include allowances for unpaved access to a stream for aesthetic or recreational enjoyment with defined limits on clearing to avoid impacts and minimizing soil, vegetation, and habitat disturbances: this is an allowance we support. That said, construction of trails could allow greater access for pets and other high intensity recreation, which may increase predation on, and/or disturbance of fish and wildlife species. Regulations should minimize impacts from recreational trails and interpretive facilities to the extent practicable, informed by PHS data and associated management recommendations.



A sculpture titled "The Indian Chief" greets visitors at the entrance to the Beebe Springs Natural Area along the Columbia River near Chelan./Alan Bauer

3.2.2. Project-specific Riparian Habitat Management Plans

When reviewing proposed projects near streams, local governments typically require applicants to provide detailed site-specific HMPs (often called a Critical Area Report). Here we describe six aspects of Riparian HMPs that we recommend be addressed in CAOs:

1. When HMPs are required;
2. Which additional critical areas must be delineated, and how;
3. Which specific land use actions must be identified, and how;
4. Mitigation requirements;
5. Monitoring and Adaptive Management requirements; and
6. Articulate who must prepare and review the HMP.

1. **When required** – We recommend jurisdictions require an HMP whenever someone proposes a land use activity in an RMZ (regardless of the jurisdiction's regulatory RMZ delineation) or when a proposal likely could affect riparian or aquatic functions. In cases where there is less confidence in the spatial accuracy of the RMZ, consider requiring a Riparian HMP when impacts occur adjacent to the RMZ's zone of influence.



It is not uncommon for riparian areas to overlap with other types of critical areas, including geologically hazardous areas, where landslides may bring input like large wood to streams./ Terra Hegy, WDFW

Maps, DNR's stream layers, the National Hydrography Dataset (NHD), and other (e.g., local) stream layers are important for triggering HMPs. An HMP should be required whenever a stream is present near proposed development activities, including but not limited to subdivisions (plats, short plats, and large lot subdivisions), land/vegetation disturbing activities (e.g., clearing and grading, septic drain field siting), and stormwater routing.

2. **Critical Area Delineation** – HMPs should have the extent of critical areas within and adjacent to a proposed project site identified, along with ecosystem functions that need protection. Follow the RMZ delineation procedure outlined in Chapter 2, along with locations of other critical areas on or near the site (e.g., wetlands, geologic hazards, frequently flooded, critical aquifer recharge areas; informed by Ecology). Also, identify salmon and other priority aquatic species that use the stream network in the immediate vicinity as well as up- and downstream. Likewise, HMPs should identify Priority Species that may use the riparian corridor and any other Priority Habitats to which the corridor is connected. Attach the delineation map (1) to the property's title to inform future property owners of the site's critical areas, and (2) use it to update the jurisdiction's critical areas maps.

3. **Land Use Action Identification** – A complete HMP should describe relevant management recommendations for Priority Habitats and Species found on or near the site. Include a map in the HMP showing the location of proposed land use actions. It should identify and quantify current and proposed disturbances to the RMZ and other FWHCAs.

4. **Mitigation** – The HMP should have a description of the project proponent's mitigation sequencing. It should describe in detail measures to avoid impacts and minimize unavoidable impacts (e.g., clustering, conservation easements, and seasonal construction restrictions). If mitigation or compensation is necessary, the HMP should identify ways to improve riparian ecosystem function by enhancing riparian corridor connectivity (e.g., removal of stream barriers) or by improving the quality of the riparian area (e.g., replacing invasive vegetation with appropriate native vegetation).

5. **Monitoring and Adaptive Management** –The HMP should describe requirements for monitoring and adaptive management. In addition, it should identify measurable standards and expectations to monitor compliance (e.g., areal extent of vegetative cover, composition of riparian tree species, maximum invasive plant cover). The HMP should identify frequency of visits to monitor the site (e.g., at year 1, 2, 3, 5, 8, and 10) as well as measurable triggers for requiring more actions (e.g., maximum percent area coverage of invasive plants). The HMP should specify who is responsible for preparing, reviewing, and submitting reports. Finally, if deemed necessary by the jurisdiction, the report should include a cost estimate for monitoring, and the project proponent should post a bond for this amount or more to allow for overages.

6. **Preparer and Reviewer** – A qualified professional biologist, botanist, or ecologist should prepare the HMP; additional expertise related to CMZs, unstable slopes, and wetlands may also be necessary. Additionally, an independent professional with similar qualifications should review the HMP. WDFW's regional habitat biologists can often serve in this role, especially for larger projects. USFWS or NOAA Fisheries should also review the HMP if the project might affect a federally listed fish or wildlife species.

3.3. Riparian Management in Urban Areas

Some people have raised questions about the applicability of RMZs to urban and urbanizing areas. These concerns generally fall into two categories: (1) the science on RMZs comes largely from agricultural and forestry settings, and so is perceived to be irrelevant to urban areas; and (2) there is a belief that the need to maximize density of development in urban areas is in direct conflict with the protection of riparian areas.

Concerns over the relevancy of literature on riparian functions to urban areas is largely unfounded. While most riparian ecosystem studies are from non-urban settings, the principles are the same. Functions of shade, bank stability, large wood recruitment, nutrient inputs, and pollutant removal operate similarly in urban areas as they do in other settings. However, within urban areas, these riparian ecosystem functions are often greatly diminished or even absent altogether.



Fish-bearing stream within an urban area of King County/Elizabeth Torrey, WDFW

The role that urban RMZs play in delivering habitat functions for aquatic and many terrestrial species is also like that in non-urban areas. Factors that may be different in urban areas are that urban riparian ecosystems may perform some functions at reduced levels due to their position in developed watersheds, which are often heavily degraded. However, intact RMZs in urban areas function as wildlife corridors that link habitat patches, which is critical for many species. In fact, sometimes RMZs in urban areas may be more important from a habitat standpoint, because within urban areas, adjacent uplands are often even more degraded than the RMZs, which then are often the only remaining areas where habitat functions are provided. Thus, a key element to maintain in urban RMZs is connectivity, both in and along streams.

Many Puget Sound salmon move through channelized streams, traversing heavily urbanized areas prior to reaching spawning grounds and as juveniles on a reciprocal journey to marine waters. Salmon must pass through a wide spectrum of development. For example, adults returning to spawn often start in urban cores (e.g., downtown Seattle), where streams are often channelized; then pass through areas with small lots and high urban density and into suburban

creeks where larger lots allow for more riparian protection; and finally, to rural lots with less development and better ecosystem health. When juveniles make their journeys in reverse, they generally spending more time in each of these areas than their parents did, and yet because of their small size, they are also at much greater risk of not surviving any of them. While the decades-long decline of many of our native salmon stocks illustrate just how challenging this is, their persistence—especially the subspecies which are showing signs of improvement—shows us what is possible. Therefore, it is critical that the urban environment maintain and enhance the ability of different species and ages of salmon to not just survive, but thrive, while in these disturbed areas.

Many of the actions we recommend urban communities focus on are the same or similar to those appropriate in less densely developed areas. For example, it is critical to maintain connectivity through properly sized culverts such that all fish can pass through at all relevant life stages. Additional riparian function can be achieved through revegetation efforts using native plants and by improving connectivity between habitat patches. A landscape analysis can help identify existing connections to protect, as well as areas where restoring connectivity is a priority. On the other hand, some actions are particularly well-suited to urban jurisdictions, like standards for Low Impact Development (LID) and state-of-the-art stormwater management. Further, when changes are made to urban infrastructure, this may create opportunities to improve riparian functions while contributing to new or improved public open spaces.

Recommendations for urban riparian ecosystems:

1. Delineate urban RMZs to protect what areas remain and to highlight lost or degraded areas to target for restoration.
2. Quantify current conditions, with a goal of maintaining and improving functions through regulatory and voluntary means.
3. Identify and prioritize restoration opportunities and projects within the RMZ:
    - Protect riparian functions that remain, especially in places that are relatively high functioning; implement actions that enhance degraded functions (see Chapter 4).
    - Prioritize opportunities to maintain and restore in-stream and riparian connectivity.
    - Adopt a stormwater design manual equivalent to Ecology's most current manual for western and eastern Washington.
    - Manage stormwater by adopting Ecology's latest manual regarding LID for new development, redevelopment and retrofit projects.

4. When replacing or removing existing infrastructure within an RMZ:
    - Map RMZ to pinpoint the best sites to restore – consider connectivity and adjacency to other Priority Habitats;
    - Improve aquatic connectivity by replacing culverts and removing barriers to movement;
    - Revegetate with native plants and consider improvements for wildlife by integrating structures necessary for nesting, breeding, and foraging;
    - As infrastructure is remodeled or replaced, incorporate additional setbacks from streams;
    - Control access to RMZ to limit soil compaction;
    - Avoid operating equipment near the stream to reduce sedimentation and soil compaction; and
    - Avoid using chemicals in the RMZ which are not approved for use there by Ecology.

3.4. Managing Watersheds



Tieton River on Oak Creek Wildlife Area in Yakima County, looking west toward the Cascade Mountains./Justin Haug, WDFW

As described in Chapter 8 of Volume 1, land use activities in a watershed can affect the stream network, even when the riparian ecosystem itself is relatively undisturbed. "Watershed management" is a land management approach that seeks to minimize negative effects of upland land uses on aquatic systems, which include riparian areas. The remainder of this chapter focuses on key watershed elements important to managing and protecting functional aquatic systems. Many of the approaches we outline here are non-regulatory and can complement regulatory efforts; as previously stated, we recommend cities and counties inventory current conditions of critical areas and, based on that inventory, develop watershed scale management plans accordingly.

Fully functional riparian ecosystems, in combination with targeted watershed protections, provide significant benefits to humans. These benefits, often described as ecosystem goods and services, include clean water; decreased flooding; increased nutrient cycling, sediment and pollutant filtering; reduced erosion; carbon sequestration; and cultural services such as recreational, spiritual, and other nonmaterial benefits. These services provide real but often unquantified economic benefits to individuals and society that largely go unnoticed until they are lacking.

3.4.1. Watershed-Scale Recommendations to Protect Aquatic Systems

To achieve desired ecosystem goods and services watershed managers should focus on influencing watershed processes that act upon water, wood, sediment, nutrients, vegetation, and pollutants at both the site- and watershed-scale. This section focuses on watershed-scale management.

Restore and Protect Watershed Processes – Efforts to improve watershed conditions should first focus on protecting and restoring watershed processes (e.g., natural disturbances) that create and retain habitat for fish and wildlife. Maintain the frequencies, magnitudes, and durations of natural disturbances (flood and fire being the most common) to the greatest extent that surrounding land uses can tolerate.

Manage Land for Stormwater – Stormwater runoff can change the timing, quality, and quantity of water provided to streams. Land uses should avoid/minimize changes to surface water flows. Protection and restoration efforts should focus on attenuating peak flows and reducing pollutants. Primary tools available to local governments include land use designations/zoning code, and stormwater regulations. See City of Redmond Watershed Management Plan (City of Redmond 2013).



Chum salmon gathered at a blocked culvert in Kitsap County./Brittany Gordon, WDFW

Manage Land for Stream Temperatures – Reduced riparian vegetation cover, decreased streamflow, and simplified stream channels (e.g., increased width-to-depth ratio and reduced groundwater exchange) can lead to increased water temperature (Volume 1, Chapter 4). Modifications like these are often the result of land use activities such as riparian vegetation removal; water diversions; unmanaged livestock grazing; and stream channelization associated with roads, levees, and other forms of development. Identify and restore thermally sensitive stream reaches at the watershed scale to maintain optimal stream temperatures for sensitive aquatic species such as salmonids.

Restore and Protect Connectivity – Manage watersheds to avoid creating longitudinal (e.g., dams, road crossings), lateral (e.g., levees and roads/buildings that cut off riparian areas and floodplains from their stream), and vertical (water withdrawals, reductions of floodplains) barriers to fish and wildlife movement and fragmentation of their habitat. This is especially important for highly mobile species that require a variety of habitat components across large areas. For example, where CMZs interact with floodplains, dikes and levees restrict the movement of the river or stream and also serve as a barrier for fish and many forms of wildlife.

Restoration to correct existing barriers to movement of water, wood, sediment, and species (e.g., removing blocking culverts) is a high priority with proven benefits for salmon. Connectivity to achieve nearly or completely contiguous RMZs is important to water quality and to achieve connectivity among patches. Ensuring connectivity both for terrestrial and aquatic wildlife works towards a more interconnected and healthy riparian system.

Plan for Climate Change – Impending changes to aquatic systems caused by climate change increases risk to species already threatened, and riparian ecosystem protection is one of the most useful responses to ameliorate those risks. For example, because more intense rainfall events will lead to wider streams, larger culverts will be necessary to support fish passage. WDFW, in collaboration with the University of Washington's Climate Impacts Group, created an online tool (UWCIG 2017) that estimates how much a stream's channel width will increase with climate change in the years 2040 and 2080. Connectivity within the RMZ allows voluntary migration for species and helps minimize temperature change and increase off-channel storage of water to reduce low flows.

Conduct Monitoring and Adaptive Management – Monitoring and adaptive management are important elements to both site-scale and watershed-scale; this is addressed further in Chapter 5.

3.4.2. Tools and Key References for Assessing Current Watershed Conditions

Washington's State agencies, including WDFW, have developed multiple tools to assist local government in assessing watershed conditions. Jurisdictions can utilize these resources—many available at no cost—to quantify changes in land cover, tailor planning for specific species, coordinate monitoring activities, inform restoration, and assess watershed health.

WDFW's High Resolution Change Detection (HRCD) is a spatial dataset that characterizes changes in land cover. This tool allows jurisdictions to evaluate in specific ways how watersheds are changing at a sub-parcel scale over 2- to 3-year intervals. This dataset is currently available throughout the entire Puget Sound basin and in some Eastern Washington watersheds. HRCD data is available at https://hrcd-wdfw.hub.arcgis.com/.

WDFW's Priority Habitats and Species program has several resources of interest to watershed planners. In addition to this two-volume document on riparian ecosystems, readers will find useful ideas in Land Use Planning for Salmon, Steelhead and Trout: A land use planner's guide to salmonid habitat protection and recovery (Knight 2009) and Landscape Planning for Washington's Wildlife: *Managing for Biodiversity in Developing Areas* (Azerrad et al. 2009).

Since 2004, the Pacific Northwest Aquatic Monitoring Partnership has collaborated with West Coast federal, state, and tribal agencies to coordinate monitoring activities and develop common approaches. This partnership provides best practices, mapping tools, and protocols, and serves as a voluntary clearinghouse for a wide variety of monitoring projects.

Since 2009, Ecology's Watershed Health Monitoring Project has been monitoring sites throughout the state to assess watershed health. This project's protocols can be adapted by jurisdictions and scaled to watersheds of various sizes. Data is stored in the Environmental Information Management database. This sophisticated database allows users to input and retrieve data via the web, reliably store it, and make it available for analysis. Quality assurance/quality control measures ensure data put into the database are of high quality.

Ecology's Puget Sound Watershed Characterization is a Puget Sound-wide tool that compares areas based on their suitability and value for restoration and protection. This tool informs two fundamental questions: (1) where to focus protection and restoration on the landscape first, and (2) what types of activities and actions (i.e., restoration, protection, conservation, or development) are most appropriate to that place. With insights gained by this tool, decision-makers can incorporate information regarding watershed processes to improve plans (e.g., comprehensive plans, subarea plans, CAOs, stormwater plans) and conservation efforts (e.g., in-lieu fee programs, open space tax credits, open space land acquisitions).

In 2016, the Washington Department of Commerce (Commerce) published Building Cities in the Rain (Ballash 2016) to help communities improve watersheds while redeveloping and revitalizing urban areas. The guidance describes an optional three-step process for prioritizing watersheds for stormwater retrofits in urban areas. Commerce's Puget Sound Mapping Project uses an interactive map to help users develop insights about how current and expected development patterns might affect the region's environmental health. The tool is designed to help decision makers consider information from the Puget Sound Watershed Characterization (described above) when making decisions regarding development projects, urban growth boundaries, and compensatory mitigation.

Finally, the University of Washington's Climate Impacts Group has developed a suite of tools, many in concert with WDFW, which may be useful for landowners and land use decision makers including climate trends, culvert design projections, and habitat connectivity.

Chapter 4. Restoring Riparian Ecosystems

4.1. Introduction

This chapter provides high-level guidance to landowners, land use decision makers, and conservation partners to promote restoration of riparian areas. Despite recent efforts to protect existing riparian systems, imperiled salmon stocks and other riparian dependent endangered species are not recovering as hoped (Table 4.1). Since non-indigenous settlement of Washington began in the 1800s, between 50 percent and 90 percent of riparian ecosystems have been lost or extensively modified (RCO 2019). While two subspecies (Hood Canal summer chum and Snake River fall Chinook) are moving towards recovery, most listed salmon in Washington are below recovery goals (Table 4.1).

The lack of recovery is also evidenced in the ongoing decline of salmon fishing, which affects the long-term health of Washington's tribes, Washington's economy, and our shared cultural heritage. The lack of salmon is one of the primary reasons Southern Resident Killer Whales are at risk of extinction, in addition to other impacts such as vessel disturbance and pollutants. (Lacy et al. 2017, Murray et al. 2019)

Table 4.1. Non-statistical evaluation of natural origin (wild) fish that returned to spawn with consideration for threats and factors affecting health including habitat, harvest, and hydropower. (Adapted from RCO 2019; Data sources: WDFW, Indian tribes, NOAA).

Below Goal (Endangered Species Act-Listed Salmon in Washington)			**Near Goal**
Getting Worse	*Not Making Progress*	*Showing Signs of Progress*	*Approaching Goal*
Upper Columbia River Spring Chinook	Upper Columbia River Steelhead	Mid-Columbia River Steelhead	Hood Canal Summer Chum
	Lower Columbia River Chum	Lake Ozette Sockeye	
	Lower Columbia River Coho	Lower Columbia River Steelhead	
Puget Sound Chinook	Lower Columbia River Fall Chinook	Snake River Steelhead	Snake River Fall Chinook
	Lower Columbia River Spring Chinook	Puget Sound Steelhead	
	Snake River Spring Chinook		
	Snake River Summer Chinook		



Former lake-bed above the area where the Glines Canyon Dam once stood on the Elwha River, Clallam County. Following dam removal, salmonids returned even faster than expected./Rachel Blomker, WDFW

Given the extent of historical loss, WDFW recognizes that protection alone of remaining riparian ecosystems, will not recover salmon or the Southern Resident Killer Whale population. Therefore, WDFW recommends restoring and enhancing riparian ecosystems to achieve healthy, intact, and fully functioning riparian systems statewide. Continued investments in restoration will be required at all levels of government and in concert with Washington tribes.

4.2. Restoration Actions

Although this section focuses on restoring riparian areas for the benefit of salmon, emulating historical conditions benefits many other aquatic and terrestrial species as well. WDFW is available to provide technical assistance and species-specific guidance for terrestrial species-focused restoration and recovery efforts. To recover salmon, we must protect all remaining existing riparian and watershed functions, while seeking opportunities to restore functions that have been lost over time. We provide the following information to assist the restoration community[10] in understanding what is important to restore.

4.2.1. Developing a Restoration Strategy

Aquatic restoration strategies typically start with a clear set of goals and objectives. The selection of appropriate restoration strategies is informed by the political, social, and ecological context of the watershed, and bounded by the extent of opportunities and constraints. It is important in ecosystem restoration to consider the habitat attributes and scale necessary for a desired suite of species, be they aquatic or terrestrial. At a watershed scale, restoration efforts should focus first on projects that offer the greatest potential for success. The Stream Habitat Restoration Guidelines (Cramer 2012) suggest the following prioritization of stream habitat restoration strategies that are specific to instream related activities most often geared at anadromous fish:

1. **Protect existing habitat.** Protect areas that provide healthy, high-quality habitat functions (strongholds, refugia, and key sub-watersheds) to prevent further degradation. Secure, expand, and link protected areas.

2. **Connect habitat.** Connect and provide access to isolated habitat, including instream, off-channel, and estuarine habitat made inaccessible by culverts, levees, fragmentation, or other man-made obstructions.

3. **Restore habitat-forming processes.** Employ land use recovery and watershed restoration techniques to restore processes that create, maintain, and connect habitats (including restoring sediment dynamics, large wood dynamics, and flow regimes; avoiding/removing manmade disturbances within the riparian ecosystem; and maintaining water quality, floodplain connectivity, and channel evolutionary processes). Employ a combination of active or passive restoration techniques, as necessary. Active restoration involves accelerating processes or attempting to change the trajectory of succession; passive restoration simply involves ceasing environmental stressors such as agriculture, grazing, or timber harvest, and then allowing nature to take its course.

10 Many watersheds in Washington have salmon recovery restoration goals that can be obtained from regional Salmon Recovery Boards or Lead Entities for Salmon Recovery. Lead Entities and Salmon Recovery Boards are in every region of the state, including those areas without salmon or other anadromous fish (https://www.rco.wa.gov/salmon_recovery/regions/regional_orgs.shtml).

4. **Create new or enhance existing habitat.** Improve existing or create new habitat for specific species by installing instream structures such as large woody debris; reconfiguring channel shape, cross-section, or profile to reduce incision or restore flow; or constructing one or more new side channels.

In conjunction with other state agencies and partners, WDFW provides multiple technical guidance documents to help design and implement riparian restoration projects that have proven successful in different types of landscapes, including on marine shorelines, and on river- and streambanks. These are part of a suite of Aquatic Habitat Guidelines found at https://wdfw.wa.gov/licenses/environmental/hpa/application/assistance. They include:

- Water Crossing Design Guidelines (Barnard et al. 2013)
- Stream Habitat Restoration Guidelines (Cramer 2012)
- Integrated Streambank Protection Guidelines (Cramer et al. 2002)
- Land Use Planning for Salmon, Steelhead and Trout: A land use planner's guide to salmonid habitat protection and recovery (Knight 2009)
- Draft Fishway Guidelines for Washington State (Bates 2000)
- Draft Fish Protection Screen Guidelines for Washington State (Nordlund and Bates 2000) Marine Shoreline Design Guidelines (Johannessen et al. 2014)
- Your Marine Waterfront (WDFW 2016)
- Protecting Nearshore Habitat and Functions in Puget Sound (AHGP 2010)

4.3. Implementing Riparian Strategies Through Incentives

There are several types of conservation incentives available to individuals and local governments:

- **Financial assistance:** grant programs that provide funding for conservation activities
- **Tax adjustment:** tax reductions for landowners undertaking conservation activities
- **Technical assistance:** advice and/or hands-on help for landowners on tools or techniques
- **Recognition:** promotion of landowners who undertake conservation actions

Each of these will be described (and examples provided) in more detail, below.

4.3.1. Financial Assistance

State and federal grant funds are available for riparian ecosystem conservation and restoration projects on public and private lands through the Recreation and Conservation Office (RCO) and Salmon Recovery Funding Board. To access these funds and to learn more, go to https://www.rco.wa.gov. Grant programs include:

- Aquatic Lands Enhancement Account
- Washington Wildlife and Recreation Program (Farmland, Forestland, Habitat, and Recreation categories)
- Estuary and Salmon Restoration Program—a program of WDFW
- Land and Water Conservation Fund
- Salmon Recovery and Puget Sound Acquisition and Restoration

Land trusts also help land owners conserve habitat for key aquatic and terrestrial species, often leveraging funds from foundations and other non-governmental sources; see www.walandtrusts.org for a county-specific list of land trusts.

For agricultural property owners, local conservation districts and the Washington State Conservation Commission (WSCC) can provide technical assistance to find an approach that works for the farmer and improves riparian ecosystem function. Technical assistance is also available from the federal Natural Resources Conservation Service (NRCS), Washington State University Extension, and WDFW. Additionally, a host of state and federal financial incentives to expand and maintain riparian functions within the riparian management zone (RMZ) are available, some of which are listed below. For example, the Conservation Reserve Enhancement Program (CREP) provides funding to landowners for riparian preservation and is the most successful riparian buffer program in Washington. Since CREP's 1999 inception in our state, more than 900 miles of stream buffers have been planted, and as of October 2020, producers had over 13,500 acres actively enrolled in CREP. Contact your local conservation district or the RCO to learn more.

- Conservation Reserve Enhancement Program (NRCS)
- Environmental Quality Incentives Program (NRCS)
- Conservation Stewardship Program (NRCS)
- Conservation Reserve Program (NRCS)
- Regional Conservation Partnership Program (NRCS)
- Agricultural Conservation Easement Program (NRCS)
- Agricultural Land Easements (NRCS)
- WWRP Farmland Preservation Grants (RCO)

Timber landowners have access to a variety of forestry-oriented conservation incentive programs (see list, below) and can also receive technical assistance from DNR's Forest Stewardship Program (foreststewardship@dnr.wa.gov, 360-902-1428):

- Forestry Riparian Easement (DNR)
- Rivers and Habitat Open Space Program (DNR)
- Healthy Forests Reserve Program (NRCS)
- Family Forest Fish Passage Program (DNR)
- Forest Legacy (USFS)
- WWRP Forestland Preservation Grants (RCO)



The federal Conservation Reserve Enhancement Program (CREP) funded this vegetation planting project along a stream in Skagit County./Wendy Cole, WDFW

4.3.2. Tax Reduction Incentives

Landowners can receive a substantial tax reduction by converting land into "open space" status because of the Open Space Taxation Act (WAC 458-30), enacted in 1970. Lands with riparian areas often qualify for this incentive; see your county assessor and local planning department for details.

4.3.3. Technical Assistance

Local governments and individual landowners who want to improve riparian habitat for a suite of species can request land use advice from a variety of sources, including:

- WDFW regional habitat and district wildlife biologists. Go to http://arcg.is/1SgsHqk to find the names and direct contact information for your local biologists, or call the regional office in your area:
  - Region 1 – Eastern: 509-892-1001
  - Region 2 – North Central: 509-754-4624
  - Region 3 – South Central: 509-575-2740
  - Region 4 – North Puget Sound: 425-775-1311
  - Region 5 – Southwest: 360-696-6211
  - Region 6 – Coastal: 360-249-4628
- Salmon Recovery Lead Entities or Regional Fisheries Enhancement Groups
- Tribal natural resource departments
- Local Conservation Districts



4.4. Suggested Restoration Practices

The following section provides a series of suggested restoration practices promoted by WDFW, other state and federal agencies, and conservation partners. We encourage consideration of these activities and others within and adjacent to the RMZ, as delineated in accordance with our recommendations in Chapter 2. Further, it is not unusual to find other types of Priority Habitats (e.g., wetlands, shrub-steppe) adjacent to riparian areas. In such cases, restoration practices should not degrade or disturb the adjacent habitat, but rather—if feasible—improve it in addition to improving the riparian habitat. The same approach should be used where riparian-adjacent Priority Species areas are present.

Like most restoration practices, the ones recommended below can range in complexity, both biologically and technically, so landowners are strongly encouraged to seek technical assistance from WDFW and other experts before taking any action: This will help save money, time, and greatly increase the likelihood of success for any restoration activity. Landowners should also be aware that many of these activities may require permits[11,12] issued by one or more

11 The Governor's ORIA Office provides additional assistance for general permitting questions (https://www.oria.wa.gov/site/alias__oria/347/Permitting.aspx)
12 Larger projects may also trigger permit requirements with federal agencies, such as the U.S. Army Corps of Engineers (USACE).

agencies such as WDFW for the Hydraulic Code rules, and DNR for the Forest Practices rules; as well as permits from the local jurisdiction.



Cooperative riparian enhancement project led by the Lower Columbia Fish Enhancement Group along the Toutle River, Cowlitz County/Josh Nicholas, WDFW

1. Improve quality of vegetation for both aquatic and terrestrial wildlife by removing invasive species wherever present. Further, to avoid the likely return of invasive species, cleared areas should be replaced with native riparian vegetation: specifically, native vegetation that provides needed ecosystem functions as described in Volume 1 and throughout this document (e.g., shade, large wood, pollution removal).

2. Where riparian areas already possess some native vegetation, enhance them with a greater mixture of native plants that provide necessary habitat components (forage, cover, breeding, roosting, etc.) for a diversity of species and multiple riparian functions (e.g., streambank stability, wood recruitment, organic litter input, and pollutant removal). The specific mix of vegetation will vary by ecoregion and local needs, but likely includes conifers, grasses, and herbaceous plants.

3. Increase off-channel habitat and improve natural flow regimes by removing dikes or levees and restoring access to and within the floodplain.

4. In areas of incised channels, reintroduce beaver or construct beaver dam surrogates to store sediments, raise streambed elevation, raise water table elevation, and restore riparian vegetation.

5. Remove reed canary grass, which can greatly inhibit channel morphology and aquatic species movement. (Management techniques for reed canary grass vary and are often site-specific: contact your local WDFW regional habitat biologist for technical assistance.)

6. Through proper consultation with WDFW and tribal biologists, increase the presence of large wood in streams and rivers to improve habitat for salmon, resident fish species, and aquatic amphibians.

7. Increase connectivity through removal of non-fish passing culverts. If replacement culverts are needed, ensure they are adequately sized and climate-change-resilient; see WDFW's online resource on Incorporating Climate Change into the Design of Water Crossing Structures (Wilhere et al. 2016).

8. Reduce soil erosion by increasing vegetation complexity and density, excluding (or substantially minimizing) soil compacting activities, and implementing upland soil management techniques where applicable.

9. For agricultural operators: add and/or improve fencing structures to increase the amount of riparian area acreage from which livestock are excluded to reduce compaction, erosion, and overgrazing.

Chapter 5. Improving Protection Through Adaptive Management

5.1. Introduction

Adaptive management is widely recognized as an essential component of effective natural resource management because it provides a systematic process for continually improving policies and management through outcome-based learning. The adaptive management process is a continual cycle of planning, acting, monitoring, evaluating, and adjusting (Figure 5.1). This feedback loop provides information for making adjustments that focus on improving decisions in all phases of resource management. The utility of adaptive management programs should be considered by conservation practitioners, landowners, and land use planners to ensure that conservation actions achieve desired outcomes: in the case of this document, that means preserving, protecting, and restoring healthy, intact, and fully functioning riparian areas. In addition to improving ecosystem outcomes, adaptive management should improve clarity of regulations–resulting in increased transparency to all stakeholders.

All cities and counties are currently protecting critical areas, including riparian ecosystems, through a variety of regulatory and non-regulatory mechanisms. One regulatory challenge is understanding how well these mechanisms meet their intent of protecting ecosystem functions and values and how to make improvements where they are falling short. This chapter was written in collaboration with the Washington Department of Commerce (Commerce) and relies heavily on the Commerce's 2018 update of the Critical Areas Ordinance Handbook (Bonlender 2018), with one exception, as noted.

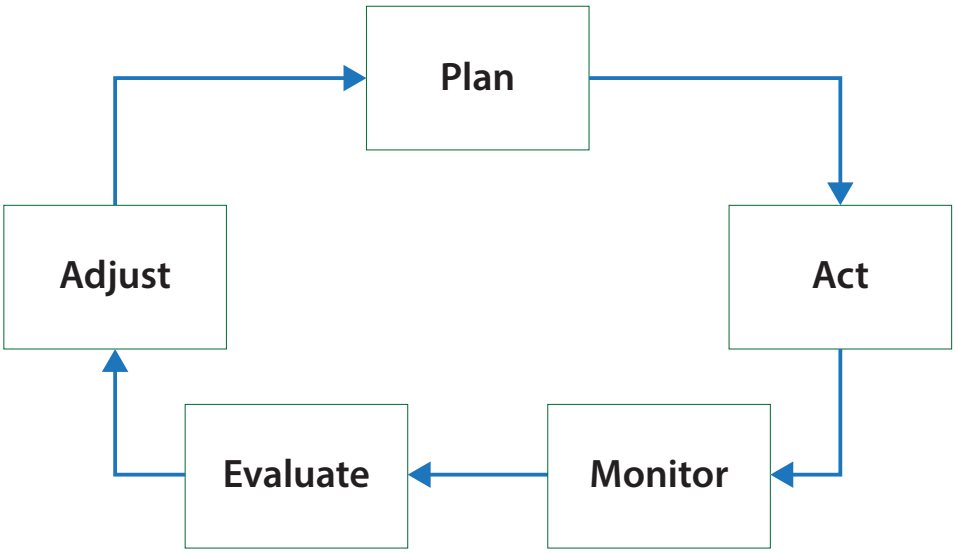


Figure 5.1. A simple depiction of the adaptive management cycle (modified from Bormann et al. 1994).

The process for monitoring we describe here supports both local and larger-scale actions that improve our collective efforts to protect riparian ecosystems throughout the state. For example, the Puget Sound Partnership (Partnership) uses "Vital Signs" of ecosystem health and recovery, such as riparian forest cover, to understand ecosystem condition, articulate shared goals and progress, and inspire action towards meeting those goals.

Adopting an adaptive management program can allow local governments to respond more quickly and meaningfully as new information become available. A willingness to address issues identified through this process is critical to the idea of adaptive management.

5.2. Common Questions Addressed by Adaptive Management

Adaptive management does not have to be expensive or complicated to be useful. We believe local jurisdictions can maximize their investment in adaptive management by focusing on two types of monitoring related to their own regulatory process (explained in more detail in the next section).

We begin by discussing three basic types of monitoring because we have found it instructive to understand how different monitoring types can be hierarchically or sequentially staged, based on the types of questions they seek to answer: implementation monitoring[13], effectiveness monitoring , and validation monitoring.

5.2.1. Implementation Monitoring

Implementation monitoring typically helps the permit issuer (permittor) answer the following questions about its permitting system, by looking at the outcomes of individual permits:

- Are permits consistent with regulations?
- Do permits contain all necessary conditions or provisions for a project?
- Does the permittor issue consistent permits (same requirements) for all permittees?

Implementation monitoring can also include:

- Permit *compliance monitoring,* which asks if the permitte followed or complied with each permit condition or provision and refrained from conducting unpermitted activities. Compliance monitoring usually takes place very soon after completion of permitted work.
- Keeping track of unpermitted activities; that is, finding changes in land use or management that require a permit but where no permit of any kind was issued.

13 As explained further in Section 5.2.2, we describe and use the term effectiveness monitoring somewhat differently than how it is described in Commerce's 2018 Critical Areas Handbook.



Fast-growing alder trees, like these shown in a low area along the Methow River in Okanogan County, can improve bank stability and increase summer shade more quickly than most conifers./Scott Fitkin, WDFW

5.2.2. Effectiveness Monitoring

In Commerce's 2018 Critical Areas Handbook, effectiveness monitoring is a form of long-term implementation monitoring. In other words, effectiveness monitoring looks at permit compliance as a while to determine whether permit conditions/provisions (e.g., buffer widths) are followed over time.

For the purposes of this document, we describe effectiveness monitoring a bit differently: Specifically, effectiveness monitoring is a way to determine whether permit conditions/provisions are working relative to intended environmental outcomes. For example, "Are permit conditions/provisions leading to the riparian function(s) (e.g., shade, bank stability) that they were intended to provide?" Effectiveness monitoring typically involves some on-the-ground measurement of environmental variables affected by land use activities.

5.2.3. Validation Monitoring

Research within the adaptive management framework is often referred to as validation monitoring. In the context of land use regulations, the questions relate to how management of critical areas (e.g., riparian) affects the specific environmental resource it was intended to protect (e.g., water quality, salmon). Validation monitoring may be beyond the fiscal means of most local governments. Moreover, it often involves questions that must be addressed over large spatial extents (e.g., at watershed or multi-watershed scale). In comparison, implementation and effectiveness monitoring are often tied to local jurisdiction's regulatory processes at the site scale: For these reasons, the next two sections focus more on these two types of monitoring.

5.3. Recommended Implementation Monitoring Efforts

We advise local governments to focus first on using implementation monitoring to evaluate their regulatory processes that affect riparian ecosystems. Implementation monitoring tracks execution of the permitting system from the perspective of both the permit issuer (permittor) and permit holder (permittee) (Figure 5.2). This effort can result in regular status reports that help demonstrate how well local governments and permittees are working together to meet resource objectives in a fair and consistent manner.

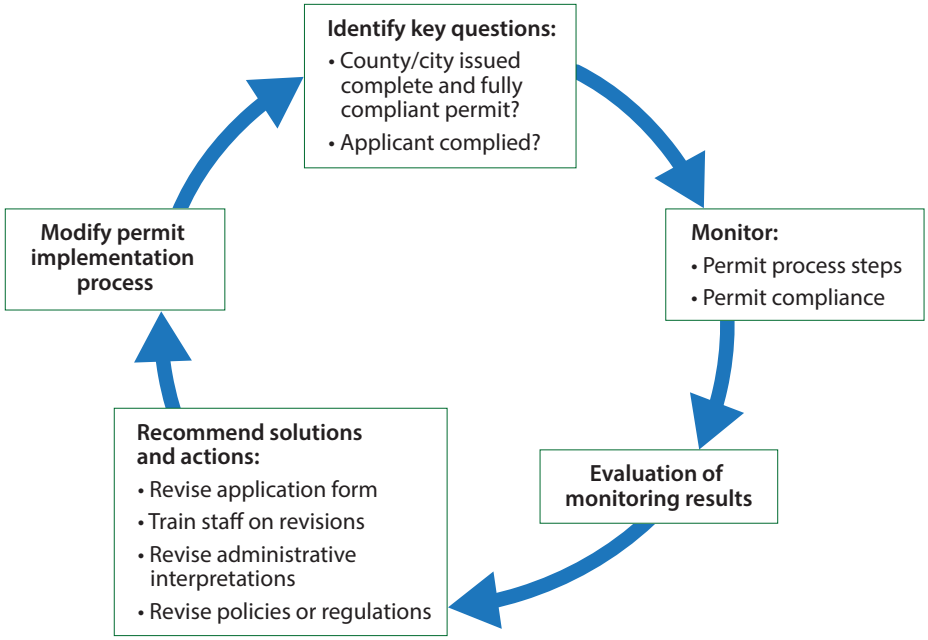


Figure 5.2. Depiction of the adaptive management cycle specific to permit compliance.

Implementation monitoring provides key information for permitting process improvement (5.2; Table 5.1). Even in situations where local governments cannot monitor all steps in their permitting process, monitoring any step—regulations to permit conditions/provisions, permit provisions to construction, construction to inspections, or inspections to enforcement—can provide valuable feedback about the quality of regulatory processes.

Monitoring does not have to be complicated. Even if a city or county chooses to do only permit implementation monitoring, this will provide key information that can improve the permit process, and an individual landowner can check whether choices like enhancing native plantings produce the desired results.

Table 5.1. Key questions for implementation monitoring during the Critical Areas permit review process.

Process Steps	Key study questions to evaluate permit implementation	Proposed metrics
Application	Was adequate information gathered from the permit applicant? Did the local government provide timely and necessary technical assistance to the permit applicant?	Number and percent of complete applications. i.e., include all information necessary to issue a permit. Number and percent by type of permit applications missing information.
Permit	Do permit provisions follow the local government code?	Number and percent of permit provisions by type consistent with code.
Permit	Do permit provision identify intent of protection and how it can be accomplished? (e.g., area of tree retention, distance of structure from stream, clearing, grading, or storm water provisions, replanting requirements, extent of impervious surface.)	Number and percent of (complete) permits (i.e., include all provisions that enable a permittee to be fully compliant with the permit). Number, percent, and type of missing provision/ information.
Permit (variance)	If a variance was granted, is the reason for the variance clearly stated?	Percent of variances by type justified by code or policy. Percent of permits with variances by type.
Permit (mitigation)	If compensatory mitigation was required, were the unavoidable impacts clearly identified/quantified? Was the rationale clearly stated?	Number and percent of permits by type with unavoidable impacts. Percent of permits by type with quantified mitigation requirements
Compliance	Post-Construction Visit: Did the permittee comply with the permit? (Requires field measurements of some or all the provisions in the permit. For riparian ecosystems, key provisions to inspect include RMZ width, retention of trees, replanting, structure distances from stream, area of impervious surface, and implementation of storm water provisions.)	Number and percent by type of provision that were out of compliance.
Enforcement	Are enforcement actions necessary to meet permit provisions and/or the regulations?	Number and percent by type of permit enforcement actions.

Because little or no fieldwork is required, the easiest and least expensive step to monitor is the link between regulations and permit provisions: that is, whether local land use regulations have been translated into permit provisions that can be understood easily by permittees. We recommend that some implementation monitoring become part of all local regulatory programs, even if it only on a relatively small subset of permits selected at random. A database for storing information on each step (i.e., a permit tracking system–see Table 5.1, Figure 5.3) is a critical tool for creating a complete system of accountability.

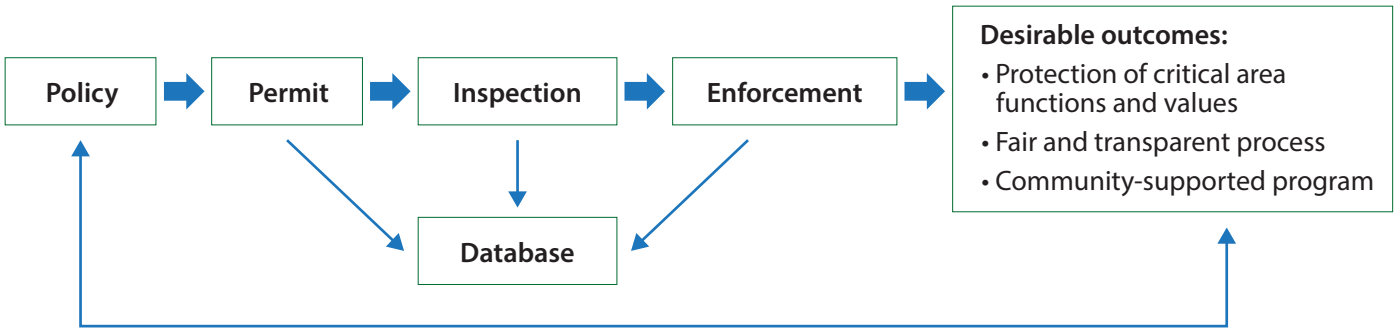


Figure 5.3. One system of permit accountability that includes implementation monitoring of internal permit processes, inspection for permit compliance, a database from which to judge outcomes, and a feedback loop connecting outcomes with policy intent.

Long-term implementation monitoring can help answer additional questions, such as: "Are rules/regulations intended to provide long-term protection of critical areas (e.g., RMZs) actually followed or maintained over time?" One way to answer this is by looking at changes in land cover, which describes the type and amount of vegetation, roads, and buildings occurring on the landscape. By comparing high quality aerial photographs taken of the same locations over time, change can be quantified and attributed to specific activities, both from natural disturbances (e.g., wildfires, river channel migration) and human activities (e.g., timber harvesting, residential subdivision construction, highway widening). In Section 5.5, we describe one such process WDFW developed and for which information for many parts of the state are already available.

5.4. Effectiveness of Regulatory Protections of Critical Areas

Where implementation monitoring has been successful, that is, either documenting a highly functional permitting process or improving poorly performing permitting process, we encourage additional effort on effectiveness monitoring. As described above, our primary goal for effectiveness monitoring would focus on understanding how well the permit conditions/provisions lead to measurable outcomes on the ground (e.g., protection/restoration of one or more riparian functions or values) over an extended period.

5.5. Using Land Cover Change to Understand Long-term Regulatory Protection

High Resolution Change Detection (HRCD) is a tool that is useful for detecting changes in two specific types of land cover (tree canopy and impervious surfaces) over set time periods. Land cover change analysis like HRCD can show jurisdictions the degree to which critical area regulations are maintaining RMZs as intended. This information can then help shape if, where, why, and how adjustments to permitting processes should occur. By combining land cover change analysis with targeted questions about permitting processes, jurisdictions can begin to adaptively manage changes to their overall regulatory system.

Adaptive Management Framework in the Voluntary Stewardship Program

The Voluntary Stewardship Program (VSP) was authorized by the Legislature in 2011 through RCW 36.70A.705. The goals of VSP are to protect and enhance critical areas where agricultural activities are conducted, maintain and improve the long-term viability of agriculture in the State of Washington, and reduce conversion of farmland to other uses. The program provides counties with an alternative approach from traditional development regulations that require protection (and encourage enhancement) of critical areas at the individual parcel scale. Instead, VSP relies upon voluntary practices and incentive programs to protect (and enhance) at a watershed scale. Counties "opted-in" to VSP, and as of 2019, 27 of the state's 39 counties are participating.

Under VSP, local workgroups created work plans that include benchmarks for protection and enhancement of critical areas designed to be achieved through voluntary and incentive-based actions. VSP requires monitoring and adaptive management to maintain and enhance critical areas, including riparian ecosystems, and directs workgroups to monitor at the watershed or sub-watershed scale. Key requirements for county-level programs include:

1. Establishing a durable system to track and report goals, benchmarks, and performance metrics.
2. Developing implementation and effectiveness monitoring programs and conducting monitoring on a pre-determined schedule.
3. Establishing an adaptive management program with (a) "triggers"; (b) subsequent actions to take; and (c) a process to review/update both the triggers and actions over time.
4. Reporting on the achievement of protection and enhancement goals and benchmarks at specified intervals.

Numerous counties have utilized WDFW's recommended VSP Adaptive Management Matrix in approved VSP Work Plans. Examples include:

- Chelan County, Appendix I (Approved April 2017)
- Grant County, Tables 5-7 through 5-10 (Approved June 2017)
- Asotin County, Tables 5-3 through 5-5 (Approved May 2018)
- Okanogan County, Chapter 6 (Approved September 2018)
- Spokane County, Section 4 (Approved November 2018)

Jurisdictions can adapt matrices as templates for connecting goals, benchmarks, performance metrics, monitoring, and adaptive management for other uses beyond VSP. These matrices can be modified as frameworks to identify specific elements of any adaptive management plan.

The example in the following section is adapted from Commerce's Critical Areas Handbook (Bonlender 2018). Chapter 7 of that document provides a number of similar monitoring program examples, nearly all of which were developed by cities or counties.

5.5.1. Example: WDFW/Thurston County Shoreline Master Program

In 2015, Thurston County and WDFW utilized a National Estuary Program grant to quantify shoreline vegetation, land cover change, and evaluate land use permit compliance. Specifically, Thurston County used WDFW's HRCD data to monitor compliance within the County's Shoreline Master Program (SMP) jurisdiction. This project developed a protocol manual for using HRCD for this purpose, available to all jurisdictions within the Puget Sound region.

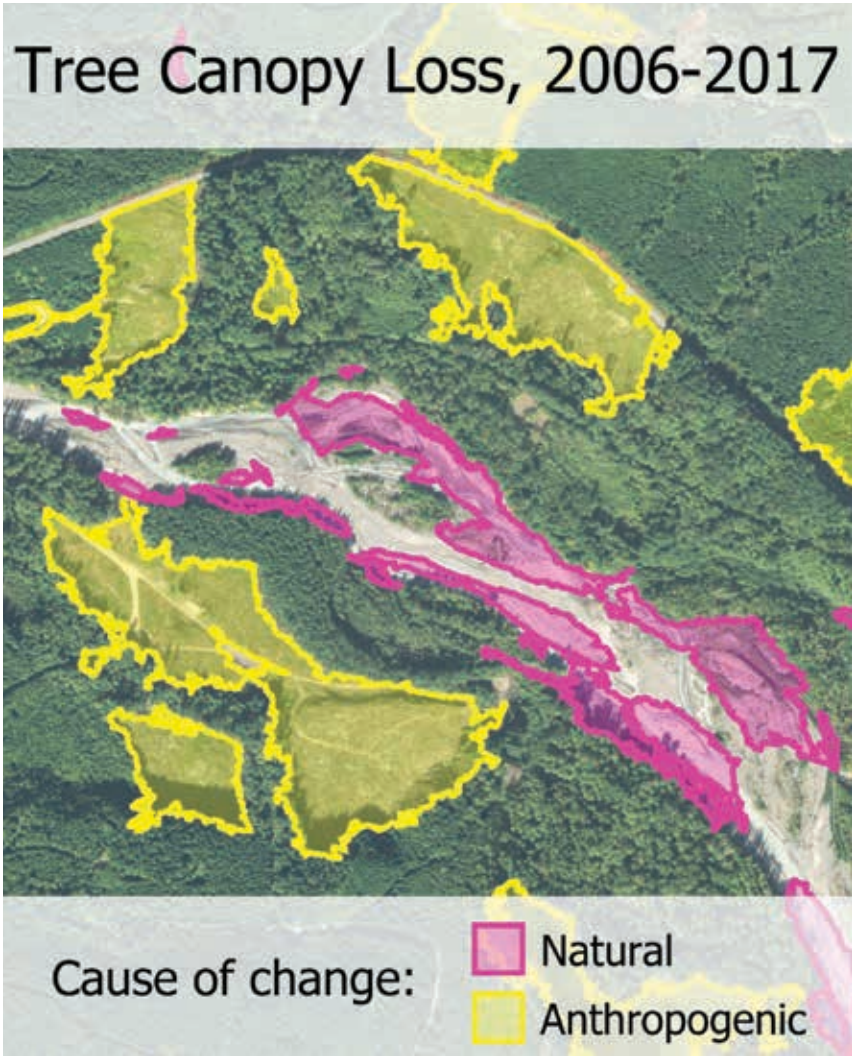
One goal of the pilot project was to answer several related sets of questions:

For Thurston County:

- What land cover change is happening within designated SMP areas? What change is happening throughout the Deschutes River watershed (WRIA 13)?
- How does change known by permit records compare with detected changes by HRCD?
- What changes, if any, can be made to the land use permits or permitting process that could increase the relevancy or efficacy in utilizing the HRCD in compliance monitoring?

For WDFW:

- How well can HRCD detect changes relative to land use permit records?
- Using Thurston County's SMP area as an example test area, what land cover changes are happening which HRCD is not capturing?
- With the development of a HRCD user manual, can HRCD be successfully utilized by other entities in the absence of direct assistance by WDFW?



High Resolution Change Detection (HRCD) analysis showing changes in tree canopy along and above a river in Thurston County. Pink polygons show where trees that existed prior to 2017 are no longer standing, apparently due to natural causes (e.g., where the river meandered). Yellow polygons show places where trees were removed as a result of timber harvesting./HRCD team, WDFW

The pilot quantified increases in impervious surfaces and decrease in tree canopy within marine areas of the SMP jurisdiction and checked for relevant permits issued. It consisted of five phases:

Phase 1: Initial SMP Change Analysis: Staff from WDFW's Habitat Program and the County's Long-Range Planning Department intersected the HRCD dataset with the County's SMP area and tax parcel data within ArcGIS for three time periods of HRCD availability (2006 to 2009, 2009 to 2011, and 2011 to 2013). Staff compared known areas of change to those locations with the county's land use permit records to find locations of observed change via HRCD without any permit record. During this phase, land cover change statistics were also produced, including total area of change and discrete occurrences of land cover change events.

Phase 2: Learning What the HRCD Misses: Using the SMP area in the County, WDFW staff manually looked for land cover changes not captured by the HRCD analysis, to understand how accurate HRCD was in capturing all land cover change situations (rates of omission error).

Phase 3: Developing a Standardized Method for Utilizing the HRCD: A major goal of this project was to develop support materials for others to be able to utilize HRCD to answer land use management questions independent of WDFW staff assistance. Using lessons learned in Phases 1 and 2, WDFW and the County agreed upon a recommended method for applying HRCD to a specific management question, and collaboratively developed a "how-to" manual. In this phase, WDFW staff also developed a web-based service (https://hrcd-wdfw.hub.arcgis.com) where users can download the HRCD dataset, detail the methodology of HRCD construction, find WDFW contact information, and more.

Phase 4: Testing the Manual through Remaining SMP Analysis in WRIA 13: Using only the HRCD dataset and the manual produced in Phase 3, County staff examined land cover change within the remaining SMP areas within WRIA 13 successfully for the same three time periods that HRCD data was available and utilized in the earlier phase.

Phase 5: Training and Outreach: With the lessons learned and products derived from Phases 1 through 4 of the project, staff worked in conjunction with the Coastal Training Program, managed by Ecology, to develop and deliver a workshop for planning staff within other state agencies, local governments, and some non-governmental organizations. WDFW also used this opportunity to train internal staff on the benefits, limitations, and uses of HRCD.

The evaluators analyzed land cover change within Thurston County's SMP area between 2006 and 2013, pulling permit records from timeframes that corresponded with the available HRCD datasets. The project's findings were very helpful, not only because of the information collected, but also in providing proof of concept for several of the steps/tools. For example: The utility of HRCD in analyzing patterns of land cover change in a specific geographic area of concern were well demonstrated. The HRCD analysis found that, from 2006 to 2013, less than half of one percent (0.39%) of the riparian area contained within the SMP had land cover change – approximately two-thirds of this was due to canopy loss, with one-third due to new impervious surfaces. The HRCD analysis did not find any permitted developments that were out of compliance, though it did find unpermitted events (e.g., tree removal) in each time period studied.

Furthermore, the HRCD dataset proved to be relatively simple to use. With the development of standard application methods, Thurston County was able to complete an analysis of their remaining SMP area without any further assistance from WDFW.

On the flip side, Thurston County found that comparing actual permit compliance with HRCD data was "tedious and difficult" because of limitations with the county's permit tracking database. For example, in many cases, land use permits did not include enough information to determine conclusively that a parcel with observed change via HRCD was out of compliance or determine that the parcel had a permit record during the study's timeframe in question.

Local governments can use HRCD analysis at the start to find land cover changes that are otherwise unknown; as they begin to understand patterns, HRCD analysis provides indications to identify locations that warrant closer investigation through other methods.

5.6. Conclusion

Implementation and effectiveness monitoring are important parts of adaptive management and can be undertaken relatively easily by local governments. Many of our riparian ecosystems are already degraded and stressed, so it is worth our while to investigate whether the actions put in place to protect them are being carried out as required and leading to the specific environmental responses that were intended. This is now more important than ever, because in spite of advances in science and efforts to improve regulatory processes, climate change and population pressures are increasingly confronting many parts of the state. Using monitoring and adaptive management to track successes and failures and then learning from both will make our challenges easier to overcome.



To install the lawn seen on the right of this photo, all vegetation was removed from the riparian area except a single row of cottonwood trees at the water's edge./Jennifer Nelson, WDFW

Literature Cited

Volume 1 serves as the primary source and citation for this document:

Quinn, T., G. Wilhere, and K. Krueger (managing editors). 2020. Riparian Ecosystems, Volume 1: Science Synthesis and Management Implications. Habitat Program, Washington Department of Fish and Wildlife, Olympia, Washington.

Anderson, P.S., S. Meyer, P. Olson, and E. Stockdale. 2016. Determining the ordinary high water mark for Shoreline Management Act compliance in Washington State. Publication No. 16-06-029. Washington State Department of Ecology, Olympia, Washington. (https://fortress.wa.gov/ecy/publications/documents/1606029.pdf)

Arid Lands Initiative. 2014. The Arid Lands Initiative: shared priorities for conservation at a landscape scale. Summary prepared by S.A. Hall and the Arid Lands Initiative Core Team. SAH Ecologia LLC, Wenatchee, Washington. Available at (https://www.sciencebase.gov/catalog/file/get/546d0a6ae4b0fc7976bf1db0?f=__disk__ab%2Fd6%2F7d%2Fabd67df8a73f48f87922d184ffec6e9b8dac635c)

Ashcroft, M.B. 2010. Identifying refugia from climate change. Journal of Biogeography 37:1407-1413.

Azerrad, J., J. Carleton, J. Davis, T. Quinn, C. Sato, M. Tirhi, G. Wilhere, and S. Tomassi. 2009. Landscape planning for Washington's wildlife: managing for biodiversity in developing areas. Habitat Program, Washington Department of Fish and Wildlife. Olympia, Washington. (https://wdfw.wa.gov/publications/00023)

Ballash, H. 2016. Building cities in the rain. Washington State Department of Commerce. Olympia, Washington. (https://www.ezview.wa.gov/site/alias__1780/overview/34828/overview.aspx)

Barnard, R. J., J. Johnson, P. Brooks, K. M. Bates, B. Heiner, J. P. Klavas, D.C. Ponder, P.D. Smith, and P. D. Powers. 2013. Water crossings design guidelines. Habitat Program, Washington Department of Fish and Wildlife, Olympia, Washington. (https://wdfw.wa.gov/publications/01501)

Bermingham, B., C. Douglas, B. Floyd, D. Koellmann, P. Mugunthan, and J. Small. 2013. Final draft semi-arid riparian functions and associated regulatory protections to support shoreline master program updates. Anchor QEA LLC., Kennewick, Washington.

Bonlender, B. 2018. Critical area handbook: A handbook for reviewing critical areas regulation. Washington State Department of Commerce, Olympia, Washington. (https://www.commerce.wa.gov/serving-communities/growth-management/growth-management-topics/critical-areas/)

Bormann, B.T., P.G. Cunningham, M.H. Brookes, V.W. Manning, and M.W. Collopy. 1994. Adaptive ecosystem management in the Pacific Northwest. PNW-GTR-341. U.S. Forest Service, Pacific Northwest Research Station, Portland, Oregon.

BLM (Bureau of Land Management). 2015. Riparian area management: proper functioning condition assessment for lotic areas. Technical Reference 1737-15. BLM, National Operations Center, Denver, Colorado.

City of Redmond. 2013. City of Redmond, Washington citywide watershed management plan. Prepared by Herrera Environmental Consultants, Inc. Seattle, Washington. (https://www.redmond.gov/DocumentCenter/View/11707/Watershed-Management-Plan-2013-PDF)

Cordell, H. K., D. Murphy, K.H. Ritters, and J.E. Harvard III. 2005. The natural ecological value of wilderness. Pages 205-249 in H.K. Cordell, J.C. Bergstrom, J. M. Bowker (editors). The Multiple Values of Wilderness. Venture Publishing, State College, Pennsylvania.

Cramer, M.L. (managing editor). 2012. Stream habitat restoration guidelines. Co-published by the Washington Departments of Fish and Wildlife, Natural Resources, Transportation, and Ecology, Washington State Recreation and Conservation Office, Puget Sound Partnership, and the U.S. Fish and Wildlife Service, Olympia, Washington.

Cramer, M., K. Bates, D. Miller, K. Boyd, L. Fortherby, P. Skidmore, and T. Hoitsma. 2002. Integrated streambank protection guidelines. Washington Department of Fish and Wildlife, Olympia, Washington. (https://wdfw.wa.gov/publications/00046)

DNR (Washington Department of Natural Resources). 2004. Forest Practices Board Manual, Section M2: standard methods for identifying bankfull channel features and channel migration zones. DNR, Forest Practices Division, Olympia, Washington. (https://www.dnr.wa.gov/publications/fp_board_manual.pdf?amcgpv)

EnviroVision, Herrera Environmental, and Aquatic Habitat Guidelines Working Group. 2010. Protecting nearshore habitat and functions in Puget Sound, revised edition. Washington State Department of Fish and Wildlife, Olympia, Washington. (https://wdfw.wa.gov/publications/00047)

Fetherston, K.L., R.J. Naiman, and R.E. Bilby. 1995; Large woody debris, physical process, and riparian forest succession in montane river networks of the Pacific Northwest. Geomorphology 13:133-144.

Fox, M.J. 2003. Spatial organization, position, and source characteristics of large woody debris in 2485 natural systems. Ph.D. Dissertation. University of Washington, Seattle, Washington.

Harris, R.R. 1987. Occurrence of vegetation on geomorphic surfaces in the active floodplain of a California alluvial stream. American Midland Naturalist 118:393-405.

Hilty, J.A., and A.M. Merenlender. 2004. Use of riparian corridors and vineyards by mammalian predators in northern California. Conservation Biology 18:126-135.

Johannessen, J., A. MacLennan, A. Blue, J. Waggoner, S. Williams, W. Gerstel, R. Barnard, R. Carman, and H. Shipman. 2014. Marine shoreline design guidelines. Washington Department of Fish and Wildlife, Olympia, Washington. (https://wdfw.wa.gov/publications/01583)

Johnson, D.H., and T.A. O'Neil. 2001. Wildlife Habitat Relationships in Oregon and Washington. Oregon State University Press, Corvallis, Oregon.

Keppel, G., K.P. Van Niel, G.W. Wardell-Johnson, C.J. Yates, M. Byrne, L. Mucina, A.G.T. Schut, S.D. Hopper, and S.E. Franklin. 2012. Refugia: identifying and understanding safe havens for biodiversity under climate change. Global Ecology and Biogeography 21:393-404.

Knight, K. 2009. Land use planning for salmon, steelhead and trout: a land use planner's guide to salmonid habitat protection and recovery. Habitat Program, Washington Department of Fish and Wildlife, Olympia, Washington. (https://wdfw.wa.gov/publications/00033)

Knutson, K.L., and V.L. Naef. 1997. Management recommendations for Washington's Priority Habitats: riparian. Habitat Program, Washington Department of Fish and Wildlife, Olympia, Washington. (https://wdfw.wa.gov/publications/00029)

Krosby, M., D.M. Theobald, R. Norheim, and B.H. McRae. 2018. Identifying riparian climate corridors to inform climate adaptation planning. PLOS ONE 13(11): e0205156.

Lacy, R.C., Williams, R., Ashe, E., Balcomb III, K.C., Brent, L.J., Clark, C.W., Croft, D.P., Giles, D.A., MacDuffee, M. and Paquet, P.C. (2017). Evaluating anthropogenic threats to endangered killer whales to inform effective recovery plans. Scientific reports, 7(1), 1-12.

Legg, N.T., and P.L. Olson. 2015. Screening tools for identifying migrating stream channels in western Washington – geospatial data layers and visual assessments. Publication No. 15-06-003. Washington State Department of Ecology, Olympia, Washington. (https://fortress.wa.gov/ecy/publications/documents/1506003.pdf)

Legg, N.T., and P.L. Olson. 2014. Channel migration processes and patterns in western Washington: A synthesis for floodplain management and restoration. Publication No. 14-06-028. Washington State Department of Ecology, Olympia, Washington. (https://fortress.wa.gov/ecy/publications/documents/1406028.pdf)

Lichvar, R.W., N.C. Melvin, M.L Butterwick, and W.N Kirchner. 2012. National wetland plant list indicator rating definitions. ERCD/CRREL TN-12-1. U.S. Army Corps of Engineers, Washington, D.C.

Murray, C.C., Hannah, L.C., Doniol-Valcroze, T., Wright, B., Stredulinsky, E., Locke, A., and R. Lacy. (2019). Cumulative Effects Assessment for Northern and Southern Resident Killer Whale Populations in the Northeast Pacific. Department of Fisheries and Oceans, Canadian Scientific Advisory Research Document 2019/056. x. + 88 pp.

Naiman, R. J., and R. E. Bilby. 1998. (editors) River ecology and management: lessons from the Pacific Coastal Ecoregion. Springer Science & Business Media, New York.

Naiman, R.J., H. Decamps, and M. Pollock. 1993. The role of riparian corridors in maintaining regional biodiversity. Ecological Applications 3:209-212.

Nordland, B., and K. Bates. 2000. Draft fish protection and screen guidelines for Washington State. Habitat Program, Washington Department of Fish and Wildlife, Olympia, Washington. (https://wdfw.wa.gov/publications/00050)

NRC (National Research Council). 2002. Riparian areas: functions and strategies for management. The National Academies Press, Washington, D.C. https://doi.org/10.17226/10327.

Olson, P. L., N. T. Legg, T. B. Abbe, M. A. Reinhart, and J. K. Radloff. 2014. A methodology for delineating planning-level channel migration zones. Publication No. 14-06-025. Washington State Department of Ecology, Olympia, Washington. (https://fortress.wa.gov/ecy/publications/documents/1406025.pdf)

Patten, D.T. 1998. Riparian ecosystems of semi-arid North America: diversity and human impacts. Wetlands 18:498-512. https://doi.org/10.1007/BF03161668.

Puget Sound Partnership. 2020. Puget Sound Vital Signs. Available: https://www.psp.wa.gov/evaluating-vital-signs.php (December 2020).

Quinn, T., et al. 1998. Habitat Associations of the riparian-dependent amphibian, reptile, mammals, and mollusks in commercial forest lands of Washington State: a report to the Timber, Fish & Wildlife policy committee. Washington Department of Natural Resources, Olympia, Washington.

Rapp, C.F., and T.B. Abbe. 2003. A framework for delineating channel migration zones. Publication No. 03-06-027. Washington State Department of Ecology, Olympia, Washington. (https://fortress.wa.gov/ecy/publications/documents/0306027.pdf)

RCO (Recreation and Conservation Office). 2019. State of Salmon. RCO, Olympia, Washington. https://stateofsalmon.wa.gov/exec-summary/ Retrieved July 23, 2019.

Richardson, J.S., R.J. Naiman, F.J. Swanson, and D.E. Hibbs. 2005. Riparian communities associated with Pacific Northwest headwater streams: assemblages, processes, and uniqueness. Journal of American Water Resources Association 41:935-947.

Rogers, L.E, R.E. Fitzner, L.L. Cadwell, and B.E. Vaughan. 1988. Terrestrial animal habitats and population responses. Pages 182-257 in W.H. Rickard, L.E. Rogers, B.E. Vaughan, and S.F. Liebetrau (editors). Shrub-steppe: balance and change in a semi-arid terrestrial ecosystem. Elsevier, New York.

Rosgen, D.L. 1996. Applied river morphology: Second edition. Wildland Hydrology Books, Fort Collins, Colorado.

Seavy, N.E., T. Gardali, G.H. Golet, F.T. Griggs, C.A. Howell, R. Kelsey, S.L. Small, J.H. Viers, and J.F. Weigand. 2009. Why climate change makes riparian restoration more important than ever: recommendations for practice and research. Ecological Restoration 27:330-338.

Shared Strategy Development Committee. 2007. Puget Sound salmon recovery plan. Shared Strategy for Puget Sound, Seattle, Washington.

Smith, D. 2005. Off-channel habitat inventory and assessment for the upper Skagit River basin. Report to non-flow coordinating committee of the Skagit River Hydroelectric Project (FERC No. 553). Skagit River System Cooperative, La Conner, Washington.

Thomas, F.M. 2014. Ecology of phreatophytes. Progress in Botany 75:335-375.

Thomas, J.W. (technical editor]). 1979. Wildlife Habitats in Managed Forests: The Blue Mountains of Oregon and Washington. Agriculture Handbook No. 553. U.S. Forest Service, Washington, D.C. (https://www.srs.fs.usda.gov/pubs/gtr/uncaptured/gtr_pnw080.pdf)

Thomas, J.W., J.F. Franklin, J. Gordon, and K.N. Johnson. 2006. The Northwest Forest Plan: Origins, components, implementation experience and suggestions for change. Conservation Biology 20:277-87.

USFS (U.S. Forest Service). 2008. Stream simulation: an ecological approach to providing passage for aquatic organisms at road-crossings. National Technology and Development Program, San Dimas, California.

USFS (U.S. Forest Service). 2001. Selway and Middle Fork Clearwater Rivers Subbasin Assessment. Nez Perce, Clearwater, and Bitterroot National Forests, Idaho. Retrieved August 26, 2019.

Vander Haegen, M.W. 2007. Fragmentation by agriculture influences reproductive success of birds in a shrub-steppe landscape. Ecological Applications 17: 934-947.

Ward, J.V., and J.A. Stanford. 1995. Ecological connectivity in alluvial river ecosystems and its disruption by flow regulation. Regulated Rivers: Research & Management 11:105-119.

Washington Sea Grant. 2009. Protection of marine riparian functions in Puget Sound, Washington. Washington Department of Fish and Wildlife, Olympia, Washington. (https://wdfw.wa.gov/publications/00693)

WDFW (Washington Department of Fish and Wildlife). 2005. Washington's comprehensive wildlife conservation strategy, final draft. WDFW, Olympia, Washington.

WDFW (Washington Department of Fish and Wildlife). 2016. Your marine waterfront: A guide to protecting your property while promoting healthy shorelines. WDFW, Olympia, Washington. (https://wdfw.wa.gov/publications/01791)

Williams, P.B., E. Andrews, J.J. Opperman, S. Bozkurt, and P.B. Moyle. 2009. Quantifying activated floodplains on a lowland regulated river: its application to floodplain restoration in the Sacramento Valley. San Francisco Estuary and Watershed Science 7(1).

Wolman, M.G., and L.B Leopold. 1957. River flood plains: some observations on their formation. Geological Survey Professional Paper 282-C. U.S. Government Printing Office, Washington, D.C.



Riparian area below the south slope of Mt. St. Helens. The area is still recovering from the mountain's volcanic eruption in May 1980. Skamania County/Brendan O'Doherty

Glossary of Terms

Active channel: The active channel is defined by the lower limit of continuous riparian vegetation (Naiman et al. 1998) and may be delineated by absence of both moss on rocks and rooted vegetation (USFS 2008). The upper most elevation of the active channel is sometimes equated with the ordinary high-water mark.

Active floodplain: Located between the active channel and adjacent terrace or hillslopes (Fetherston et al. 1995; Harris 1987). Depending on the watershed, the flood return interval of the active floodplain varies between 1 and 10 years (Wolman and Leopold 1957; Ward and Stanford 1995; Lichvar et al. 2006; Williams et al. 2009; BLM 2015).

Adaptive management: The systematic acquisition and application of reliable information to improve management over time. It often includes treating management decisions as experiments in order to address critical uncertainties and learn more quickly from experience. It involves setting objectives, monitoring conditions, and adjusting management based on results. Hallmarks of a sound adaptive management program include: (1) adequate funding for monitoring and research, (2) a willingness to change course when pre-established triggers are reached, and (3) a commitment to gather data and evaluate conditions at appropriate spatial extents and time scales. See Ecosystem-based management and WAC 365-195-920(2).

Anadromous fisheries: The commercial, recreational or subsistence harvest of fish that are born in freshwater, rear at sea, and return to freshwater to spawn. Anadromous fisheries of Washington include salmon (Chinook, coho, chum, sockeye, and pink), steelhead, bull trout, coastal cutthroat trout, green sturgeon, white sturgeon, eulachon, longfin smelt, and Pacific lamprey.

Aquatic species: Wildlife species that live in marine or freshwater including fish, shellfish (e.g., clams, snails, mussels), amphibians (e.g., frogs, salamanders), reptiles (e.g., turtles), crustaceans (e.g., crayfish), insects (e.g., larval mayflies, stoneflies, caddisflies, dragonflies) and various other invertebrates.

Best Available Science: Information produced through a valid scientific process that WDFW or another local, state or federal agency has determined represents the best available science consistent with criteria set out in WAC 365-195-900 through 365-195-925. (Volume 1 of this document is an example of Best Available Science regarding riparian ecosystems.)

Biota: The animal and plant life of a region, habitat, or geological period.

Buffer: The area around a critical area that separates the critical area from incompatible uses. For example, a 200m buffer may be established around a heron-nesting colony (the critical area) to keep suburban land uses from disrupting the colony. See WAC 365-190-130(3)(a). Riparian ecosystems are both buffers (for instream habitat) and critical areas on their own merit.

Channel Migration Zone: The area within which a river channel is likely to migrate and occupy over a specified time period (e.g., 100 years).

Channel slope or gradient: The average steepness of a stream segment measured as its change in elevation divided by its length. Typically, a segment's gradient is considered low if less than 2%, moderate between 2% and 4%, and high if greater than 4%.

Classification (critical area): Defining categories to which critical areas are assigned. The Priority Habitats and Species (PHS) program provides WDFW's recommended classification scheme for Fish and Wildlife Habitat Conservation Areas. Classification precedes designation in counties' and cities' effort to protect critical areas. *See* WAC 365-190-040(4).

Complexity: The complicated state seen in dynamic environments that contain multiple components and processes that interact with one another in a web of interactions whose outcomes are often unpredictable. Complexity can be described with conceptual models; outcomes of well-understood complex phenomena can be partially predicted using computer models.

Connectivity: Landscape connectivity is the physical relationship between landscape elements. Functional connectivity describes the degree to which landscapes facilitate or impede the movement of organisms between areas of habitat.

Critical Aquifer Recharge Area: Areas with an essential recharging effect on aquifers used for potable water. One of five types of Critical Areas identified in the Growth Management Act.

Critical Area(s): Places that the Growth Management Act requires all counties and cities to designate and protect, specifically, (1) Wetlands; (2) Critical Aquifer Recharge Areas; (3) Fish and Wildlife Habitat Conservation Areas (e.g., Riparian Management Zones); (4) Frequently Flooded Areas; and (5) Geologically Hazardous Areas. In developing policies and regulations to protect the functions and values of critical areas, counties and cities are required to include best available science and give special consideration to conservation or protection measures necessary to preserve or enhance anadromous fisheries. *See* RCW 36.70A.172(1). The presence of a critical area may limit some land development options. *See* WAC 365-190-040(6).

Delineation (critical area): The act of applying definitions or performance standards in the field to identify the boundary of a critical area.

Designation (critical area): Assigning critical areas into established categories and specifying their general distribution, location, and extent. Designation can be made by maps (which are useful for public awareness and for identifying if a proposal may affect a critical area) and by performance standards or definitions (which allow for specific identification and site-scale delineation during permit review). WDFW's Priority Habitats and Species (PHS) program provides the agency's recommended designation maps and performance standards/definitions for Fish and Wildlife Habitat Conservation Areas. Designation occurs after classification in counties' and cities' efforts to protect critical areas. *See* WAC 365-190-040(5).

Disturbance regime: The frequency, magnitude, and duration of disturbance events.

Disturbance: A pronounced, temporary change in environmental conditions within an ecosystem. Disturbances often act quickly and can alter ecosystem composition, structure, and function.

Ecological (biological) **integrity:** Ability of an ecological system to support and maintain a community of organism that has species composition, diversity, and functional organization comparable to those of natural habitats within a region. An ecological system has integrity when its dominant ecological characteristics (composition, structure, function, and processes) occur within their historical ranges of natural variability. See Historical condition and Range of natural variability.

Ecosystem(s): A spatially explicit unit of the Earth that includes all the organisms, along with all components of the abiotic (chemical and physical) environment. Ecosystems have composition, structure, and functions.

Ecosystem composition (or ecological composition): All living (biotic) and nonliving parts of an ecosystem.

Ecosystem function(ing) (or ecological function): (1) The process or cause and effect relationship underlying two or more interacting components, e.g., terrestrial plant material as food/substrate for aquatic invertebrates. (2) The sum of processes that sustain the system. (3) The capacity of natural processes and components to provide goods and services that satisfy human needs, either directly or indirectly. Ecosystem functions can be conceived as a subset of ecological processes (See *Ecosystem process*).

Ecosystem process (or ecological process): Interactions among components of an ecosystem, biotic (living organisms) and abiotic (chemical and physical) components. Many processes involve transfer, conversion, or storage of matter or energy (See *Ecosystem process*).

Ecosystem structure (or ecological structure): The arrangement of and relations among the parts or elements (components) of an ecosystem.

Ecosystem-based management (EBM): Management driven by explicit goals; executed by policies, protocols, and practices; and made adaptable by monitoring and research; based on our best understanding of the ecological interactions and processes necessary to sustain ecosystem composition, structure, and function. EBM acknowledges that humans are an important ecosystem component and focuses on managing human activities within ecosystems. EBM often involves balancing ecological, economic, and social objectives within the context of existing laws and policies.

Enhance: To improve a critical area's existing ecosystem processes, structure, and/or functions so that its ecological integrity is more like its historical condition.

Erosion: The loosening and transport of soil particles and other sediment by water. Terrestrial erosion includes raindrop splash erosion, overland flow sheet erosion, surface flow rill (shallow) and gully (deeper) erosion. Channel erosion includes streambank erosion and channel incision (gouging). Rill and gully erosion diminish the ability of the riparian area to trap sediment and pollutants and can often be avoided with intact riparian vegetation.

Fish and Wildlife Habitat Conservation Areas (FWHCA): A type of Critical Area specified in the Growth Management Act. The intent of FWHCAs are to maintain populations of species in suitable habitats within their natural geographic distribution so that (1) the habitat available is sufficient to support viable populations over the long term, and (2)

isolated subpopulations are not created. FWHCAs come in a variety of types including waters of the state, places with which listed species have a primary association, habitats and species of local importance, and riparian ecosystems. See WAC 365-190-130.

Flow regime (stream): The distribution of stream flow through space and time. Flow regimes can be described by their magnitude (e.g., mean annual, hourly maximum), timing, frequency or return periodicity, duration, spatial distribution, and rate of change. The pathways that water takes to reach a stream (e.g., surface runoff) and within a stream exert a strong influence on the flow regime.

Function: Physical, chemical, or biological processes that occur within an ecosystem. WAC 365-196-830 says, "Functions are the conditions and processes that support the ecosystem. Conditions and processes operate on varying geographic scales ranging from site-specific to watershed and even regional scales." See also *Ecosystem function(ing)* and *Ecosystem process.*

Habitat: The resources and conditions presented in an area that support the functional needs of a species (e.g., hiding, migration, resting, feeding, breeding, and rearing), and which are necessary for its survival and reproduction. Habitat is species-specific, scale dependent, and more than vegetation composition or structure.

Hazard Tree: A tree that a jurisdiction's building official or other recognized professional (e.g., certified arborist, registered landscape architect, or certified forester) has determined poses a near-term hazard to public safety or to an existing permanent structure or public utility.

Herbaceous: Non-woody plants such as grasses and ferns.

Historical condition: *See* Ecological integrity and Range of natural variability.

Hydrology: Description of the properties, distribution, movement, and storage of water on and below the Earth's surface.

Impervious surface: Ground surfaces that resist or prevent water infiltration, e.g., roofs of houses, roadways.

Imputed: Estimated; a value assigned to missing data by inference from the values of data within the same dataset.

Infiltration: The rate or process by which water on the ground enters the soil.

Instream: Within flowing freshwater; also, the area waterward of the Ordinary High-Water Mark.

Large Woody Debris: Large dead woody material (such as fallen trees and branches) in various stages of decomposition that provide nutrient capital to forest and aquatic resources and serve as habitat in forest and riparian ecosystems. Large wood is usually defined as having diameter greater than 4 in (10 cm) and length greater than 6 ft (≈ 2 m).

Low Impact Development (LID): A storm water and land-use management strategy that tries to mimic natural hydrologic conditions by emphasizing pre-disturbance hydrologic processes of infiltration, filtration, storage, evaporation, and transpiration.

Mitigation: General category of measures that a proponent may take to avoid, minimize, and compensate for impacts.

Mitigation sequence: The stepwise process of protecting a critical area through, first (1) avoiding harm to the critical area to the maximum extent practicable, then (2) minimizing unavoidable harm to the maximum extent practicable, and finally (3) providing compensation for all unavoidable harm by restoring, creating, enhancing, or preserving the critical area's ecological functions and values to replace those impacted or lost through permitted activities.

Monitoring: The process of observing and checking the progress or quality environmental conditions for the purposes of adaptive management. Often described as having three types – implementation, effectiveness, and validation.

Morphology (stream channel, aka fluvial geomorphology): A stream channel's shape and how it changes over time. Channel morphology is influenced by the abundance and variation in sediment sources, the ability of water to transport sediment downstream, and interactions of sediment with riparian vegetation and woody debris.

Off-Channel Habitat: Overflow channels, sloughs, alcoves, wetlands, and small streams found within the floodplains of larger river channels. Off-channel habitat consists of waters connected to and draining into rivers and streams by inundation during peak flow events (Smith 2005; WAC 222-16-031). Off-channel habitat provides habitat for salmonids and other aquatic species which often afford (1) spawning habitat that does not experience scouring high flows; and (2) summer rearing habitat that does not experience loss of stream flow.

Ordinary High Water Mark (OHWM): (1) That mark that will be found by examining the bed and banks and ascertaining where the presence and action of waters are so common and usual, and so long continued in all ordinary years, as to mark upon the soil a character distinct from that of the abutting upland (Washington Department of Ecology 2016). (2) That line on the shore established by the fluctuations of water and indicated by physical characteristics such as a clear, natural line impressed on the bank, shelving, changes in the character of soil, destruction of terrestrial vegetation, the presence of litter and debris, or other appropriate means that consider the characteristics of the surrounding areas (U.S. Army Corps of Engineers, 2014).

Organic litter: Plant, leaf, tree, or soil litter, and duff are dead plant materials that have fallen to the ground. In this document, organic litter is referenced as available for contributions to the stream system.

Passive Restoration: Allowing natural succession to occur in an ecosystem after removing a source of disturbance.

Population viability (local): The likelihood that a population of a species will persist for some length of time.

Precautionary principle: Erring on the side of not harming resources when faced with uncertainty, especially for potential harm that is essentially irreversible. Utilizing a precautionary approach in land use planning involves: (1) taking preventive action (avoiding impacts); (2) shifting the burden of proof to the project proponents; (3) exploring a wide range of potential alternatives; and/or (4) including multiple stakeholders and disciplines in decision making.

Priority Area: The area within a Priority Species' natural geographic distribution within which protective measures and/or management actions are needed to (1) support viable populations over the long term and (2) avoid creating isolated subpopulations.

Priority Habitat: A State of Washington habitat type with unique or significant value to many species; an area with one or more of the following attributes: (1) comparatively high fish and wildlife density; (2) comparatively high species diversity; (3) important breeding habitat; (4) important seasonal ranges; (5) important movement corridors; (6) limited availability; (7) high vulnerability to habitat alteration; or (8) unique or dependent species. Examples of Priority Habitats include but are not limited to instream, riparian, shrub steppe, Oregon white oak woodlands, freshwater wetlands, and marine nearshore.

Priority Habitats & Species (PHS): WDFW's primary means of transferring fish and wildlife information from resource experts to local governments, landowners, and others for the protection of fish, wildlife, and habitat. Includes endangered, threatened, sensitive, candidate, and vulnerable species and habitats deemed priorities of WDFW and reflective of best available science. See WAC 365-190-130.

Priority Species: A State of Washington fish or wildlife species requiring protective measures and/or management actions to ensure its survival. A Priority Species fits one or more of the following criteria: (1) is a state-listed endangered, threatened, sensitive, or candidate species, (2) has vulnerable aggregations, or (3) is of recreational, commercial, and/or tribal importance. Examples of Priority Species include but are not limited to steelhead/rainbow trout, bull trout/Dolly Varden, great blue heron, cavity-nesting ducks, sage grouse, fisher, orca, and elk.

Process: See *Ecosystem process.*

Protect: To prevent the degradation of existing ecosystem functions and values.

Range of natural variability (or Historical range of natural variability): Refers to the range of ecological conditions (components, structures and functions) in a time period before widespread anthropogenic changes.

Recruitment (wood): The process of wood moving from a riparian area to the stream channel. Sources of recruitment include bank erosion, windthrow, landslides, debris flows, snow avalanches, and tree mortality due to, for example, fire, ice storms, beavers, insects, or disease. Dominant factors include, but are not limited to, channel width, slope steepness, slope stability, forest composition and structure, and local wind patterns.

Refugia (singular Refugium): sites to which biota retreat, persist in and potentially expand from under changing environmental conditions (Keppel et al. 2012).

Riparian: An adjective meaning alongside a waterbody: stream, river, lake, pond, bay, sea, and ocean. Riparian areas are sometimes referred to by different names: riparian ecosystems, riparian habitats, riparian corridors, or riparian zones. Depending on the contexts, these terms may have somewhat different meanings.

Riparian area: A defined area encompassing both sides of a water body, composed of aquatic ecosystems (i.e., the river or stream), riparian ecosystem, and riverine wetlands. Riparian areas are three dimensional: longitudinal up and down streams, lateral to the width of the riparian ecosystem, and vertical from below the water table to above the canopy of mature site-potential trees (NRC 2002).

Riparian buffer: Buffer refers to its purpose, which is to reduce or prevent adverse impacts to water quality, fisheries, and aquatic biodiversity from human activities occurring upslope of the buffer. Riparian buffers managed specifically for pollutant removal may also be called a vegetated filter strip.

Riparian ecosystem: Riparian areas are transitional between terrestrial and aquatic ecosystems and distinguished by gradients in biophysical conditions, ecological processes, and biota. They are areas through which surface and subsurface hydrology connect waterbodies with their adjacent uplands. They include those portions of the ecosystem distinguished by gradients (i.e., riparian zones) and portions of terrestrial ecosystems that significantly influence exchanges of energy and matter with aquatic ecosystems (i.e., the Zone of Influence). Our definition of riparian ecosystem does not include adjacent waters (i.e., rivers or streams, but does include riverine wetlands) and recognizes the riparian zone as a distinctive area within riparian ecosystems.

Riparian Management Zone: A delineable area defined in a land use regulation; often synonymous with riparian buffer. For the purposes of this document, we define the RMZ as the area that has the potential to provide full riparian functions. In many forested regions of the state this area occurs within one 200-year site-potential tree height measured from the edge of the stream channel. In situations where a CMZ is present, this occurs within one site-potential tree height measured from the edges of the CMZ. In non-forest zones the RMZ is defined by the greater of the outermost point of the riparian vegetative community or the pollution removal function, at 100-feet.

Riparian values: The benefits that riparian ecosystems provide to society, including but not limited to flood damage reduction, water quality improvement, provision of harvestable populations of salmon, and provision of recreational opportunities. Riparian values have direct economic consequences to local communities through fishing opportunities, and flood and water quality protection, among others.

Riparian zone: A distinctive area within riparian ecosystems. The riparian zone contains wet or moist soils and plants adapted to growing conditions associated with periodically saturated soils. See *Riparian ecosystem.*

Risk: A situation involving exposure to danger, harm, or loss. Risk reflects the magnitude of the adverse impact and its probability of occurring. Risk is appropriately managed by applying the precautionary principle (especially for irreversible losses) and through adaptive management.

Salmonid: A family of fish comprised of salmon, trout and whitefish. Native salmonid species in Washington State include: Chinook Salmon (*Oncorhynchus tshawytscha*), Chum Salmon (*O. keta*), Coho Salmon (*O. kisutch*), Pink Salmon (*O. gorbuscha*), Sockeye Salmon/Kokanee (*O. nerka*), Steelhead/Rainbow Trout (*O. mykiss*), Cutthroat Trout (*O. clarki*), Bull Trout (*Salvelinus confluentus*), Dolly Varden (*S. malma*), Pygmy Whitefish (*Prosopium coulteri*), and Mountain Whitefish (*P. williamsoni*). This list does not include names of subspecies. (See *Anadromous* fisheries).

Site class: The classification of a site based on the productivity of its dominant tree species. Site classes vary based on local differences in soil nutrients and moisture, light and temperature regimes, and topography. Site classes are typically described as most productive (I) through least productive (V).

Site-Potential Tree Height: The average maximum height of the tallest dominant trees for a given age and site class.

Stronghold: Habitat strongholds are refugia watersheds that contain high quality habitat with depressed or weak populations. The habitat in these areas has a high to very high potential to support these species. The population level in these areas is not considered to be a function of habitat, but other factors (USFS2001).

Structure: See *Ecosystem structure.*

Succession: Ecological succession is the process by which the biological community composition recovers over time following a disturbance event.

Uncertainty (scientific): The absence of information about the state of something or a relevant variable. Sources of uncertainty include, but are not limited to natural variation (i.e., because outcomes vary in difficult-to-predict ways through time and space), model uncertainty (i.e., we do not understand how things interact with each other), systematic error (e.g., poorly designed experiments or calibrated instruments), or measurement error. See *Risk*.

Values: The level of benefits that the space, water, minerals, biota, and all other factors that make up a natural ecosystem provide to support native life forms, including humans (Cordell et al. 2005).

Vegetative filter strips: A riparian buffer designed to capture nutrients, contaminant compounds, and sediment transported by run-off. Filter strips are sometimes synonymous with riparian buffers.

Water quality: Physical, chemical, and biological characteristics of water that describe its suitability to meet human needs or habitat requirements for fish and wildlife.

Watershed processes: The fluxes of energy (e.g., sunlight, wildfire) and materials (particularly water and sediment) that interact with biota (e.g., vegetative cover, salmon, beavers, soil microbes) to form a watershed's physical features and characteristics, which give rise to its instream physical and ecological conditions. These processes occur within a context that reflects the watershed's climate, geology, topography, and existing human land use. See *Ecosystem process.*

Watershed: A land area that drains to a common waterbody.

Wetland: Those areas that are inundated or saturated by surface or ground water at a frequency and duration sufficient to support—and that under normal circumstances do support—a prevalence of vegetation typically adapted for life in saturated soil conditions. Examples include but are not limited to swamps, marshes, and bogs.

Zone of Influence: The portions of terrestrial ecosystems that significantly influence exchanges of energy (e.g., sunlight) and matter (e.g., large wood, sediment, nutrients) with aquatic ecosystems.

Appendix. Site-Potential Tree Height Mapping Tool

The Site-Potential Tree Height (SPTH) Mapping Tool helps users find information they need to conserve, protect, and restore riparian ecosystems within a project site. The SPTH mapping tool works on personal computers (PCs) and mobile devices (tablets and smartphones).

Site-Potential Tree Height Map Data

The SPTH mapping tool contains several GIS data layers, explained below:

1. Site-potential Tree Height at 200 Years ($SPTH_{200}$),
2. Imputed[14] $SPTH_{200}$ Values for Urban areas,
3. Dryland Ecosystems – No SPTH Values, and
4. Other Lands – No SPTH Values.

Site-potential Tree Height at 200 Years ($SPTH_{200}$)

WDFW derived the $SPTH_{200}$ values from forest productivity site index information using Natural Resource Conservation Service (NRCS) soil polygons and its Soil Data Viewer tool for ArcGIS. The NRCS-provided forest productivity site index values, in feet, were for ages 50 years in Western Washington and typically 100 years in Eastern Washington. WDFW determined $SPTH_{200}$ values using tree site index equations. Each soil polygon has one or more tree species records with associated $SPTH_{200}$. When multiple tree species records with associated $SPTH_{200}$ are available, WDFW recommends using the largest $SPTH_{200}$ value of the tree species historically present at the site (such trees may currently be found on the site, but also may not). For example, if a project site contains mostly red alder but Douglas-fir is present (or was present prior to modern human alterations), use the Douglas-fir $SPTH_{200}$ for that soil polygon.

Imputed $SPTH_{200}$ Values

Four large urban areas (Seattle, Spokane, Tacoma, and Bellingham) lacked NRCS soil polygons; therefore, forest productivity information could not be mapped for most locations within those areas. Similarly, numerous soil polygons labelled as "Urban Land" lacked forest productivity information. For each of these four urban areas, WDFW calculated an imputed $SPTH_{200}$ by using an area-weighted average for 200-year site index values within a two-mile buffer around the perimeter. WDFW recommends the use of this imputed $SPTH_{200}$ as a guide for delineating RMZs in these urban areas. At the time of publication, WDFW had calculated imputed $SPTH_{200}$ information for those large urban areas. WDFW expects to continue to update the map.

[14] Imputed: estimated; a value assigned to something by inference from the value of the products or processes to which it contributes.

Dryland Ecosystems and Other Lands

Not all soil polygons are forested, or have forest productivity information from NRCS; therefore, not all of them have associated $SPTH_{200}$ values. In addition, Benton, Franklin, Grant, and Adams counties had no forest productivity information in their NRCS soil polygons. These areas without $SPTH_{200}$ values were classified in one of two ways: as "dryland ecosystems", or "other lands."

- WDFW approximated the area contained within "dryland ecosystems" using the Arid Lands Initiative study area boundary (Arid Lands Initiative, 2014) and have developed associated process steps that we recommend be used to derive RMZ widths (Volume 2, Section 2.2.3).

- The "other lands" comprise the remaining soil polygons and are small and dispersed across the landscape. These polygons include the NRCS soil map unit name, if applicable, and often represent soils that do not support tree growth, such as beaches and wetlands, as well as certain types of heavily modified sites like gravel pits. Please consult with a WDFW regional habitat biologist on deriving RMZs for "other lands" and consider following a similar process for delineation in dryland ecosystems.

Using the Site-Potential Tree Height Mapping Tool

The mapping tool can be accessed from several locations:

- WDFW website (https://wdfw.wa.gov/species-habitats/at-risk/phs/recommendations),
- Washington Geospatial Open Data Portal (http://geo.wa.gov/), and
- ArcGIS Online (AGOL) (https://wdfw.maps.arcgis.com/apps/MapSeries/index.html?appid=919ea98204eb4f5fa70eca99cd5b0de1).

The mapping tool consists of the statewide map with the four riparian datasets described above; user tools; and a sidebar explaining map contents, how to use the map, and links to supporting documents.

The four riparian datasets have unique colors indicating where the information occurs.

- **Green:** Area where $SPTH_{200}$ has been calculated.
- **Orange:** Areas where $SPTH_{200}$ values have been imputed.
- **Pale brown:** Dryland ecosystems where there is no tree height information.
- **Beige:** Places for which no SPTH site index information is available.

Tribal and publicly owned/managed lands federal and tribal lands are typically subject to different riparian regulations. Tribal, federal, and state lands are displayed in shades of grey. County-owned lands are shown in lavender, and city-owned lands are light blue.

The mapping tool contains the following tools (Figure A1):

- **Zoom slider:** zoom in or out on the center of the map.
- **Address search tool:** zooms to a street address, place name, or latitude and longitude.
- **Legend:** displays the map layers currently visible. For example, map layers displayed at a site-specific scale will not appear in the legend when zoomed out to the statewide extent.
- **Home icon:** resets map to statewide extent.
- **Target icon:** allows the user to zoom directly to their current location.
- **Measurement tool:** use this to measure the distance between objects (e.g. edge of stream to another point), or to measure an area (square feet of an area surrounding a project site).
- **Basemap selector:** change the basemap to show a different view of the landscape: aerial imagery (default), topographic map, open street map, terrain with labels, and USGS national map.
- **Scale bar:** shows the scale that the map is zoomed to. At a statewide extent, the scale bar will show 0 to 60 miles. When zoomed to a scale where you can view the project area, the scale bar will show 0 to 100 feet or 200 feet.
- **Coordinates:** latitude and longitude (decimal degrees) are shown where the cursor is located on the map.
- **Panning:** move the map by placing the cursor over a desired location and dragging it to the center of the map display.

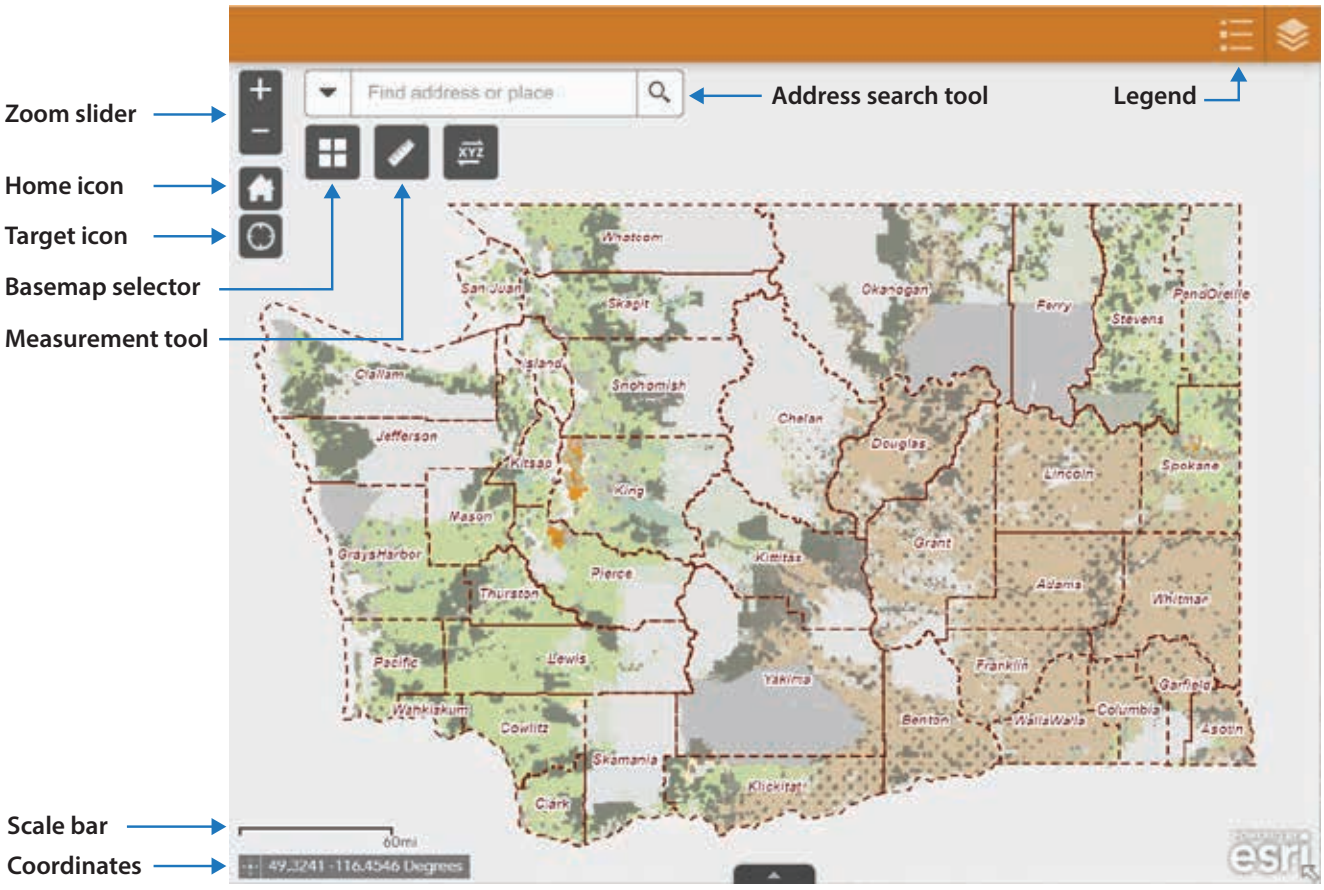


Figure A1. Tools available on the SPTH200 and RMZ Online Map.

To zoom to a site location, use the Address Search tool or use a combination of the Zoom Slider and panning. (If using the Address Search tool, select the "ArcGIS World Geocoding Service" from the dropdown menu to the left of the search field for faster results.) Once the site is located, a click (on PCs) or tap (on mobile devices) of the cursor will open a popup window with information about that location. Be sure to review each window if multiple records are selected.

The NRCS soil polygons form a complex mosaic across the landscape, so you must zoom in close enough to clearly see your project site. Clicking (or tapping, on mobile devices) on the map when it is zoomed out will result in erroneous returns of the $SPTH_{200}$ values. Below is an example of using these tools to obtain riparian information at a project site.

Mapping Tool Example #1

1. Start up the Online Map.

2. Type the project location into the Address Search tool (Figure A2). If the address is unknown, use a nearby place name or latitude and longitude. This example uses 16018 Mill Creek Boulevard, Mill Creek, Washington.

3. Select the correct address from the drop-down menu or continue to enter manually. Click (on a **PC**) or tap (on a **mobile device**) the search button. The map will zoom to that location, shown as a small blue box and a popup titled "Search result" (Figure A3).

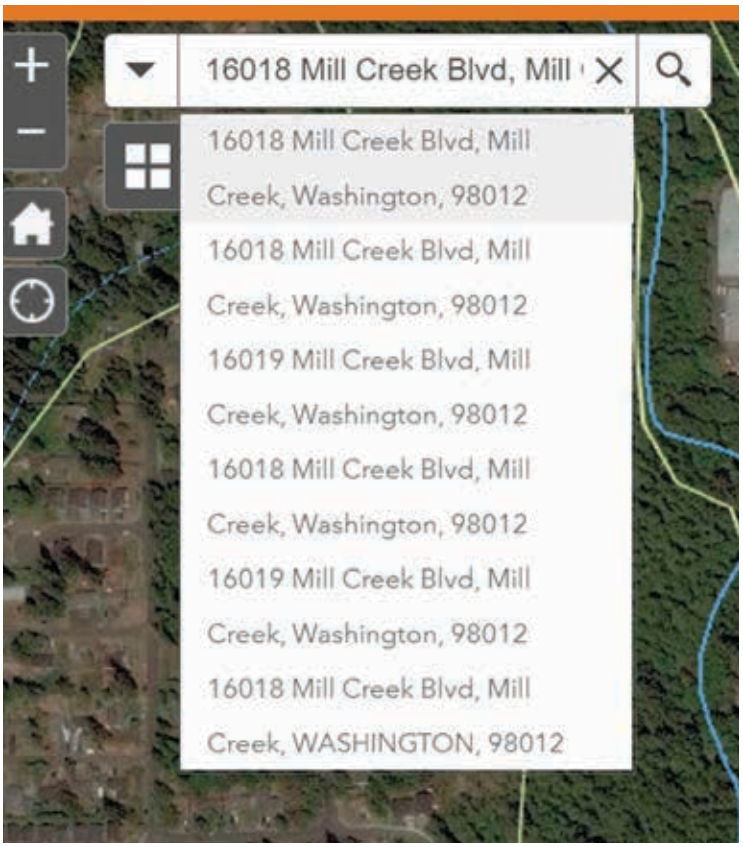


Figure A2. Using the Address Search tool.

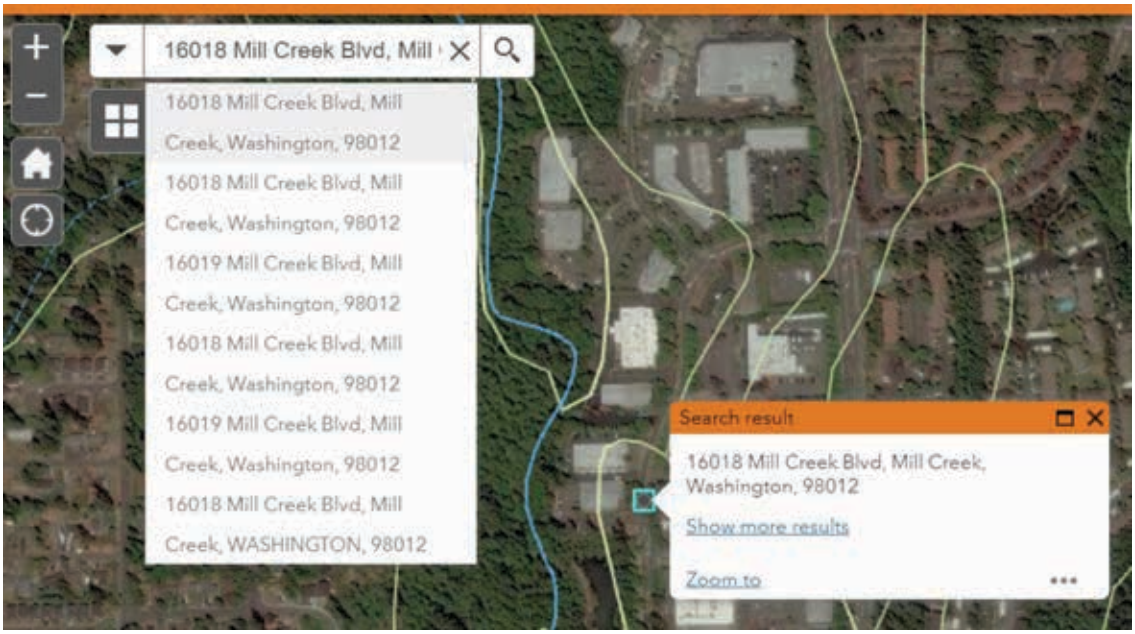


Figure A3. Zoomed in aerial image of the site address.

4. Click (or tap) on the "X" in the Address Search tool to close the popup. Zoom and pan until you can clearly see where the project site is on the landscape (Figure A4).

   In this example, the project site lies in a wooded area to the west of the address selected in the previous screen. We panned west to center the map display over the project site. In this screen, you can see outlines of the soil polygons.



Figure A4. Adjusting the map display over the project site.

5. Click (or tap) near a stream on the project site. The outline of the soil polygon selected will turn blue, and a popup window will provide information about the $SPTH_{200}$ (Figure A5). On a PC, the popup should automatically show (1) the $SPTH_{200}$ in feet, (2) the species of tree it is based on, and (3) the reference study used to derive the height value. On a mobile device, tap the arrow on the right side of the popup to display this information.

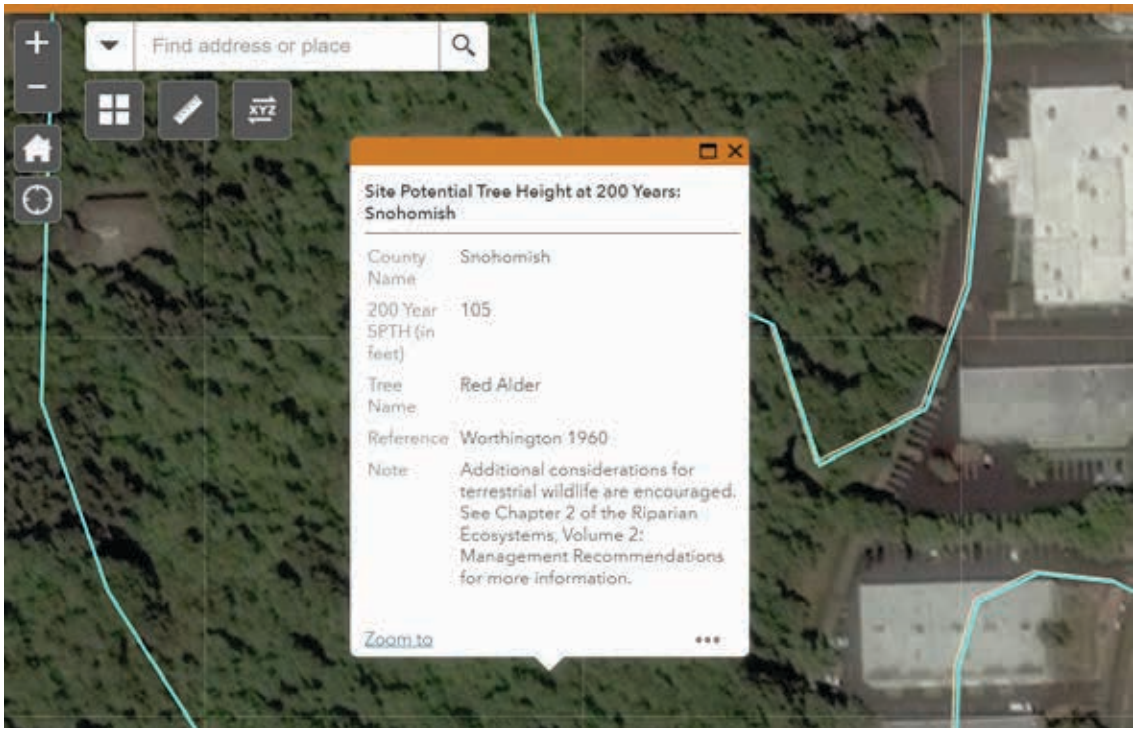


Figure A5. Bringing up the $SPTH_{200}$ information at the project site.

In Example #1, the soil polygon for the project site only showed one tree species: Red Alder. Sometimes soil polygons will list more than one tree species, as shown in Example #2.

Mapping Tool Example #2

Example #2, the project site was at a different location. Steps 1-3 in Example #1 were repeated to zoom to the project site. For this site, the popup window for the selected soil polygon looked different:

- The upper left corner of the popup window says "(1 of 2)"; and
- There is a small arrow near the upper right corner of the popup window.

This means that this soil polygon has two different associated tree species. The first is Douglas-fir (see Figure A6a).

To view the information for the second tree species, click on the small arrow. The second tree species is western hemlock (see Figure A6b).

For project locations with multiple tree species, WDFW recommends using the largest $SPTH_{200}$ value, even if the largest tree species is not the most numerous (or even currently present) onsite.

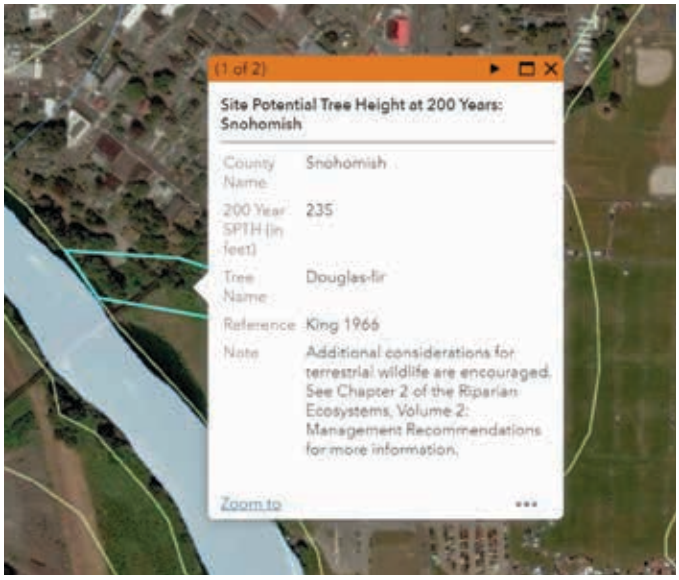


Figure A6a. SPTH information for the first of multiple tree species at a given site.

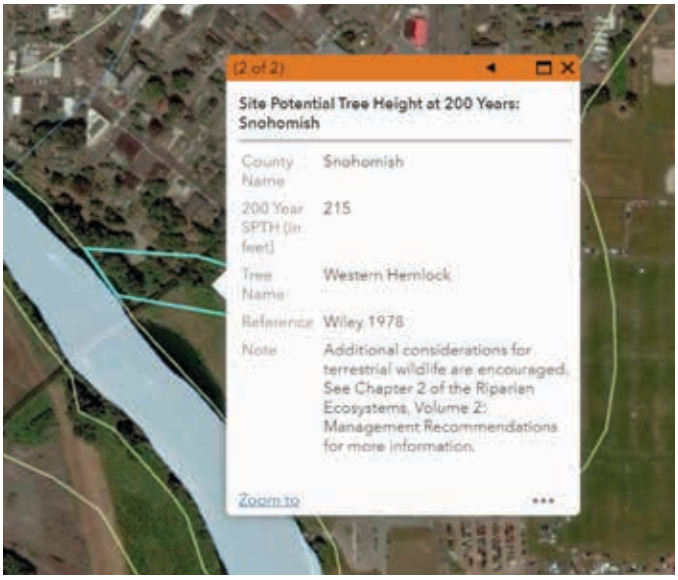


Figure A6b. SPTH$_{200}$ information for the second of multiple tree species at a given site.

Appendix References: Tree Site Index Curves

The following studies were used to determine SPTH$_{200}$ throughout the state:

Alexander, R.R. 1966. Site indexes for lodgepole pine, with corrections for stand density: instructions for field use. Research Paper RM-24. U.S., Forest Service, Rocky Mountain Forest and Range Experiment Station, Fort Collins, Colorado.

Alexander, R.R. 1967. Site indexes for Engelmann spruce. Research Paper RM-32. U.S., Forest Service, Rocky Mountain Forest and Range Experiment Station, Fort Collins, Colorado.

Baker, F.S. 1925. Aspen in the Central Rocky Mountain Region. Bulletin 1291. United States Department of Agriculture, \Washington, D.C.

Barnes, G.H. 1962. Yield of even-aged stands of western hemlock. Technical Bulletin 1273. U.S. Forest Service, Pacific Northwest Forest and Range Experiment Station, Portland, Oregon.

British Columbia Forest Service (BCFS). 1977. Site index curves for cottonwood (as adapted by W.J. Sauerwein). pp. 852-853 *in* Pocket Woodland Handbook. U.S. Department of Agriculture, Soil Conservation Service, Portland, Oregon.

Cochran, P.H. 1979a. Gross yields for even-aged stands of white or Douglas-fir and white or grand fir east of the Cascades in Oregon and Washington. Research Paper PNW-263. U.S. Forest Service, Pacific Northwest Forest and Range Experiment Station, Portland, Oregon.

Cochran, P.H. 1979b. Site index and height growth curves for managed, even-aged stands of Douglas-fir east of the Cascades in Oregon and Washington. Research Paper PNW-251. U.S. Forest Service, Pacific Northwest Forest and Range Experiment Station, Portland, Oregon.

Cochran, P.H. 1985. Site index, height growth, normal yields, and stocking levels for larch in Oregon and Washington. Research Note PNW-424. U.S. Forest Service, Pacific Northwest Forest and Range Experiment Station, Portland, Oregon.

Haig, I.T. 1932. Second-growth yield, stand, and volume tables for the western white pine type. Technical Bulletin 323. United States Department of Agriculture, Washington, D.C.

Hegyi, F., J.J. Jelinek, J. Viszlai, and D.B. Carpenter. 1979. Site index equations and curves for the major tree species in British Columbia. Forest Inventory Report No. 1. Ministry of Forestry, Victoria, British Columbia.

Herman, F.R., R.O. Curtis, and D.J. Demars. 1978. Height growth and site index estimates for noble fir in high-elevation forests of the Oregon-Washington Cascades. Research Paper PNW-243. U.S. Forest Service Pacific Northwest Forest and Range Experiment Station, Portland, Oregon.

Hoyer, G.D., and F.R. Herman. 1989. Height-age and site index curves for Pacific silver fir in the Pacific Northwest. Research Paper RP-418. U.S., Forest Service. Pacific Northwest Research Station, Portland, Oregon.

King, J.E. 1966. Site index curves for Douglas-fir in the Pacific Northwest. Forestry Paper 8. Weyerhaeuser Company, Forestry Research Center, Centralia, Washington.

Kurucz, J.F. 1978. Preliminary, polymorphic site index curves for western red cedar (*Thuja plicata Donn*) in coastal British Columbia. Forest Research Note No. 3. MacMillan Bloedel, Nanaimo, British Columbia.

Meyer, W.H. 1961. Yield of even-aged stands of ponderosa pine. Technical Bulletin 630 (revised 1961). United States Department of Agriculture, Washington, D.C.

Meyer, W.H. 1937. Yield of even-aged stands of Sitka spruce and western hemlock. Technical Bulletin 544. United States Department of Agriculture, Washington, D.C.

Monserud, R.A. 1985. Applying height growth and site index curves for inland Douglas-fir. Research Paper INT-347. U.S. Forest Service. Intermountain Research Station, Ogden, Utah.

Schmidt, W.C., R.C. Shearer, and A.L. Roe. 1976. Ecology and silviculture of western larch forests. Technical Bulletin 1520. U.S. Forest Service, Washington, D.C.

Wiley, K.N. 1978. Site index tables for western hemlock in the Pacific Northwest. Forestry Paper No. 17. Weyerhaeuser Company, Western Forestry Research Center, Centralia, Washington.

Worthington, N.P., F.A. Johnson, G.R. Staebler, and W.J. Lloyd. 1960. Research Paper No. 36. Normal yield tables for red alder. U.S. Forest Service, Pacific Northwest Forest and Range Experiment Station, Portland, Oregon.













Washington Department of FISH and WILDLIFE

Comment #28

Robby Eckroth

From: Tim Trohimovich <Tim@futurewise.org>
Sent: Thursday, May 8, 2025 3:24 PM
To: PDS comments
Subject: 2025 Development Regulations and Critical Areas Ordinance Update

Dear Staff:

Thank you for the opportunity to comment on the Skagit County Critical Areas Ordinance Update. Futurewise supports the update, the ordinance, and the recommended improvements. We do have some recommendations set out below.

Futurewise works throughout Washington State to support land-use policies that encourage healthy, equitable and opportunity-rich communities, and that protect our most valuable farmlands, forests, and water resources. Futurewise has members and supporters throughout Washington State including Skagit County. Our recommendations follow.

SCC 14.24.230(5) which allows the use a previous buffer should require the current buffer widths if additional uses or more intensive uses are being permitted. See page 33 of 73.

Current wetland science supports the buffers in SCC 14.24.230.[1] SCC 14.24.230(5) allows the use of existing buffers that do not meet the current buffer requirements for new or expanded uses. We appreciate and support the additional limits being proposed. However, this accommodation should not apply where more intensive uses or additional uses that will adversely impact the wetland are being allowed. If SCC 14.24.230(5) applies in this circumstance the critical areas regulations will violate the Growth Management Act requirement that critical areas regulations must also at least "protect[s] critical areas by maintaining existing conditions."[2]

Futurewise supports SCC 14.24.350, the Instream Flow Rules, and recommends they be updated to comply with RCW 36.70A.590 and RCW 90.44.050. See pages 48 – 53 of 73

Futurewise supports SCC 14.24.350 Instream Flow Rules. RCW 36.70A.070(1) provides that "[t]he land use element shall provide for protection of the quality and quantity of groundwater used for public water supplies." RCW 36.70A.070(5)(c)(iv) provides that "[t]he rural element shall include measures that apply to rural development and protect the rural character of the area, as established by the county, by: … Protecting surface water and groundwater resources." The Growth Management Act (GMA) in RCW 36.70A.590 also provides that:

> For the purposes of complying with the requirements of this chapter [the GMA] relating to surface and groundwater resources, a county or city may rely on or refer to applicable minimum instream flow rules adopted by the department of ecology under chapters 90.22 and 90.54 RCW. Development regulations must ensure that proposed water uses are consistent with RCW 90.44.050 and with applicable rules adopted pursuant to chapters 90.22 and 90.54 RCW when making decisions under RCW 19.27.097 and 58.17.110.

Development regulations must comply with the GMA including the critical areas regulations.[3] These development regulations are required because overuse of surface or ground water often harms senior water rights holders and fish and wildlife habitat. For example:

> Although domestic water use in rural areas uses a small amount of water, the cumulative impact of many domestic water users can together impair streamflows, especially in

> tributaries. Hydrogeologic studies and computer models show that domestic wells impact streamflows in the Skagit Basin.[4]

To comply with RCW 36.70A.070(1), RCW 36.70A.070(5)(c)(iv), and RCW 36.70A.590, the critical areas regulations should adopt regulations to ensure development complies with the water codes and the applicable instream flow rules.

RCW 36.70A.590 requires the policies and development regulations to ensure that proposed water uses are consistent with RCW 90.44.050. To comply with RCW 90.44.050 for residential permit exempt wells, the policies and development regulations must require that the County when determining if a development, land division, or use qualifies for a permit exempt well under RCW 90.44.050 ensure that the water used by the parent parcel that existed in 2002, any lots created from the parent parcel, and any development built on or after 2002 on those lots does not in total exceed the 5,000 gallons a day allowed by RCW 90.44.050. Under the State Supreme Court's *Campbell and Gwinn* decision, each lot is entitled to one 5,000 gallon per day permit exempt withdrawal for single or group domestic uses under RCW 90.44.050.[5] A "developer may not claim multiple exemptions for the homeowners."[6] So each lot that existed in 2002, the year the *Campbell and Gwinn* decision was decided, is entitled to one permit-exempt withdrawal under RCW 90.44.050.

As lots are subdivided or developed over time, part or all of the permit exempt withdrawals are used by the lots created or the development authorized. To qualify for a permit-exempt groundwater withdrawal authorized under RCW 90.44.050, the lot must have some remaining water from the parent parcel's single 5,000 gallon per day permit exempt withdrawal for single or group domestic uses.

Therefore, the required development regulations can only authorize the use of a permit exempt-well or well system for single or group domestic uses if the water use does not exceed the 5,000 gallons a day allowed by RCW 90.44.050 including the parent parcel that existed in 2002, any lots created from the parent parcel, and any development built on or after 2002. To comply with RCW 36.70A.590, SCC 14.24.350 must include this important limitation. Therefore, we recommend SCC 14.24.350 limit each lot that existed in 2002 to one permit-exempt withdrawal under RCW 90.44.050 including the water used by any land divisions or developments and also comply with RCW 36.70A.590.

This regulation also helps to protect families that buy lots and houses that rely on permit exempt wells. Developments that are approved in violation of RCW 36.70A.590 and RCW 90.44.050 do not have a legal water right. Their current and future water use is not legal.

Adopt stream, lake, and marine buffer widths that consistent with the current best available sciences and that protect the functions and values of salmon habitat. Please see SCC 14.24.530(1) on pages 65 — 66 of 73

The southern resident orcas depend on the chinook salmon to live and recover their numbers.[7] The *2022 State of Salmon in Watersheds* report rated the Puget Sound Chinook salmon as "in crisis," the Governor's Salmon Recovery Office's worst rating.[8] The Puget Sound Steelhead are also "in crisis."[9] Other salmon and steelhead are also declining.[10] The key factors causing the decline in salmon and steelhead include habitat degradation.[11] An analysis by the National Oceanic and Atmospheric Administration and the State of Washington Department of Fish and Wildlife ranked the Northern Puget Sound Fall Chinook salmon from the Nooksack, Elwha, Dungeness, Skagit, Stillaguamish, and Snohomish Rivers as the highest in importance as food sources for the southern resident orcas.[12] New Year Eve saw the death of another orca calf and once again the calf's mother is carrying her around Puget Sound for all of us to see.[13] The Washington State Academy of Sciences concluded that **"[c]learly, there have been net losses of species and habitats in Washington. The committee is reasonably confident that without policy changes, these types of losses will continue** and will contribute to the disappearance of distinct habitats and ecosystem types from Washington's terrestrial and aquatic landscapes."[14] For the sake of the chinook salmon and the southern resident orcas we can and must better protect their habitat.

"Preserving habitat is far less expensive than restoring degraded habitat."[15] We are not achieving no net loss of riparian vegetation that is necessary to protect salmon habitat. This is in part because the critical areas regulation buffers for rivers, streams, and shorelines are too narrow.

The State of Washington Department of Fish and Wildlife has developed new recommendations for protecting riparian areas. "Under WAC 365-190-130(4)(b), the [State of Washington] Department [of Fish and Wildlife]'s priority species habitat information is considered best available science."[16] The updated management recommendations document that fish and wildlife depend on protecting riparian vegetation and the functions this vegetation performs such as maintaining a complex food web that supports salmon and maintaining temperature regimes to name just a few of the functions.[17]

The updated *Riparian Ecosystems, Volume 1: Science synthesis and management implications* scientific report concludes that the "[p]rotection and restoration of riparian ecosystems continues to be critically important because: a) they are disproportionately important, relative to area, for aquatic species, e.g., salmon, and terrestrial wildlife, b) they provide ecosystem services such as water purification and fisheries (Naiman and Bilby 2001; NRC 2002; Richardson et al. 2012), and c) by interacting with watershed-scale processes, they contribute to the creation and maintenance of aquatic habitats."[18] The report states that "[t]he width of the riparian ecosystem is estimated by one 200-year site-potential tree height (SPTH) measured from the edge of the active channel or active floodplain. Protecting functions within at least one 200-year SPTH is a scientifically supported approach if the goal is to protect and maintain full function of the riparian ecosystem."[19] For Skagit County, this generally requires 200-foot buffers on streams, rivers, and shorelines that are home to salmon and other fish species and 100-foot buffers on other streams and shorelines measured from the channel migration zone edge or active flood plain. The buffers should be updated to include these buffers.

SCC 14.24.600, SCC 14.24.610, and SCC 14.24.630 should be updated to protect people and property from sea level rise. Please see pages 71 – 72 of 73

Sea level rise is a real problem that is happening now. Sea level is rising and floods and erosion are increasing. In 2012 the National Research Council concluded that global sea level had risen by about seven inches in the 20th Century.[20] A recent analysis of sea-level measurements for tide-gage stations, including the Seattle, Washington tide-gauge, shows that sea level rise is accelerating.[21]

The report *Projected Sea Level Rise for Washington State – A 2018 Assessment* projects that for a low greenhouse gas emission scenario there is a 50 percent probability that sea level rise will reach or exceed 1.6 feet by 2100 in Skagit County at Latitude 48.3 degrees north and Longitude -122.4 degrees west.[22] *Projected Sea Level Rise for Washington State – A 2018 Assessment* projects that for a higher emission scenario there is a 50 percent probability that sea level rise will reach or exceed 2.1 feet by 2100 in Skagit County at Latitude 48.3 degrees north and Longitude -122.4 degrees west.[23] Projections are available for all of the marine shorelines in Skagit County.[24]

The extent of the sea level rise currently projected for Skagit County can be seen on the NOAA Office for Coastal Management Digitalcoast Sea Level Rise Viewer available at: https://coast.noaa.gov/digitalcoast/tools/slr.html. A copy of the map from the viewer showing two feet of sea level rise is in a separate email with the filename: "Skagit Cty 2 ft Sea Level Rise.pdf."

Projected sea level rise will substantially increase flooding. As Ecology writes, "[s]ea level rise and storm surge[s] will increase the frequency and severity of flooding, erosion, and seawater intrusion—thus increasing risks to vulnerable communities, infrastructure, and coastal ecosystems."[25] Not only our marine shorelines will be impacted, as Ecology writes "[m]ore frequent extreme storms are likely to cause river and coastal flooding, leading to increased injuries and loss of life."[26]

Zillow recently estimated that 31,235 homes in Washington State may be underwater by 2100, 1.32 percent of the state's total housing stock. The value of the submerged homes is an estimated $13.7 billon.[27] Zillow wrote:

> It's important to note that 2100 is a long way off, and it's certainly possible that communities [may] take steps to mitigate these risks. Then again, given the enduring popularity of living near the sea despite its many dangers and drawbacks, it may be that even more homes will be located closer to the water in a century's time, and these estimates could turn out to be very conservative. Either way, left unchecked, it is clear the threats posed by climate change and rising sea levels have the potential to destroy housing values on an enormous scale.[28]

Sea level rise will have an impact beyond rising seas, floods, and storm surges. The National Research Council wrote that:

> Rising sea levels and increasing wave heights will exacerbate coastal erosion and shoreline retreat in all geomorphic environments along the west coast. Projections of future cliff and bluff retreat are limited by sparse data in Oregon and Washington and by a high degree of geomorphic variability along the coast. Projections using only historic rates of cliff erosion predict 10–30 meters [33 to 98 feet] or more of retreat along the west coast by 2100. An increase in the rate of sea-level rise combined with larger waves could significantly increase these rates. Future retreat of beaches will depend on the rate of sea-level rise and, to a lesser extent, the amount of sediment input and loss.[29]

These impacts are why the Washington State Department of Ecology recommends "[l]imiting new development in highly vulnerable areas."[30]

Unless wetlands and shoreline vegetation can migrate landward, their area and ecological functions will decline.[31] If development regulations are not updated to address the need for vegetation to migrate landward in feasible locations, wetlands and shoreline vegetation will decline. According to Ecology "[d]evelopment of coastal areas and shoreline armoring (e.g., bulkheads, seawalls) prevent habitat areas from reestablishing inland" in response to sea level rise.[32] Ecology provides more detailed documentation of these adverse impacts:

The prospect of more flooding, erosion, and storm damage may lead communities and property owners to seek to build seawalls, dikes, and tidal barriers. The construction and placement of these structures will have a direct and immediate impact on natural shoreline environments. These structures will also lead to the progressive loss of beach and marsh habitat as those areas are squeezed between the rising sea and a more intensively engineered shoreline. Predicted decreases in size or transitions in tidal marshes, salt marshes, and tidal flats will affect the species these habitats support. It is predicted that while some species may be able to locate alternate habitats or food sources, others will not (Glick, 2007).

Shellfish, forage fish, shorebirds, and salmon are among those identified as examples of species at risk (Glick, 2007). Sea level rise will also lead to other changes in coastal ecosystems, such as shifting of stream mouths and tidal inlets, reconfigured estuaries and wetlands, and more frequently disturbed riparian zones.[33]

"Loss of salt marsh and related habitats may be significant in systems constrained by surrounding development."[34] This loss of shoreline vegetation will harm the environment. It will also deprive marine shorelines of the vegetation that protects property from erosion and storm damage by modifying soils and accreting sediment.[35] This will increase damage to upland properties. Enclosed with this letter are maps showing the extent of wetlands at mean higher high water and at two feet of sea level rise in western Skagit County.[36] A comparison of these maps shows that there will be migration of wetlands in Skagit County if the wetlands are not blocked by development.

Flood plain regulations are not enough to address sea level rise for three reasons. *Projected Sea Level Rise for Washington State – A 2018 Assessment* explains two of them:

> Finally, it is worth emphasizing that sea level rise projections are different from Federal Emergency Management Agency (FEMA) flood insurance studies, because (1) FEMA studies only consider past

events, and (2) flood insurance studies only consider the 100-year event, whereas sea level rise affects coastal water elevations at all times.[37]

The third reason is that flood plain regulations allow fills and piling to elevate structures and also allow commercial buildings to be flood proofed in certain areas. While this affords some protection to the structure, it does not protect the marshes and wetlands that need to migrate.

Because of these significant impacts on people, property, and the environment, "[n]early six in ten Americans supported prohibiting development in flood-prone areas (57%)."[38] It is time for Washington state and local governments to follow the lead of the American people and adopt policies and regulations to protect people, property, and the environment from sea level rise. This is why RCW 36.70A.070(9)(e)(i)(C) requires county and city comprehensive plans to "[a]ddress natural hazards created or aggravated by climate change, including sea level rise, landslides, flooding, drought, heat, smoke, wildfire, and other effects of changes to temperature and precipitation patterns." RCW 36.70A.040(3) requires counties and cities development regulations that are consistent with and implement the comprehensive plan and to address these natural hazards. We recommend the addition of the following regulations as part of the critical areas update:

X. New lots shall be designed and located so that the buildable area is outside the area likely to be inundated by sea level rise in 2100 and outside of the area in which wetlands and aquatic vegetation will likely migrate during that time.

X2. Where lots are large enough, new structures and buildings shall be located so that they are outside the area likely to be inundated by sea level rise in 2100 and outside of the area in which wetlands and aquatic vegetation will likely migrate during that time.

X3. New and substantially improved structures shall be elevated above the likely sea level rise elevation in 2100 or for the life of the building, whichever is less.

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[1] Washington State Department of Ecology Shorelands and Environmental Assistance Program, *Wetland Guidance for Critical Areas Ordinance (CAO) Updates: Western and Eastern Washington* pp. 20 – 25 (Olympia, Wash.: Oct. 2022, Publication #22-06-014) last accessed on May 8, 2025, at: https://apps.ecology.wa.gov/publications/SummaryPages/2206014.html and available in a separate email with the filename: "2206014.pdf."

[2] *Swinomish Indian Tribal Cmty. v. W. Washington Growth Mgmt. Hearings Bd.*, 161 Wn.2d 415, 430, 166 P.3d 1198, 1206 (2007), as corrected (Nov. 28, 2007), as corrected (Apr. 3, 2008).

[3] *Kittitas Cnty. v. E. Washington Growth Mgmt. Hearings Bd.*, 172 Wn.2d 144, 164, 256 P.3d 1193, 1203 (2011) *citing* RCW 36.70A.130(1); *accord* RCW 36.70A.290(2).

[4] State of Washington Department of Ecology Water Resources Program, *Water Availability for Skagit Basin Landowners: Frequently asked questions WRIA 11 Nisqually Watershed Water Availability* p. 3 (Publication 13-11-006, Revised Aug. 2023) last accessed on May 5, 2025, at: https://apps.ecology.wa.gov/publications/documents/1311006.pdf.

[5] *State Dep't of Ecology v. Campbell & Gwinn, L.L.C.*, 146 Wn.2d 1, 14, 43 P.3d 4, 110 (2002).

[6] *Id.*

[7] NOAA Fisheries, *Southern Resident Killer Whale Priority Chinook Salmon Stocks - Questions and Answers* webpage last accessed on Jan. 9, 2025, at: https://www.fisheries.noaa.gov/west-coast/endangered-species-conservation/southern-resident-killer-whale-priority-chinook-salmon and in an another email with the filename: "Southern Resident Killer Whale Priority Chinook Stocks Q and A.pdf."

[8] Washington State Recreation and Conservation Office, Governor's Salmon Recovery Office, *2022 State of Salmon in Watersheds Executive Summary* p. 7 (Feb. 2023) last accessed on) last accessed on May 5, 2025, at: https://stateofsalmon.wa.gov/wp-content/uploads/2023/02/SOS-ExecSummary-2022.pdf.

[9] *Id*.

[10] *Id*. p. 6.

[11] *Id*. pp. 14 – 15.

[12] National Oceanic and Atmospheric Administration and the State of Washington Department of Fish and Wildlife, *Southern Resident Killer Whale Priority Chinook Stocks* p. 6 (June 22, 2018) last accessed on May 5, 2025, at: https://media.fisheries.noaa.gov/dam-migration/srkw_priority_chinook_stocks_conceptual_model_report___list_22june2018.pdf and in a sperate email with the filename: "srkw_priority_chinook_stocks_conceptual_model_report___list_22june2018.pdf."

[13] Lynda V. Mapes, *Mother orca Tahlequah once again carrying her dead calf* The Seattle Times (Jan. 1, 2025 at 6:41 pm) last accessed on Jan. 9, 2025, at: https://www.seattletimes.com/seattle-news/climate-lab/mother-orca-tahlequah-once-again-carrying-her-dead-calf/.

[14] Washington State Academy of Sciences, *Assessment of No Net Loss and Recommendations for Net Ecological Gain Metrics, Indicators, and Monitoring: Prepared for the Washington State Department of Fish and Wildlife* p. 4 (June 2022) in Washington Department of Fish and Wildlife (WDFW), *Net Ecological Gain Standard Proviso Summary Report* (Dec. 2022) bold in the original last accessed on May 8, 2025, at: https://wdfw.wa.gov/sites/default/files/publications/02357/wdfw02357.pdf and in a separate email with the filename: "wdfw02357.pdf."

[15] Washington State Recreation and Conservation Office Governor's Salmon Recovery Office, *2022 State of Salmon in Watersheds Executive Summary* p. 15 (Feb. 2023).

[16] *Whidbey Env't Action Network v. Growth Mgmt. Hearings Bd.*, 14 Wn. App. 2d 514, 526, 471 P.3d 960, 968 (2020).

[17] Timothy Quinn, George F. Wilhere, and Kirk L. Krueger, technical editors, *Riparian Ecosystems, Volume 1: Science Synthesis and Management Implications* pp. 265 – 68 & p. 270 (A Priority Habitat and Species Document of the Washington Department of Fish and Wildlife, Olympia, WA: Updated July 2020) last accessed on Jan. 9, 2025, at: https://wdfw.wa.gov/publications/01987/ and in a separate email with the filename: "wdfw01987.pdf." This report was peer-reviewed. *Id*. at pp. 11 – 12. *See also* Terra Rentz, Amy Windrope, Keith Folkerts, and Jeff Azerrad, technical editors, *Riparian Ecosystems, Volume 2: Management Recommendations* (A Priority Habitat and Species Document of the Washington Department of Fish and Wildlife, Olympia, WA: Dec. 2020) last accessed on Jan. 9, 2025, at: https://wdfw.wa.gov/sites/default/files/publications/01988/wdfw01988.pdf and in a separate email with the filename: "wdfw01988.pdf."

[18] Timothy Quinn, George F. Wilhere, and Kirk L. Krueger, technical editors, *Riparian Ecosystems, Volume 1: Science Synthesis and Management Implications* p. 270 (A Priority Habitat and Species Document of the Washington Department of Fish and Wildlife, Olympia, WA: Updated July 2020).

[19] *Id*. at p. 271.

[20] National Research Council, *Sea-Level Rise for the Coasts of California, Oregon, and Washington: Past, Present, and Future* p. 23, p. 156, p. 96, p. 102 (2012) last accessed on May 6, 2025, at: https://www.nap.edu/download/13389.

[21] William and Mary Virginia Institute of Marine Science, U.S. West Coast Sea-Level Trends & Processes Trend Values for 2024 last accessed on May 6, 2025, at: https://www.vims.edu/research/products/slrc/compare/west_coast/index.php.

[22] University of Washington Climate Impacts Group, *Visualization #1: Projected sea level change by year for Projected sea level change by year Lat 48.3 Long 122.4 Skagit County*, accessed on April 1, 2022, at: https://cig.uw.edu/our-work/applied-research/wcrp/sea-level-rise-data-visualization/ and enclosed in a separate email with the filename: "Projected sea level change by year Lat 48.3 Long -122.4 Skagit Cty.pdf." The methodology used for these projections is available in Miller, I.M., Morgan, H., Mauger, G., Newton, T., Weldon, R., Schmidt, D., Welch, M., Grossman, E, *Projected Sea Level Rise for Washington State – A 2018 Assessment* (A collaboration of Washington Sea Grant, University of Washington Climate Impacts Group, Oregon State University, University of Washington, and US Geological Survey. Prepared for the Washington Coastal Resilience Project: updated 07/2019) last accessed on May 6, 2025, at: https://cig.uw.edu/wp-content/uploads/sites/2/2019/07/SLR-Report-Miller-et-al-2018-updated-07_2019.pdf and in a separate email with the filename: "SLR-Report-Miller-et-al-2018-updated-07_2019.pdf."

[23] University of Washington Climate Impacts Group, *Visualization #1: Projected sea level change by year for Projected sea level change by year Lat 48.3 Long 122.4 Skagit County*.

[24] Miller, I.M., Morgan, H., Mauger, G., Newton, T., Weldon, R., Schmidt, D., Welch, M., Grossman, E,. *Projected Sea Level Rise for Washington State – A 2018 Assessment* p. 6 & p. 9 of 24 (A collaboration of Washington Sea Grant, University of Washington Climate Impacts Group, Oregon State University, University of Washington, and US Geological Survey. Prepared for the Washington Coastal Resilience Project: updated 07/2019).

[25] State of Washington Department of Ecology, *Preparing for a Changing Climate Washington State's Integrated Climate Response Strategy* p. 90 (Publication No. 12-01-004: April 2012) last accessed on May 6, 2025, at: https://fortress.wa.gov/ecy/publications/publications/1201004.pdf.

[26] *Id*. p. 17.

[27] Krishna Rao, *Climate Change and Housing: Will a Rising Tide Sink all Homes?* Zillow webpage (Jun. 2, 2017) last accessed on May 6, 2025, at: http://www.zillow.com/research/climate-change-underwater-homes-12890/.

[28] *Id*.

[29] National Research Council, *Sea-Level Rise for the Coasts of California, Oregon, and Washington: Past, Present, and Future* p. 135 (2012).

[30] State of Washington Department of Ecology, *Preparing for a Changing Climate Washington State's Integrated Climate Response Strategy* p. 90 (Publication No. 12-01-004: April 2012).

[31] Christopher Craft, Jonathan Clough, Jeff Ehman, Samantha Joye, Richard Park, Steve Pennings, Hongyu Guo, and Megan Machmuller, *Forecasting the effects of accelerated sea-level rise on tidal marsh ecosystem services* Front Ecol Environ 2009; 7, doi:10.1890/070219 p. *6 last accessed on May 6, 2025, at: https://www2.clark.wa.gov/files/dept/community-planning/shoreline-master-program/proposal-comments-received/futurewise-data-cd/craft-et-al-2009.pdf#page=1.00&gsr=0. Frontiers in Ecology and the Environment is a peer-reviewed scientific journal. Frontiers in Ecology and the Environment Journal Overview webpage last accessed on May 6, 2025 at: https://esajournals.onlinelibrary.wiley.com/hub/journal/15409309/aims-and-

scope/read-full-aims-and-scope. Both in another email with the filename: "Craft et al 2009.pdf" and "Frontiers in Ecology and the Environment - Journal Overview" respectively.

[32] Washington State Department of Ecology, *Preparing for a Changing Climate: Washington State's Integrated Climate Response Strategy* p. 68 (Publication No. 12-01-004: April 2012).

[33] State of Washington Department of Ecology, *Shoreline Master Program Handbook Appendix A: Addressing Sea Level Rise in Shoreline Master Programs* pp. 3 – 4 (Publication Number 11-06-010: rev. 12/17).

[34] *Id*. p. 4.

[35] R. A. Feagin, S. M. Lozada-Bernard, T. M. Ravens, I. Möller, K. M. Yeagei, A. H. Baird and David H. Thomas, *Does Vegetation Prevent Wave Erosion of Salt Marsh Edges?* 106 Proceedings of the National Academy of Sciences of the United States of America pp. 10110-10111 (Jun. 23, 2009) last accessed on May 6, 2025, at: http://www.pnas.org/content/106/25/10109.full and in a separate email with the filename: "10109.full.pdf." This journal is peer-reviewed. *Id*. p. 10113.

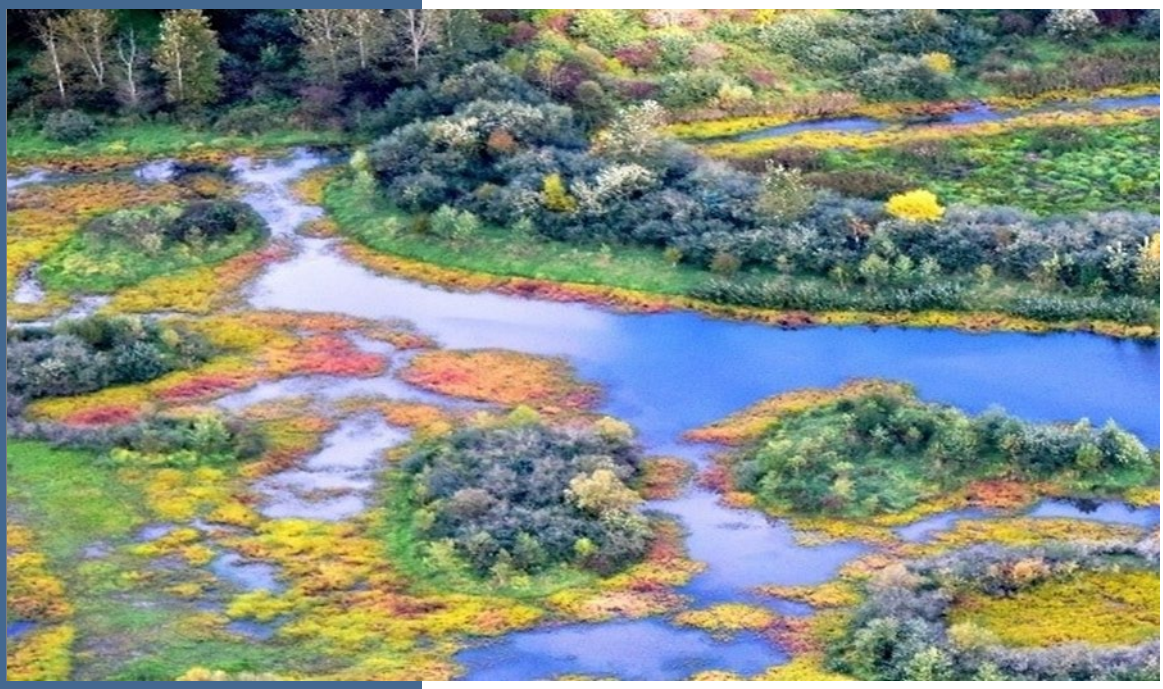
[36] Enclosed in a separate email with the filenames: "Marsh Skagit Cty MHHW.pdf" and "Marsh Migration Skagit Cty 2 ft Sea Level Rise.pdf." Three maps of the same view are needed to show the three parts of the legend, so that is why there are three pages in the Marsh Migration Skagit Cty 2 ft Sea Level Rise.pdf.

[37] Miller, I.M., Morgan, H., Mauger, G., Newton, T., Weldon, R., Schmidt, D., Welch, M., Grossman, E,. *Projected Sea Level Rise for Washington State – A 2018 Assessment* p. 8 of 24 (A collaboration of Washington Sea Grant, University of Washington Climate Impacts Group, Oregon State University, University of Washington, and US Geological Survey. Prepared for the Washington Coastal Resilience Project: updated 07/2019).

[38] Bo MacInnis and Jon A. Krosnick, *Climate Insights 2020: Surveying American Public Opinion on Climate Change and the Environment Report: Natural Disasters* p. 8 (Washington, DC: Resources for the Future, 2020) last accessed on May 6, 2025, at: https://www.rff.org/publications/reports/climateinsights2020-natural-disasters/.

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Wetland Guidance for Critical Areas Ordinance (CAO) Updates

Western and Eastern Washington

Shorelands and Environmental Assistance Program

Washington State Department of Ecology

Olympia, Washington

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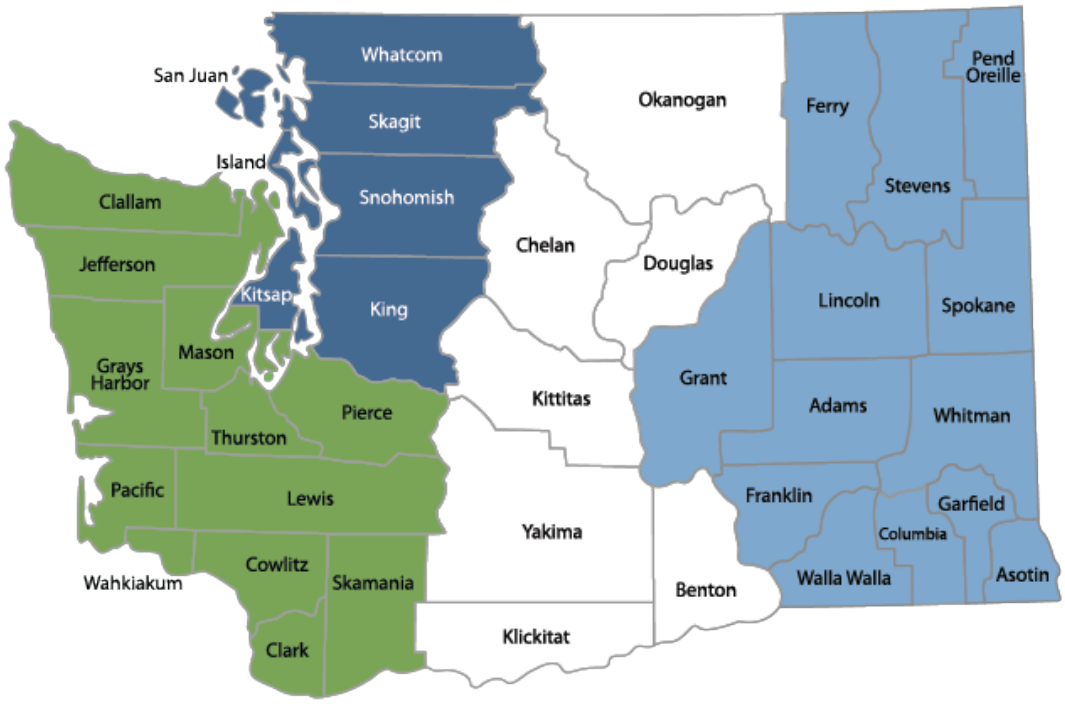
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[1] https://apps.ecology.wa.gov/publications/summarypages/2206014.html
[2] https://ecology.wa.gov/accessibility

Department of Ecology's Regional Offices

Map of Counties Served



Southwest Region 360-407-6300	Northwest Region 425-594-0000	Central Region 509-575-2490	Eastern Region 509-329-3400

Region	Counties served	Mailing Address	Phone
Southwest	Clallam, Clark, Cowlitz, Grays Harbor, Jefferson, Mason, Lewis, Pacific, Pierce, Skamania, Thurston, Wahkiakum	PO Box 47775 Olympia, WA 98504	360-407-6300
Northwest	Island, King, Kitsap, San Juan, Skagit, Snohomish, Whatcom	PO Box 330316 Shoreline, WA 98133	206-594-0000
Central	Benton, Chelan, Douglas, Kittitas, Klickitat, Okanogan, Yakima	1250 W Alder St Union Gap, WA 98903	509-575-2490
Eastern	Adams, Asotin, Columbia, Ferry, Franklin, Garfield, Grant, Lincoln, Pend Oreille, Spokane, Stevens, Walla Walla, Whitman	4601 N Monroe Spokane, WA 99205	509-329-3400
Headquarters	Across Washington	PO Box 46700 Olympia, WA 98504	360-407-6000

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Preface

This publication updates *Wetland Guidance for CAO Updates* (Western Washington and Eastern Washington) (Bunten et al., 2016a; Bunten et al., 2016b). It is informed by our earlier best available science (BAS) document, *Wetlands in Washington State - Volume 1: A Synthesis of the Science* (Sheldon et al., 2005) and stems from the guidance in *Wetlands in Washington State, Volume 2: Guidance for Protecting and Managing Wetlands* (Granger et al., 2005)—hereafter referred to as *Wetlands in Washington State, Volume 2*. This guidance is a concise and current representation of the many strategies and approaches for managing wetlands found in those earlier volumes. It combines both western and eastern Washington guidance into one document.

This guidance is for local jurisdictions working on designating and protecting wetlands as critical areas under the Washington State Growth Management Act (GMA).

In providing guidance to all jurisdictions of the state, the first issue we encounter is how to address the large differences among 320 jurisdictions—from the unique environments and variable climates across the state, and from small towns to large cities to counties. While these differences are complex and trigger a wide array of responses, the common trait they all have is a requirement to use BAS. Under the GMA, the regulatory approach to protection of wetlands as critical areas must be informed by BAS (WAC 365-190-080[3]).

In our role of supporting local jurisdictions, the Department of Ecology's Wetlands Section has worked to assemble, evaluate, and refine the most up-to-date scientific information available about the functions and values of wetlands. As part of this work, Ecology has provided information about the approaches, tools, and examples that are available to jurisdictions in their work to manage wetland resources. The suggestions here have evolved as BAS has evolved, and have changed as experience has given us a better understanding of the needs and questions faced by jurisdictions.

Science tells us that buffers are necessary to protect wetland functions and values. We recognize that a single buffer approach does not fit all situations. This guidance includes three different approaches to addressing buffers in the wetlands chapter of a critical areas ordinance (CAO). They range from the simplest (least flexible/most conservative) to the most detailed (adaptable/flexible). These approaches are different for wetlands in western and eastern Washington and are listed separately in Appendix C (Buffer Approaches for Western Washington) and Appendix D (Buffer Approaches for Eastern Washington).

[3] https://app.leg.wa.gov/wac/default.aspx?cite=365-190-080

The buffer recommendations contained herein are based on a moderate-risk approach. In this document, risk is addressed by tailoring the degree of protection to several factors the scientific literature says are important. The widths recommended in this guidance were selected from the middle of the range of buffers suggested in the literature. In combination with other strategies like limiting buffer reductions, buffer averaging, and exemptions, it represents a moderate-risk approach to determining buffer widths. To learn more about how Ecology evaluated these recommendations in the context of risk, see Wetlands in Washington State - Volume 2[4] (Section 1.8 and Appendix 8-E; Granger et al., 2005).

As you work on your CAO's wetlands chapter, Ecology can provide feedback, recommendations, guidance, and support. We recognize that each jurisdiction will have unique circumstances and needs. Ecology's wetland specialists can help identify appropriate protections for your jurisdiction and guide you to the available resources and tools. Contact Ecology wetland staff[5] for more information about using this guidance in your jurisdiction.

Specific changes in this updated guidance include:

- Reformatted buffer tables, including the incorporation of previous adjustments to the range of habitat scores based on review of the reference wetland data used to calibrate the Washington wetland rating system
- Updated and expanded minimization measures table for use with the buffer tables
- Improved correlation between the discussion and the sample regulations
- New section on functionally disconnected buffers
- Clarified corridor requirements and expanded applicability
- Clarified geographic scope of exemption guidance for small wetlands
- New language addressing agricultural activities in non-Voluntary Stewardship Program (VSP) jurisdictions
- Recommendations from the 2021 interagency wetland mitigation guidance document
- Updated links to resource documents and webpages
- Updated definitions
- New language addressing the role of wetland functions in mitigating climate change (e.g., carbon sequestration)

[4] https://apps.ecology.wa.gov/publications/summarypages/0506008.html
[5] https://ecology.wa.gov/Water-Shorelines/Wetlands/Tools-resources/Contacts-by-subject-region

Introduction

This publication is intended to help jurisdictions in the process of updating the wetlands chapter of their critical areas ordinance (CAO) to meet the Growth Management Act (GMA) requirements. Wetlands are one of the five types of critical areas identified in the GMA. The GMA requires specific protections for wetlands because they provide a wide variety of essential environmental benefits. Without protection or mitigation, even minor disturbances to wetlands can reduce or eliminate these benefits.

This document provides guidance, tools, and suggested language that can be useful in developing CAO's for wetland protection under the GMA. We recognize that many local governments lack the planning staff and resources necessary to develop and implement wetland standards that are both locally appropriate and based on best available science (BAS). However, all jurisdictions must comply with the GMA requirement to designate and protect wetlands and are required to substantively consider BAS during that process (WAC 365-190-080[6]).[7]

Wetlands play a vital role in the overall well-being of Washington State. Washington's wetlands protect water quality, reduce flooding, provide aquifer recharge for drinking water and other uses, and provide critical habitat for fish and wildlife as well as carbon sequestration. Wetlands also provide many social values including recreational opportunities, aesthetic benefits, sites for research and education, and cultural resources important to tribes.

The first part of this document describes important topics that should be addressed in the wetlands section of a CAO. It includes a discussion of wetland protections based on BAS. The second part, the Appendices, provide sample wetland regulation language (Appendix A), definitions that are commonly used in wetland regulations (Appendix B), buffer approaches for western and eastern Washington (Appendices C and D), and recommended mitigation ratio tables (Appendix E). Appendices C and D include three different buffer approaches for jurisdictions to choose from:

- Option 1 is Ecology's preferred recommendation for regulatory language that allows for the most flexibility for individual sites. Buffer widths are based on three factors: the wetland category, the level of impacts from adjacent land uses, and the functions or special characteristics of the wetland that need to be protected.
- Option 2 is a recommendation that provides for buffer widths based on wetland categories and the level of impact from adjacent land uses.
- Option 3 is a recommendation for buffers based on wetland category alone.

[6] https://app.leg.wa.gov/wac/default.aspx?cite=365-190-080

[7] For additional information see: WEAN, 122 Wn.App. at 171, citing HEAL, 96 Wn.App. at 532.

Aside from the buffer tables, all other recommendations in this guidance apply to both western and eastern Washington wetlands. Please note that the sample wetland regulations (Appendix A) will need to be tailored to your document or code naming and numbering system.

This document addresses only the wetland-specific aspects of critical areas management and protection and does not include recommendations related to other types of critical areas. Recommendations for the other critical area types can be found in Appendix A of the Critical Areas Handbook[8] (Commerce, 2018). In addition, some aspects of wetland management are subject to other laws, such as the State Environmental Policy Act (SEPA). For example, SEPA is the primary mechanism used to regulate the impacts of wetland development related to climate change. Because this document focuses only on the requirements of the GMA to designate and protect wetlands, Ecology advises localities to consult with legal counsel on the applicability of other laws to local wetland programs.

The recommendations in this document are intended to provide guidance for all local governments, but they may need to be tailored to fit individual circumstances. Factors to consider include the nature and extent of the wetland resources at risk, a city or county's rate of growth, the nature and level of impact from land uses in the jurisdiction, and the staffing resources available for a jurisdiction to implement and administer its CAO. If you have questions about which approach to choose, we encourage you to contact us so we can help you determine which is best suited to your community's needs. To find Ecology's wetland specialist for your area, see Ecology's Wetland contacts webpage.[9]

[8] https://www.commerce.wa.gov/serving-communities/growth-management/guidebooks-and-resources/
[9] https://ecology.wa.gov/Water-Shorelines/Wetlands/Tools-resources/Contacts-by-subject-region

Wetland BAS, Guidance, and Tools

Ecology produced best available science (BAS), guidance, and tools that can help local governments develop a comprehensive wetlands protection program for their jurisdictions. In 2005, Ecology and the Washington Department of Fish and Wildlife (WDFW) published a two-volume guidance document to help local governments protect and manage wetlands:

- Wetlands in Washington State, Volume 1: A Synthesis of the Science[10] (Sheldon et al., 2005). This BAS volume is the result of a review of over 17,000 scientific articles and synthesizes over 1,000 peer-reviewed works relevant to the management of Washington's wetlands.
- Wetlands in Washington State, Volume 2: Managing and Protecting Wetlands[11] (Granger et al., 2005). This volume was developed with the assistance of local government planners and wetland consultants. It can be used to craft regulatory language that is based on BAS.

In October 2013, Ecology published a BAS update pertaining to wetland buffers. The 2013 update on buffers provides a refinement of our knowledge and revisits and confirms the conclusions and key points in the 2005 synthesis:

- Update on Wetland Buffers: The State of the Science[12] (Hruby, 2013)

Ecology developed wetland rating systems for western and eastern Washington. The rating systems are useful tools for grouping wetlands that have similar needs for protection:

- Washington State Wetland Rating System for Western Washington: 2014 Update[13] (Hruby, 2014a)
- Washington State Wetland Rating System for Eastern Washington: 2014 Update[14] (Hruby, 2014b)

Ecology developed a manual that provides procedures to characterize compliance with wetland buffers that are required under regulations both at the state and local levels. It can be used by state agencies and local governments to characterize both the implementation and the effectiveness of their requirements for wetland buffers. The results can also be used to inform management decisions on policies and regulations regarding buffers:

- Characterizing Wetland Buffers[15] (Hruby et al., 2017)

[10] https://apps.ecology.wa.gov/publications/summarypages/0506006.html
[11] https://apps.ecology.wa.gov/publications/summarypages/0506008.html
[12] https://apps.ecology.wa.gov/publications/SummaryPages/1306011.html
[13] https://apps.ecology.wa.gov/publications/SummaryPages/1406029.html
[14] https://apps.ecology.wa.gov/publications/SummaryPages/1406030.html
[15] https://apps.ecology.wa.gov/publications/SummaryPages/1706008.html

Ecology, in coordination with the U.S. Army Corps of Engineers and the U.S. Environmental Protection Agency, developed a two-part guidance document aimed at improving the quality and effectiveness of compensatory mitigation in Washington. Part 1 of this guidance was updated in 2021:

- Wetland Mitigation in Washington State–Part 1: Agency Policies and Guidance (Version 2)[16] (Ecology et al., 2021). Part 1 outlines the agencies' requirements and expectations for compensatory mitigation.
- Wetland Mitigation in Washington State–Part 2: Developing Mitigation Plans (Version 1)[17] (Ecology et al., 2006). Part 2 provides technical information on preparing plans for compensatory mitigation.

Ecology developed tools to improve the quality and adequacy of compensatory mitigation. These tools incorporate BAS-based approaches for selecting mitigation sites and evaluating the adequacy of compensatory mitigation:

- Selecting Wetland Mitigation Sites Using a Watershed Approach (Western Washington)[18] (Hruby et al., 2009)
- Selecting Wetland Mitigation Sites Using a Watershed Approach (Eastern Washington)[19] (Hruby et al., 2010)
- Calculating Credits and Debits for Compensatory Mitigation in Wetlands of Western Washington[20] (Hruby, 2012a)
- Calculating Credits and Debits for Compensatory Mitigation in Wetlands of Eastern Washington[21] (Hruby, 2012b)

[16] https://apps.ecology.wa.gov/publications/summarypages/2106003.html
[17] https://apps.ecology.wa.gov/publications/summarypages/0606011b.html
[18] https://apps.ecology.wa.gov/publications/SummaryPages/0906032.html
[19] https://apps.ecology.wa.gov/publications/SummaryPages/1006007.html
[20] https://apps.ecology.wa.gov/publications/summarypages/1006011.html
[21] https://apps.ecology.wa.gov/publications/summarypages/1106015.html

Watershed Characterization

Ecology develops and provides watershed characterization information to help inform local planning processes, such as comprehensive planning. Land use planning and permit decisions usually incorporate information gathered at the site but not the watershed as a whole. This means decisions are rarely informed by an understanding of ecosystem processes or watershed conditions. Over the long term this can result in cumulative impacts that significantly affect the health of terrestrial and aquatic ecosystems. Therefore, it is beneficial to plan in consideration of a broader watershed scale that may extend outside of your jurisdictional boundary.

Watershed characterization results can be used to help achieve a more functional and resilient watershed ecosystem, to identify and resolve areas of conflict between proposed land use actions and protection of watershed resources, and to identify the root cause of watershed issues to inform appropriate solutions. If a watershed characterization has been done for your jurisdiction, it can be used to inform development of your wetland regulations. For more information about implementing watershed characterization, contact Ecology's wetland critical areas ordinance review coordinator.

Ecology has a webpage that describes watershed characterization and provides links to examples of how land use planners and resource managers have used watershed characterization to develop watershed-based plans:

- Ecology's watershed characterization webpage[22]

For the entire Puget Sound drainage area—from the Olympic Mountains to the Cascades—Ecology developed a tool that identifies the most important areas, across the entire Sound and within each of the 19 Water Resource Inventory Areas (WRIAs), to protect and restore, and those areas more suitable for development:

- Puget Sound Watershed Characterization Project[23]

[22] https://ecology.wa.gov/Water-Shorelines/Puget-Sound/Watershed-characterization-project/Watershed-characterization

[23] https://apps.ecology.wa.gov/coastalatlas/wc/landingpage.html

Relationship Between the Growth Management Act (GMA) and the Shoreline Management Act (SMA)

In this section we describe two approaches to establishing critical areas protections when updating a shoreline master program (SMP). One is to integrate the critical areas ordinance (CAO) provisions into the SMP, entirely or in part, by reference. This approach may create more uniformity within your regulations. The other option is to develop critical areas regulations specifically for the SMP. Under this second option, the existing CAO would not be incorporated into the SMP.

You should be aware that the SMP may affect some provisions of your CAO. For example, certain activities allowed under a permit exemption in the CAO may not qualify for exemption under the SMP. SMP exemptions are specified and limited to those listed in the SMA (Chapter 90.58 RCW[24]).

The SMA does not allow reasonable use exceptions, providing instead a variance pathway to afford regulatory relief. If you decide to incorporate your CAO wholly, or by reference, into your SMP, an update to the SMP will need to address this potential inconsistency.

In addition, activities allowed without permits under the CAO may require permits under the SMP. If you rely on the CAO for your regulatory provisions, you may need to create some limited exceptions in your SMP. You should carefully distinguish how the differences between the two are implemented. For example, a wetland impact in areas regulated by the SMP may need to be mitigated within shoreline jurisdiction. Ecology's wetlands and shorelines staff work closely together to address these kinds of complexities and are ready to help you navigate these issues.

Ecology's role in a CAO revision and adoption process is advisory when independent of the SMP. However, the SMP is a joint document of Ecology and the local government that requires Ecology approval. Before Ecology can approve the SMP, the CAO portion must meet the "no net loss of ecological functions" requirement and incorporate the most current, accurate, and complete scientific or technical information available (WAC 173-26-186[8][b][i][25] and WAC 173-26-201[2][a][26]). CAO regulations that do not meet the standards of the SMP Guidelines[27] must be changed to meet those standards before being incorporated into the SMP.

For assistance with CAO-SMP integration, you can find the Shoreline Planning and Permitting Staff contact information on Ecology's Shoreline Management Contacts webpage.[28]

[24] https://apps.leg.wa.gov/rcw/default.aspx?cite=90.58
[25] https://app.leg.wa.gov/wac/default.aspx?cite=173-26-186
[26] https://apps.leg.wa.gov/wac/default.aspx?cite=173-26-201
[27] https://apps.leg.wa.gov/WAC/default.aspx?cite=173-26
[28] https://ecology.wa.gov/Water-Shorelines/Shoreline-coastal-management/Shoreline-coastal-planning/Contacts

Your CAO Wetlands Chapter

Below we describe important subsections in the CAO wetlands chapter and include our recommendations for protecting wetlands based on the best available science (BAS).

Purpose

The wetlands section of a CAO typically begins with a purpose statement, followed by designation criteria, which include a definition of wetlands, the methods by which they are identified and rated, and other details listed below. The purpose statement may also state that this chapter is intended to be consistent with the requirements of Chapter 36-70A RCW[29] (the GMA) and implement the goals and policies of your comprehensive plan for protecting wetlands.

Definitions

Your CAO will need to include definitions for the wetlands chapter. You may use a separate list of definitions within the wetlands section, or the definitions may be included in the general definitions section of the CAO. Appendix B contains a list of definitions relevant to your wetlands chapter. This list includes terms identified in state law and agency guidance documents. Clarity and consistency in the use of these terms will make regulatory implementation easier.

Definition of wetlands

In designating wetlands for regulatory purposes, the GMA specifies the definition of wetlands as follows**:**

> "Wetland" or "wetlands" means areas that are inundated or saturated by surface water or ground water at a frequency and duration sufficient to support, and that under normal circumstances do support, a prevalence of vegetation typically adapted for life in saturated soil conditions. Wetlands generally include swamps, marshes, bogs, and similar areas. Wetlands do not include those artificial wetlands intentionally created from non-wetland sites, including, but not limited to, irrigation and drainage ditches, grass-lined swales, canals, detention facilities, wastewater treatment facilities, farm ponds, and landscape amenities, or those wetlands created after July 1, 1990, that were unintentionally created as a result of the construction of a road, street, or highway. Wetlands may include those artificial wetlands intentionally created from non-wetland areas created to mitigate conversion of wetlands. (RCW 36-70A-030[31][30])

[29] https://apps.leg.wa.gov/rcw/default.aspx?cite=36.70a
[30] https://app.leg.wa.gov/RCW/default.aspx?cite=36.70A.030

Counties and cities are required to use the definition of wetlands in RCW 36-70A-030(31) without any changes.

Wetlands are subject to a local government's regulatory authority if they meet the criteria in this definition. This includes non-federally regulated wetlands (sometimes referred to as isolated wetlands). The GMA requires local governments to designate and protect wetlands and grants them the authority to do so—regardless of federal jurisdiction.

Wetland identification

Many jurisdictions use the National Wetland Inventory (NWI) to help determine whether wetlands exist within their boundaries. Wetlands were identified for the NWI using aerial photographs. In many areas of Washington, the NWI has not been updated since the original maps were created using imagery from the late 1970s-1980s. As with all maps generated by remote sensing, **the NWI cannot be used alone to designate wetlands**. Wetlands are dynamic systems that can change over time. Therefore, not all wetlands will appear on the NWI, and some wetlands that do appear may no longer be present or may have a different configuration.

Wetland delineation

State laws require that wetlands protected under the GMA and the Shoreline Management Act (SMA) be delineated using the U.S. Army Corps of Engineers' (Corps) manual (U.S. Army Corps of Engineers, 1987) that is adopted into statute (RCW 36-70A-175;[31] RCW 90-58-380[32]). The Corps updated and expanded its delineation manual with the addition of regional supplements. The following regional supplements are used in Washington:

- Regional Supplement to the Corps of Engineers Wetland Delineation Manual: Arid West Region (U.S. Army Corps of Engineers, 2008)
- Regional Supplement to the Corps of Engineers Wetland Delineation Manual: Western Mountains, Valleys, and Coast Region (U.S. Army Corps of Engineers, 2010)

The regional supplements are used in conjunction with the federal delineation manual. To maintain consistency between the state and federal delineation of wetlands, Ecology updated the regulations (WAC 173-22-035[33]) to state that delineations shall be done according to the currently approved federal manual and regional supplements. **Therefore, the currently approved federal manual and applicable regional supplements (Western Mountains Valleys and Coasts, Arid West, or both) must be used for delineating wetlands in GMA jurisdictions,**

[31] https://apps.leg.wa.gov/rcw/default.aspx?cite=36.70A.175
[32] https://apps.leg.wa.gov/rcw/default.aspx?cite=90.58.380
[33] https://apps.leg.wa.gov/wac/default.aspx?cite=173-22-035

and local governments should refer to this requirement in their CAOs. The Corps' delineation manual and the regional supplements can be found on the Corps' delineation manual webpage.[34]

A wetland delineation should be performed by a qualified wetland professional.[35] The delineation should result in a wetland boundary clearly marked in the field and an accurate ground-verified map of the boundaries. This map should be created using either a professional survey or using an equivalent method such as Global Positioning System (GPS) with sub-meter accuracy. The map should also include an indication of where wetlands extend off site.

Wetland characterization

CAOs should include language that characterizes different wetlands, as wetland characteristics will be used in multiple ways—from assigning buffers to evaluating different types of mitigation.

Categorizing wetlands helps establish an appropriate level of protection that should be afforded to those wetlands. Ecology developed the Washington State Wetland Rating System, with versions for western Washington (Hruby, 2014a) and eastern Washington (Hruby, 2014b), as a useful tool for grouping wetlands that have similar needs for protection. Ecology's rating system provides a quick "snapshot" characterization of wetlands, evaluating them according to a standard methodology based on BAS. This system, which is based on a current understanding of wetland functions, helps determine what is needed to protect wetlands on a case-by-case basis. It helps inform land-use planning decisions and the review of individual development proposals.

Local governments are not required to use Ecology's rating system to characterize wetlands, but if a local government uses a different wetland rating system, it must consider the criteria described in WAC 365-190-090(3)[36] and use a system that is based on BAS.

While you are not required by law to use Ecology's rating system, we strongly encourage you to adopt wetland regulations that require its use. Most jurisdictions and qualified wetland professionals are already using the rating system. In cases where state and federal permits are required, the use of the rating system will greatly assist applicants by eliminating the need to also rate wetlands according to a different local standard.

Creation of a different rating system is a complex, time-consuming (and therefore costly) process. Ecology has dedicated a large amount of resources to the creation of its rating system

[34] https://www.usace.army.mil/Missions/Civil-Works/Regulatory-Program-and-Permits/reg_supp/
[35] https://ecology.wa.gov/Water-Shorelines/Wetlands/Tools-resources/Hiring-a-qualified-wetland-professional
[36] https://app.leg.wa.gov/wac/default.aspx?cite=365-190-090

using the most up-to-date BAS in order to remove the need for local governments to produce this level of work. Using Ecology's rating system is the most cost-efficient and readily accessible method available for local jurisdictions.

Use of wetland ratings, categories, and scores in the sample wetland regulations and appendices in this document are based on the Washington State wetland rating systems. If a different wetland rating system is used, the language in the sample wetland regulations (Appendix A) would be incompatible. Alternative language consistent with BAS would need to be developed, per the requirements of the GMA.

Wetlands inventory and pre-assessment

Conducting a wetlands inventory proactively may provide valuable information and benefits for local jurisdictions. This approach includes an accurate identification of some or all of the wetlands within a jurisdiction. In addition to the location of wetlands, a jurisdiction may benefit by applying wetland ratings. The jurisdiction would use the same wetland rating system, federal wetland delineation manual, and applicable regional supplements as would be required of applicants.

A map of wetland locations and pre-assessed ratings can provide valuable information to both planning staff and the public. Developing wetland maps and ratings can be resource-intensive to initiate, but such information will allow rapid review of development proposals and can help a jurisdiction prioritize areas for preservation or acquisition. It could also be accessed by land managers, developers, and property owners to facilitate more predictability in the permitting process. At least one jurisdiction has used pre-assessment to consider and support environmental justice and equitable access by providing valuable delineation information to local communities who may have economic, technological, and other barriers to accessing the data.

An inventory and pre-assessment approach is consistent with BAS. It can support the development of a broad approach to managing and protecting wetlands in your jurisdiction. Such an analysis also facilitates and informs long-range planning. The cities of Aberdeen and Sequim have used this approach in their previous CAO updates.

Older assessments will need to be revisited periodically because wetland delineations and ratings are generally considered valid for five years. However, updating existing information is an easier task than the initial assessment.

Regulated uses and activities

Your wetlands chapter should list uses and activities that are regulated under the CAO. These include vegetation removal, excavation, grading, discharging, filling or dredging of material of any kind; draining, flooding or altering the wetland water level or water table; the construction, reconstruction, demolition or expansion of any structure; etc. More extensive examples are provided in Sections 030 and 040 of Appendix A, Sample Wetland Regulations.

In general, changes in land use that would adversely affect wetland functions or established buffers, or eliminate portions of wetlands or buffers as the result of fill or grading, are the most significant[37] impacts to ecological functions. These activities will be regulated by the CAO, and appropriate protection standards (such as buffer requirements and mitigation sequencing) are required to minimize the loss of wetland area and function.

Wetlands are often impacted by unauthorized clearing and grading that takes place before application for development permits. You should make sure your CAO adequately regulates clearing, grading, and other land modifications. Your CAO should also include enforcement provisions for those activities conducted prior to approval.

Allowed uses, exemptions, and exceptions

CAOs typically contain a section that lists allowed uses, exemptions, and exceptions. Since they may not be required to obtain permits or undergo formal review, these activities should be limited to those actions that have little or no environmental effect or are in response to an emergency that threatens public health or safety.

Allowed uses

Your wetlands section should identify those activities in wetlands or buffers that are generally allowed (not regulated), those that are regulated through permits, and those that are regulated but exempt from permit requirements. In the case of emergency response activities affecting wetlands and/or buffers, the responsible party should be required to obtain after-the-fact permits and to rectify impacts. Some jurisdictions place the permit exemptions in a section near the beginning of the CAO. However, some exemptions may apply only to wetlands, so it may be more practical to have these specific exemptions in the wetlands chapter.

Exemptions

Exempt activities within your wetlands section should be restricted to those that will not have a significant impact on a wetland's structure and function (including its water, soil, or vegetation) or those that are expected to result in only short-term effects. Local governments should consider the potential for cumulative impacts from exempted activities. Cumulative impacts

[37] For context on what constitutes a significant impact see the SEPA definition of the term "significant" in WAC 197-11-794.

can result in a loss of wetland area and function that are not replaced through compensatory mitigation. Local governments should also be aware that some of these exempt activities and their impacts could be subject to the requirements of SEPA or other regulations.

Permit exemptions need to be supported by the scientific literature and be carefully stated to minimize adverse impacts. A local government cannot assume that a particular use or activity should be exempted from the regulatory process in the absence of science to support the exemption. The language needs to clearly state whether a given activity is exempt from applicable standards in the code or whether it is exempt only from needing a permit but still needs to comply with the code. Exemptions need to be limited and construed narrowly.

The scientific literature does not support exempting wetlands from the requirement to avoid or compensate for impacts based solely on size. While we recognize an administrative desire to place size thresholds on wetlands that are to be regulated, be aware that it is not possible to conclude from size alone what functions a particular wetland may be providing. That said, not all wetlands are equal in terms of their functions and values, or their ability to be replaced through compensatory mitigation.

It is reasonable, in the context of mitigation sequencing, to create some flexibility in dealing with small, low-functioning wetlands in some cases. The exemption language in Appendix A, Sample Wetland Regulations, offers an approach that includes appropriate safeguards and science-based limitations that minimize risk to wetland resources. It is limited to those wetlands where the Regional Supplement to the Corps of Engineers Wetland Delineation Manual: Western Mountains, Valleys, and Coast Region[38] (U.S. Army Corps of Engineers, 2010) is applicable.

Impacts to small wetlands are NOT exempt from the requirement to provide compensatory mitigation—regardless of the wetlands' size, location, or category.

It is our experience that wetlands, in general, are less common in areas covered by the Regional Supplement to the Corps of Engineers Wetland Delineation Manual: Arid West Region[39] (U.S. Army Corps of Engineers, 2008). Wetlands in this geographic region, regardless of size, play an outsized role due to their rarity in the landscape. An exemption based on size or functions is not appropriate in this region.

If a mitigation bank or in-lieu fee program is available in your area, these mitigation alternatives can help prevent a net loss of wetland function and area in the watershed from impacts to small wetlands in your jurisdiction (see page 27 for additional information on these programmatic mitigation alternatives).

[38] https://usace.contentdm.oclc.org/utils/getfile/collection/p266001coll1/id/7646
[39] https://usace.contentdm.oclc.org/utils/getfile/collection/p266001coll1/id/7627

For more information on exemptions, please refer to Chapter 8, Section 8.3.3 of Wetlands in Washington State, Volume 2 (Granger et al., 2005).[40]

Exceptions

Exceptions for public actions are typically addressed differently from exemptions or allowed uses. This category is generally reserved for public agency projects that may have inherent constraints on aspects like location and methodology. One example would be public utilities.

If the application of the critical areas regulations would prohibit a development proposal by a public agency or utility, the CAO may allow the agency or utility to apply for an exception. Exceptions should include criteria for review and approval and may be similar to those found in variance provisions or through a reasonable use exemption process. Exceptions should address mitigation sequencing.

For more information about exceptions, see Chapter 3 of the Critical Areas Assistance Handbook[41] (Commerce, 2018).

Forest practices

Most forest practices (Class I, II, and III, as defined in Chapter 76-09 RCW[42]) are exempted from the provisions of the wetlands chapter in the CAO. These activities are regulated through Chapter 76-09 RCW, the Forest Practices Act. Lands on which forest practices are performed under WA Department of Natural Resources (WA DNR) approved permits are automatically subject to a six-year development moratorium. Local governments have the authority to lift the moratorium through a SEPA action (WAC 197-11-938[43]). If such a process is undertaken, the local government should ensure that its SEPA determination includes conditions to restore any impacts to wetlands or their buffers that resulted from the forest practice. Wetland and buffer protections are important for offsetting the loss of habitat, filtration, and climate change mitigation functions that can result from loss of forest land.

Class IV general forest practices should also be regulated. Class IV activities constitute an intentional conversion from forestry to some other use. The local government should attach permit conditions as needed to ensure forest practice permits are consistent with CAO wetland and buffer protections. Restoration actions (e.g., replanting, road removal, etc.) may be necessary to achieve compliance.

[40] https://apps.ecology.wa.gov/publications/summarypages/0506008.html
[41] https://www.commerce.wa.gov/serving-communities/growth-management/guidebooks-and-resources/
[42] http://apps.leg.wa.gov/rcw/default.aspx?cite=76.09
[43] https://apps.leg.wa.gov/wac/default.aspx?cite=197-11&full=true

Agricultural activities

In 2011 the Washington State Legislature created the Voluntary Stewardship Program (VSP) as an alternative for meeting GMA requirements related to protecting critical areas in the context of existing agricultural lands. **The VSP applies only to counties that have opted into the program.** Counties that have opted into VSP address critical area issues related to agriculture through a VSP work plan. For more information on this program, see the Washington State Conservation Commission's VSP webpage.[44] **The VSP does not apply to cities or towns.** If you are a city or town—even in VSP counties—you will need to regulate agricultural activities that affect critical areas in your CAO (see RCW 36-70A-710[45]).

Regardless of VSP status, new agricultural activities on lands not previously in agricultural use are subject to wetland regulations. Clearing and grading for new agricultural activities on lands that are wetlands or their buffers and were not previously cultivated or managed for agriculture need to be regulated. Such actions can eliminate habitat, water filtration, flood control, and groundwater recharge functions that wetlands and their buffers provide. Disturbing wetlands to support new agricultural operations can also release significant amounts of carbon into the atmosphere that undisturbed soils and vegetation sequester from the environment.

Ecology recommends that non-VSP jurisdictions include specific language to address agricultural activities as suggested in the sample wetland regulations in Appendix A of this guidance. Example topics for non-VSP jurisdictions to address are described below and include: existing and ongoing agricultural activities, irrigation-induced wetlands, and prior converted croplands.

Existing and ongoing agricultural activities

Existing and ongoing agricultural activities are often exempted from the provisions of a CAO. These activities should be clearly defined and should not include: removing trees, diverting or impounding water, excavation, ditching, draining, culverting, filling, grading, or similar activities that introduce adverse impacts to wetlands. Maintenance of agricultural ditches—those channels created solely for agricultural irrigation (not a channelized stream)—should be limited to removing sediment in existing ditches to a depth specified by your jurisdiction. Wetlands that are not currently in agricultural use that are converted to an agricultural use are subject to the same regulations that govern new development.

For existing and ongoing agricultural activities in non-VSP jurisdictions, Ecology encourages the use of Natural Resource Conservation Service (NRCS) Best Management Practices (BMPs), farm conservation plans, and incentive-based programs to improve agricultural practices in and near

[44] https://www.scc.wa.gov/vsp
[45] https://app.leg.wa.gov/RCW/default.aspx?cite=36.70A.710

wetlands. The goal of the BMPs should be to ensure that ongoing agricultural activities in non-VSP jurisdictions minimize their effects on wetlands, water quality, riparian ecology, salmonid populations, and wildlife habitat. For more information on the NRCS resources, see their Conservation Practice Standards webpage.[46]

Irrigation-induced wetlands

Some wetlands in agricultural settings may include irrigation-induced wetlands. Irrigation projects, such as the Irrigation District ditches in Sequim or the Columbia Basin Irrigation Project in eastern Washington, can result in human-created wetlands. Wetlands that are within irrigation ditches that were intentionally created in uplands are exempt from regulation by definition.

Sometimes, however, irrigation practices will augment natural sources of water and result in creation or expansion of wetlands. If the creation or expansion of a wetland is the unintentional by-product of irrigation activities, the wetland needs to be regulated. However, if a wetland were to disappear as the result of a change in irrigation practices, its loss would not be regulated. Many wetlands will not disappear completely as a result of local changes in irrigation practices because natural sources of water or regional irrigation influences will continue. For more information, see Ecology's Irrigation-influenced wetlands webpage.[47]

Prior Converted Croplands

Prior converted croplands (PCC) are wetlands that, prior to December 23, 1985, were drained or otherwise manipulated to enable production of an agricultural commodity crop. State laws continue to regulate PCCs as wetlands if they meet the definition of wetlands **and** a change of use from agriculture is proposed. Please see Ecology's Prior converted croplands webpage[48] for more information.

[46] https://www.nrcs.usda.gov/resources/guides-and-instructions/conservation-practice-standards
[47] https://ecology.wa.gov/Water-Shorelines/Wetlands/Regulations/State-regulations/Irrigation-influenced-wetlands
[48] https://ecology.wa.gov/Water-Shorelines/Wetlands/Regulations/State-regulations/Prior-converted-croplands

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Protecting Wetland Functions

The current general approach to wetland regulation at the local level can be summarized as: avoid, buffer, compensate, and secure. This means:

- Avoid direct impacts to a wetland and its buffer to the extent practicable by allowing impacts only when there is no reasonable alternative.
- Buffer wetlands from impacts of adjacent land use through the retention of vegetated upland surrounding the wetland.
- Compensate for unavoidable impacts by requiring the replacement of wetland and/or buffer area and function through the restoration, creation, preservation, and/or enhancement of wetlands and/or their buffers
- Secure long-term protection of wetlands and their buffer areas through legal mechanisms.

The following paragraphs discuss key elements that should be addressed in the regulatory component of any local government's wetland program. For examples of recommended code language for each of these elements, please refer to Appendix A.

Mitigation sequencing

Applicants are required by state and federal regulatory agencies to show they have followed mitigation sequencing and have first avoided and minimized impacts to wetlands wherever practicable. Your CAO needs to include the definition of mitigation from Chapter 197-11 WAC[49] and a requirement for applicants to demonstrate that they have applied mitigation sequencing. For more information and sample checklists, see Ecology's Avoidance and Minimization webpage.[50]

Your CAO will need to include requirements on how to prevent or reduce impacts to wetlands. When an alteration to a wetland is proposed, mitigation will need to be implemented in the following order (WAC 197-11-768[51]):

1. Avoiding the impact altogether by not taking a certain action or parts of an action;
2. Minimizing impacts by limiting the degree or magnitude of the action and its implementation, by using appropriate technology, or by taking affirmative steps to avoid or reduce impacts;

[49] https://app.leg.wa.gov/WAC/default.aspx?cite=197-11
[50] https://ecology.wa.gov/Water-Shorelines/Wetlands/Mitigation/Avoidance-and-minimization
[51] https://app.leg.wa.gov/wac/default.aspx?cite=197-11-768

3. Rectifying the impact by repairing, rehabilitating, or restoring the affected environment;
4. Reducing or eliminating the impact over time by preservation and maintenance operations during the life of the action;
5. Compensating for the impact by replacing, enhancing, or providing substitute resources or environments; and/or
6. Monitoring the impact and taking appropriate corrective measures.

Buffers

Buffers are vegetated areas adjacent to wetlands that can reduce impacts from adjacent land uses through various physical, chemical, and/or biological processes. **The scientific literature is clear that buffers are necessary to protect wetland functions and values**. Buffers also provide their own habitat, water quality and quantity, and climate change mitigation (e.g., carbon sequestration) values independent of wetlands. Buffers are among the most important tools we have for protecting wetlands at the site level in Washington. The intent of this buffer guidance is to provide a predictable, reasonable, and straightforward approach for establishing buffers based on BAS. The literature consistently reports that the primary factors to evaluate in determining appropriate buffer widths are:

- The wetland type and the functions needing protection
- The types of adjacent land use and their expected impacts
- The characteristics of the buffer area (slope, soils, vegetation)

The recommended widths of buffers vary widely based on these three factors. For example, providing filtration of coarse sediment from residential development next to a low-quality wetland would require only a relatively flat buffer of dense grasses or forest/shrub vegetation in the range of 20 to 30 feet. However, providing forage and nesting habitat for common wetland-dependent species such as waterfowl or amphibians in a high-quality wetland adjacent to residential development would require a buffer vegetated with native trees and shrubs in the range of 200 to 300 feet. This illustrates the necessity of using an approach to buffers that incorporates a wetland's category and its functions (based on an appropriate rating system), types of land use, and the environmental characteristics of the existing buffer.

Ecology's buffer recommendations are based on a moderate-risk approach to protecting wetland functions. This means that by adopting Ecology's recommendations, there is a moderate risk that wetland functions will be impacted. Adopting narrower buffers represents a higher-risk approach, and you need to be prepared to justify, using BAS, why such an approach is necessary and to offer alternative means of protecting wetland functions that help reduce the risk.

Jurisdictions may choose to adopt a lower-risk approach. Implementation of such an approach should be based on BAS, and may necessitate such things as wider buffers with limited exemptions, exceptions, and averaging; and no administrative buffer reductions.

Ecology's buffer recommendations are based on the assumption that the buffer area is well vegetated with native species appropriate to the ecoregion. If the required buffer area does not consist of native vegetation adequate to provide the necessary protection, then either the buffer area should be planted or the buffer width should be increased (i.e., buffers should not be reduced in exchange for planting them). Planting a buffer with sufficient vegetation avoids an increase in buffer width.

Your CAO will require buffers for activities that impact wetland functions. Ecology's current buffer recommendations were first presented in *Wetlands in Washington State, Volume 2* (see the July 2018 modified Appendix 8-C [western WA][52] and Appendix 8-D [eastern WA][53] for reference). The present document collates the information from *Wetlands in Washington State, Volume 2,* and *Wetland Guidance for CAO Updates* (Western Washington and Eastern Washington) (Bunten et al., 2016a and 2016b), and provides further clarification and detail.

This document presents three different regulatory approaches to buffers—from Ecology's preferred recommendation of flexible and adaptive but complex, to the most rigid but simple.

These three different regulatory approaches provide ready-to-adopt buffer strategies, depending on your situation as explained below. The different buffer approaches are listed in Appendix C (western) and Appendix D (eastern) of this document. The buffer tables are in a format that you can adopt without additional study or documentation. The options are derived from *Wetlands in Washington State, Volume 2*. Buffer Option 1 is Ecology's preferred recommendation**.** Buffer Options 2 or 3, however, may be preferable for your jurisdiction. Each option is presented with language specific to western or eastern Washington in the appendices.

Buffer Option 1

This approach provides the most flexibility and site-specific buffers. Buffer widths are based on three factors: the wetland category, the level of impacts from adjacent land uses, and the functions or special characteristics of the wetland that need to be protected. Wetland category, functions, and special characteristics are determined by Ecology's wetland rating system (Hruby, 2014a; Hruby 2014b).

The buffer widths in Option 1 are larger for wetlands with higher habitat scores because BAS indicates habitat is the function that requires the largest buffer widths. Wetlands with higher

[52] https://apps.ecology.wa.gov/publications/parts/0506008part3.pdf
[53] https://apps.ecology.wa.gov/publications/parts/0506008part4.pdf

habitat scores are more likely to be in a less disturbed condition and require greater protection to maintain the habitat functions on site.

This approach includes options to reduce the buffer through provision of a habitat corridor and implementation of minimization measures to reduce the level of impact from the adjacent land use (whether proposed or existing). This is the best option for assigning buffers based on the potential for a wetland to provide functions and values and its need for protection. Using Option 1 also provides for the ability to vary the buffer widths through buffer averaging. See Appendix C (western) or Appendix D (eastern) for details on buffer Option 1.

In Option 1, the buffer widths in Table 1 require the use of the minimizing measures listed in Table 2 and provision of a corridor. These criteria allow for the reduced buffer widths listed in Table 1. Use the wider buffers in Table 3 when these criteria are not met. It is important to note that the reduced buffer widths associated with Table 1 **should not be used in conjunction with other reductions or variances** that are discussed below.

As noted above, Option 1 requires the protection of a habitat corridor, such as a stream corridor. The corridor should have a minimum width of 100' and connect wetlands that score 6 or more habitat points with any of the following:

- A legally protected, relatively undisturbed and vegetated area (e.g., Priority Habitats, other compensation sites, wildlife areas/refuges, or national, county and state parks where they have management plans with identified areas designated as Natural, Natural Forest, or Natural Area Preserve)
- An area that is the site of a Watershed Project identified within and fully consistent with a Watershed Plan, as these terms are defined by RCW 89-08-460[54]
- An area where development is prohibited per the provisions of the local shoreline master program
- An area with equivalent habitat quality that has conservation status in perpetuity, in consultation with WDFW

This requirement is particularly applicable in large or rural jurisdictions where it may be possible to provide species with access to other habitats to meet their life cycle needs. The wider buffers in Table 3 allow for greater potential for species to access other habitats to meet their life cycle needs while reductions in buffers reduce that potential. If a buffer reduction is allowed, there is no assurance that these species will have adequate access to habitat without providing a connective corridor. There may be other circumstances that would allow for the

[54] https://app.leg.wa.gov/rcw/default.aspx?cite=89.08.460

implementation of habitat corridors based on your local conditions. Ecology can work with you to identify these circumstances.

In urban areas, the best solution is a landscape-based approach that takes into account actual species use and spatial arrangement and connectivity of habitats. Without such an approach, jurisdictions should use the guidance provided in Appendix A, Sample Wetland Regulations.

Option 1 considerations

Option 1 buffer tables do not consider land-use impact in the buffer calculation since it is presumed that most urban and many rural land uses will be high or moderate impact. However, if your jurisdiction has uses or developments that can be considered low impact, such as a passive recreation area or nature park with unpaved trails, you may wish to prescribe a narrower buffer adjacent to the low-impact use only. The buffer width for any area should be no less than 75 percent of the otherwise required buffer width. Such a "low-impact" buffer is not appropriate for urban residential, commercial, or industrial uses. If your jurisdiction includes extensive areas of low-impact land uses such as large parklands or natural preserves, you may want to consider using the graduated buffer tables in Appendices 8-C or 8-D of *Wetlands in Washington State, Volume 2*, as described below.

Some wetlands with special characteristics listed in the buffer tables may not be present in your jurisdiction (e.g., wetlands in coastal lagoons, interdunal wetlands, etc.). If you are certain that these wetlands do not occur within your jurisdiction and would not be introduced by future annexations, you can remove those wetland types from the buffer tables.

An expanded table with graduated buffer widths based on habitat score is also outlined in the July 2018 Appendix 8-C (western WA)[55] and Appendix 8-D (eastern WA)[56] of *Wetlands in Washington State, Volume 2*. This is an approach for those jurisdictions that prefer to have more gradual steps in buffer widths based on individual habitat scores rather than groupings. This expanded table is not included in the present document out of a desire for simplicity and the fact that it is not commonly used.

Buffer Option 2

Widths in this option are based on wetland category as determined by Ecology's wetland rating system (Hruby, 2014a; Hruby 2014b) and the level of impact from the adjacent proposed or existing land use.

This second option decreases regulatory flexibility by eliminating the options for buffer averaging and buffer reductions through the provision of corridors and minimization measures. It includes recognition that not all proposed changes in land uses have the same level of impact.

[55] https://apps.ecology.wa.gov/publications/parts/0506008part3.pdf
[56] https://apps.ecology.wa.gov/publications/parts/0506008part4.pdf

For example, one new residence being built on five acres of land near a wetland is expected to have a smaller impact than 20 houses built on the same five acres. Three categories of impacts from proposed land uses are outlined in Option 2: land uses that can create high impacts, moderate impacts, or low impacts to wetlands. Use of this alternative necessitates inclusion of a table with levels of impacts from proposed land use types, which is included in Appendices C and D.

Buffer Option 3

The width of buffers in this option is based solely on the category of the wetland as determined by Ecology's wetland rating system (Hruby, 2014a; Hruby 2014b). It is the simplest to administer; however, it is the least flexible. Under this option, buffers need to be large enough to protect the most-sensitive wetlands from the most-damaging land use impacts.

Option 3 provides the least flexibility because all types of adjacent land uses are considered at the same level of impact when assigning buffer widths, without regard for a wetland's habitat score. The widths recommended for this option are those needed to protect the wetland from adjacent, high-intensity land uses since no distinctions between levels of impact are made.

Jurisdictions with limited staff or wetland types may prefer to use this method even though it is the least flexible. Note that with this option, Category III wetlands with high habitat function (8-9 points) will not have a sufficiently wide buffer for adequate protection. Jurisdictions should determine whether Category III wetlands with high habitat function are likely present. If so, adjustments to the buffer table may be needed.

Functionally disconnected buffer areas

In some cases, regulatory buffers include areas that are functionally disconnected from the wetland. This means that existing, legally established development blocks the protective measures that a buffer provides and increasing the buffer on the far side of the development would add no protective benefit. A local CAO should anticipate these situations and provide clear direction on how to address them. The most effective provisions provide specific criteria to reduce uncertainty about how to determine whether a given area is functionally disconnected.

You should exercise care to differentiate minor developments from significant developments that completely block wetland buffer functions. Examples of minor developments that do not fully block buffer functions include trails, minor accessory structures, paths, and driveways serving a single residence. Significant developments that are unquestionably a complete barrier to the functions of the buffer area include built public infrastructure such as paved roads and railroads, and private developments such as houses or commercial structures. In addition, you should evaluate whether the interruption will affect the entirety of the buffer. Individual

structures may not fully interrupt buffer function. In such cases, the allowable buffer exclusion should be limited in scope to just that portion of the buffer that is affected.

Signs and fencing

Installation of signs and fencing are recommended methods of ensuring protection of wetlands and their buffers. During the construction phase, constructing a temporary sediment fence or "clearing limits" fence helps to ensure that the boundary is seen by equipment operators and that the wetland and buffer are protected from erosion during construction. Following construction, a permanent, wildlife-friendly fence is generally necessary to demarcate the outer boundary of the buffer and to limit human and pet access.

Placement of signs along the buffer boundary is important for two reasons: to help mark the boundary, and to help educate landowners about the purpose and value of protecting buffer areas. In areas with high potential for human intrusion and degradation of the buffer, more extensive signage explaining the value of the buffer may be necessary to develop support for protecting the buffer. Care should be taken to develop effective and accessible signage that is easily understood by all members of the community. Such an approach supports a jurisdiction's environmental justice efforts and nondiscrimination obligations.

Buffer averaging

Local governments can allow buffer widths to vary in certain circumstances. This may be reasonable if your standard buffers are adequate. The width of buffers may be averaged if this will improve the protection of wetland functions or if it is the only way to allow for reasonable use of a parcel. Buffer averaging should not be combined with other buffer reductions.

We recommend that a request for buffer averaging include a wetland report. The report should be prepared by a qualified wetland professional describing the current functions of the wetland and its buffer, and the measures that will be taken to ensure that there is no loss of wetland or buffer function due to the buffer averaging. The width of the buffer at any given point after averaging should be no narrower than 75 percent of the standard buffer, and the total area of the buffer after averaging should be equal to that of the standard buffer before averaging. This means that part of the buffer will be wider to account for the area lost where the buffer was narrowed.

Compensatory mitigation for wetland impacts

Wetland impacts must be avoided and minimized to the greatest extent practicable. **Unavoidable impacts to wetlands must be offset by compensatory mitigation to achieve no net loss of wetland function.** Your CAO should include standards for the type, location, amount, and timing of the compensatory mitigation. It should include clear guidance on the design considerations and reporting requirements for mitigation plans.

In 2008, the U.S. Army Corps of Engineers (Corps) and the U.S. Environmental Protection Agency (EPA) issued a federal rule governing compensatory mitigation. This rule established comprehensive standards for all types of mitigation under the Clean Water Act Section 404 Regulatory Program. For more information on the federal rule, see the EPA's Background about Compensatory Mitigation Requirements under CWA Section 404.[57]

Ecology, the Corps, and the EPA recently updated the state interagency mitigation guidance, which includes requirements from the federal rule and other advances in mitigation policies and tools. The updated guidance contains the policies and requirements for compensatory mitigation under both state and federal regulations. For example, compensatory mitigation should be permanently protected and include appropriate perimeter buffers. We urge all jurisdictions to consult both parts of the interagency guidance on mitigation: Wetland Mitigation in Washington State, Part 1 - Agency Policies and Guidance[58] (Ecology et al., 2021) and Developing Mitigation Plans[59] (Ecology et al., 2006). We recommend referring to Ecology's Interagency wetland mitigation guidance webpage[60] to make sure you are using the most up-to-date versions of the mitigation guidance.

By adopting mitigation standards based on the state and federal guidance and rules, you will be providing consistency for applicants who also apply for state and federal permits.

Approaches to compensatory mitigation

Applicants with unavoidable impacts to wetlands have options for meeting their compensatory mitigation requirements. The options for compensatory mitigation generally fall into two categories—programmatic approaches and permittee-responsible approaches—and are based on who bears the responsibility for successfully establishing the compensatory mitigation site. These are described as follows:

- Programmatic mitigation: the permittee pays a third-party sponsor to assume responsibility for successfully compensating for unavoidable impacts.
- Permittee-responsible mitigation (PRM): the permittee retains full responsibility to successfully compensate for unavoidable impacts.

[57] http://water.epa.gov/lawsregs/guidance/wetlands/wetlandsmitigation_index.cfm
[58] https://apps.ecology.wa.gov/publications/summarypages/2106003.html
[59] https://apps.ecology.wa.gov/publications/summarypages/0606011b.html
[60] https://ecology.wa.gov/Water-Shorelines/Wetlands/Mitigation/Interagency-guidance

Programmatic mitigation

Programmatic mitigation refers to compensatory mitigation done by a third-party sponsor. The sponsor accepts payment from the permittee with the authorized wetland impacts. In exchange, the sponsor assumes responsibility for successfully compensating for the permittee's unavoidable impacts.

Programmatic mitigation generally involves combining compensatory mitigation for two or more projects affecting wetlands or other aquatic resources. These approaches often involve compensatory mitigation projects designed to restore and maintain environmental processes in a larger landscape context. Two programmatic approaches are currently being used in Washington:

- Wetland mitigation banking (mitigation banks)
- In-lieu fee (ILF) mitigation

These two approaches are described in more detail below. It is important to note that not all programmatic approaches (if any) are available in all locations. If mitigation banks or ILF programs are available, or may be available in the future, we recommend that your CAO allow for these options. They can be effective and valuable tools in preventing a net loss of wetland area and functions.

Wetland mitigation banking

A wetland mitigation bank is a site or group of sites where a third-party sponsor re-establishes, rehabilitates, creates, preserves, or enhances wetlands to generate compensatory mitigation credits. Mitigation bank sponsors can be local jurisdictions, public agencies, tribes, or private entrepreneurs.

The mitigation bank credits are sold to permittees who need to compensate for their unavoidable impacts[61] to wetlands or other aquatic resources within the designated service area of the bank. Bank site locations and service areas are required to be chosen using a watershed approach and they are established in advance of the unavoidable impacts for which they compensate. This ensures that the banks are ecologically successful before credits are sold.

[61] Banks cannot be used to circumvent the requirement to avoid and minimize impacts.

Wetland mitigation banking has the potential to restore and preserve ecological functions, save money for project applicants, and improve efficiencies in application and permitting processes. Across the state, numerous banks have been approved through the certification process or are currently under review. To learn more about wetland mitigation banking, see Ecology's Wetland mitigation banking webpage.[62]

In-lieu fee (ILF) mitigation

In this approach to compensatory mitigation, a permittee pays a fee to a third party in lieu of conducting project-specific mitigation or buying credits from a mitigation bank. The collected fees are combined to implement a single, larger compensation site. An ILF program uses the fees collected to restore, establish, preserve, and/or enhance wetland functions within the same service area (i.e., watershed or river basin) as the wetland impacts. Only governmental or non-profit natural resource management entities may serve as ILF program sponsors since ILF programs are not-for-profit efforts.

Fees for an ILF program represent the expected costs to a third party for replacing the wetland functions lost or degraded as a result of the permittee's unavoidable impacts. Fees are typically held in trust until sufficient funds have been collected to finance a mitigation project. Federal rules require that initial work on the mitigation project must begin no more than three years after the first fees have been collected. All ILF programs have to be approved by the Corps in order to be used for Section 404 permits. Not all jurisdictions have an ILF program currently available. To learn more about ILF programs, see Ecology's In-lieu fee mitigation webpage.[63]

If a proposed project is located within the service area of a Corps-approved mitigation bank or ILF Program, per the 2008 Federal Mitigation Rule, the applicant must first consider their use as compensatory mitigation before considering the permittee-responsible mitigation options discussed in the next section.

[62] https://ecology.wa.gov/Water-Shorelines/Wetlands/Mitigation/Wetland-mitigation-banking
[63] https://ecology.wa.gov/Water-Shorelines/Wetlands/Mitigation/In-lieu-fee-mitigation

Permittee-responsible mitigation

Permittee-responsible mitigation (PRM) is an approach in which the permittee retains full responsibility to successfully compensate for unavoidable impacts. In other words, the individual or entity proposing the impact(s) must successfully implement all aspects of the compensation, including site selection, site design, construction, planting, maintenance, monitoring, and site protection. PRM is further defined by the timing of its implementation.

Concurrent mitigation

Concurrent mitigation is when the permittee performs the compensation after the permit is issued and at the time of the impacts. It may occur at the site of the permitted impacts or at an off-site location, usually within the same watershed or sub-drainage basin to support a watershed approach. The permittee is responsible for implementation and success of the compensation.

Wetland compensatory mitigation sites take time to develop. Temporal loss of wetland functions is unavoidable even though concurrent mitigation occurs at the time of impact. It can take from five to over 100 years for the compensation site to mature and replace functions or provide similar functions. In addition, there is a risk that the compensatory mitigation site will fail to provide the required amount of wetland area, the planned wetland functions, or both. Therefore, the amount of compensation required by the agencies is almost always greater than the area of impact (i.e., greater than a 1:1 ratio).

Advance mitigation

When compensatory mitigation is implemented before, and in anticipation of, future impacts to wetlands, it is referred to as "advance mitigation." Specific impacts do not need to be known at the time an advance mitigation site is established. However, the advance mitigation agreement should specify a geographic service area (i.e., the proposed area in which all potential future impacts may occur). Since the mitigation would already be in place, it would provide reduced temporal loss, decreased risk of failure, and is generally more cost effective. Advance mitigation lets an applicant provide compensation needed for one or more future projects or phases of construction affecting wetlands at one time.

Although similar to mitigation banking, advance mitigation is different in several ways. Most importantly, advance mitigation may only be used to compensate for the permittee's own impacts to wetlands. Credits cannot be sold or transferred to another permittee. If a permittee wants the ability to sell or transfer credits to another entity, the compensation project must go through the wetland mitigation banking certification process. To learn more about advance mitigation, see Ecology's Advance mitigation webpage.[64]

[64] https://ecology.wa.gov/Water-Shorelines/Wetlands/Mitigation/Advance-mitigation

Determining mitigation adequacy

Choosing the location for compensatory mitigation using a watershed approach

Selecting an appropriate location to conduct compensatory mitigation is one of the most critical aspects of providing acceptable wetland compensation. State and federal regulatory agencies require applicants to use a watershed approach for compensatory mitigation to the extent appropriate and practicable. The goal of a watershed approach is to maintain and improve the quality and quantity of aquatic resources within watersheds through strategic selection of compensatory mitigation sites.

A watershed approach may include on-site compensatory mitigation, off-site compensatory mitigation (including mitigation banks or in-lieu fee programs), or a combination of on-site and off-site compensatory mitigation. Where relevant watershed plans are available, compensation sites should be located in areas targeted by those plans for restoring environmental processes.

Ecology recommends including a stepwise watershed approach for choosing the location of a compensatory mitigation site in your wetlands chapter. An example approach can be found in Chapter 6A of Wetland Mitigation in Washington State, Part 1 - Agency Policies and Guidance[65] (Ecology et al., 2021).

Compensating for area

Compensatory mitigation has traditionally focused on the wetland area needed to offset the loss or degradation of wetland area and functions. Regulatory agencies use area-based ratios to account for authorized impacts and compensation because it is relatively easy to determine the area of a wetland. Many CAOs have ratio-based mitigation tables.

Ecology's recommendations for the amount of compensatory mitigation (ratios) are based on wetland category, function, special characteristics, risk, and temporal loss. Requiring a greater area for mitigation than the wetland area that will be impacted helps offset both the risk that compensatory mitigation will fail and the temporal loss of functions that may occur. We recommend using the recently updated ratio tables shown in Appendix E, Mitigation Ratio Tables. They are derived from the more-detailed tables in Part 1 of the interagency guidance on mitigation, Wetland Mitigation in Washington State, Part 1 – Agency Policies and Guidance[66] (Ecology et al., 2021).

[65] https://apps.ecology.wa.gov/publications/summarypages/2106003.html
[66] ibid

Some wetlands with special characteristics listed in Appendix E, Table 2, may not be present in your jurisdiction (e.g., wetlands in coastal lagoons, interdunal wetlands, etc.). If you are certain that these wetlands do not occur within your jurisdiction and would not be introduced by future annexations, you can remove those wetland types from the ratio tables.

Wetlands with special characteristics

Some types of wetlands have special characteristics that determine their rating category according to Ecology's rating system (see Hruby, 2014a; Hruby, 2014b). The Washington wetland rating system was designed to differentiate between wetlands based on their sensitivity to disturbance, their significance, their rarity, our ability to replace them, and the functions they provide. The first four criteria can be considered as values that are somewhat independent of the functions provided by a wetland. Wetlands with Special Characteristics (as identified in the Ecology's rating system) have an importance or value that may supersede their functions or that is not addressed by the rating of functions.

Methods of compensation are severely limited for certain wetlands with special characteristics. Some of these wetland types only occur naturally and have never been successfully created or rehabilitated. Some may take more than a lifetime to re-establish. Thus, avoidance is the best regulatory approach when addressing these wetlands. Refer to Chapter 6B.5 of Wetland Mitigation in Washington State Part 1 – Agency Policies and Guidance[67] for more information on methods of compensation and ratios for wetlands with special characteristics.

[67] https://apps.ecology.wa.gov/publications/summarypages/2106003.html

Compensating for functions

In addition to accounting for the area of proposed impacts and compensation, the applicant should analyze the wetland functions at both the proposed wetland impact site and the proposed compensation site. The analysis of functions at the proposed compensation site, pre- and post-mitigation, provides an estimate of the gain in functions, or "functional lift," that is expected. This lift is then compared to the functions to be lost or degraded at the impact site. In most cases, the compensatory mitigation would be sufficient only if the expected "lift" at the compensation site equals or exceeds the loss of wetland functions at the impact site.

The 2008 Federal Mitigation Rule states, "In cases where appropriate function or condition assessment methods or other suitable metrics are available, these methods should be used where practicable to determine how much compensatory mitigation is required."

Credit-Debit Method

Ecology has developed a Credit-Debit Method for calculating when a proposed wetland mitigation project adequately replaces the functions and values lost when wetlands are impacted. The tool is designed to provide guidance for both regulators and applicants during two stages of the mitigation process:

1. Estimating the functions and values lost when a wetland is altered (debits), and
2. Estimating the gain in functions and values that result from the mitigation (credits).

Ecology encourages use of the Credit-Debit Method and recommends that your CAO allow for its use. This tool provides a quantitative method for determining the adequacy of compensatory wetland mitigation, and it allows review of compensation for specific wetland functions. It is also a way to demonstrate functional lift. See the Credit-Debit web page[68] for the documents and worksheets.

Most ILF programs use the Credit-Debit Method for determining the number of debits generated by an impact project and the credits available for compensation. Mitigation banks do not currently use the Credit-Debit Method and instead rely on traditional area-based ratios. The amount of mitigation (credits) needed should be evaluated in a manner consistent with the crediting methodology found in the mitigation program's certification documents (i.e., the ILF Instrument or Mitigation Bank Instrument).

[68] https://ecology.wa.gov/Water-Shorelines/Wetlands/Tools-resources/Credit-debit-method

Securing long-term protection

Wetlands and their buffers need long-term protection to prevent degradation over time. Protection includes site ownership with legal mechanisms to prevent future development and buffers that serve to maintain the wetland functions. Site ownership, deed restrictions, and conservation easements are examples of legal mechanisms.

The most effective long-term protection is to place the wetland and buffer in a non-buildable tract that is owned and maintained by an organization dedicated to protecting them. The boundaries of that tract should be clearly marked to help prevent unintentional encroachments. Delineation, recording, and signage clearly denoting the buffer and wetland area helps prevent degradation over time. Following project approval, and prior to site construction, the buffer and wetland should be measured, recorded on binding legal documents, and clearly marked on the ground.

At a minimum, the wetland and buffer tract should be recorded on the property deed with language restricting actions that may adversely impact the wetland and buffer.

Compensatory mitigation for buffer impacts

Ecology recommends that buffer impacts be mitigated at a ratio of at least 1:1, area for area. However, if an entire wetland is lost, we do not recommend that your CAO require compensatory mitigation for the lost buffer area. In absence of the wetland, a buffer would not provide functions that protect the wetland. Instead, we recommend that the compensatory mitigation site for the lost wetland have adequate buffers, per the buffer guidance in this document.

Enforcement/Penalty Provisions

Enforcement of critical areas ordinances is vital to maintain the clean air, land and water, and reliable water supplies that residents and businesses in Washington depend on to flourish. The wetlands chapter of your CAO should contain provisions establishing enforcement authority and penalties. Appendix A includes sample language. The Critical Areas Handbook[69] (Commerce, 2018) also provides sample language for enforcement and penalty provisions. However, each jurisdiction may already have general policies and procedures regarding enforcement and penalties. Ecology advises that you work with your jurisdiction's legal counsel on how to address critical areas ordinance violations in context with this larger framework.

Regulatory Takings

Regulatory takings are complex legal issues that can arise when government regulations restrict the use of private property. You should be aware that regulatory takings can arise in the administration of your CAO. Therefore, we recommend that your CAO include a variance and reasonable use exception process to address situations where strict compliance with regulations would deprive a property owner of all reasonable use of the property. However, this does not preclude governments from imposing reasonable limitations or restrictions. The variance or reasonable use exception process should be available only in the most extreme cases. Ecology advises that you contact your jurisdiction's legal counsel to determine the best approach. A helpful summary of takings issues can be found at the Municipal Research Services Center webpage.[70] You may also consult the Critical Areas Handbook[71] (Commerce, 2018; see Chapter 3, page 12) on how to address regulatory takings.

[69] https://www.commerce.wa.gov/serving-communities/growth-management/growth-management-topics/critical-areas/

[70] http://mrsc.org/Home/Explore-Topics/Environment/Special-Topics/Flexibility-in-Environmental-Regulation.aspx

[71] https://www.commerce.wa.gov/serving-communities/growth-management/growth-management-topics/critical-areas/

Summary

To effectively protect wetlands in your jurisdiction and to meet your responsibility to protect critical areas, you should address the issues discussed in this publication in your CAO. Ecology endeavors to present these issues in a format that is easy to understand. The complexities of your individual regulatory structure will inform how you address these issues in your jurisdiction. Ecology is eager to assist you in what can seem like a complex and formidable task. Developing the wetlands chapter of your CAO can be challenging, but Ecology's technical resources and assistance can make the task more manageable and understandable.

The following is a general outline of the issues you should address in the wetlands section of your CAO and for which you will find specific guidance in this document:

1. Purpose statement
2. Definition of terms—include RCW definition of wetlands
3. Identifying wetlands
4. Delineation—use the federal wetlands delineation manual with the appropriate regional supplement
5. Characterization—we strongly recommend you use the Washington State Wetland Rating System
6. Regulated uses and activities
7. Allowed uses, exemptions, and exceptions
8. Forest practices
9. Agricultural activities
10. Mitigation sequencing
11. Buffers
12. Functionally disconnected buffers
13. Signs and fencing
14. Buffer averaging
15. Compensatory mitigation for wetland impacts
16. Mitigation approaches
17. Determining mitigation adequacy
18. Securing long-term protection
19. Enforcement/penalty provisions
20. Regulatory takings

If you have general questions about this document or need additional assistance with the wetlands chapter of your critical areas ordinance update, please contact Ecology's wetland critical areas ordinance review coordinator. You may also contact Ecology's regional wetland specialist who covers your area. They are available to work with you during your update process. For example, they may be able to offer presentations to elected officials, planning commissions, and planning staff. They can also provide technical assistance, including help with review of wetland ratings, ordinary high water mark determinations, questions about wetland delineations, and project review.

For current Ecology contacts go to Ecology's wetland contacts webpage.[72]

The Department of Commerce offers tools, resources, and assistance for a wide range of issues and situations. For example, Commerce is working with four Puget Sound counties on a Transfer of Development Rights[73] (TDR) program. For jurisdictions in these four counties, you may wish to explore their publication, A Resource Guide to Designing Transfer of Development Rights Programs in Washington State.[74]

For assistance with topics other than the wetlands section of your CAO, please contact the Department of Commerce directly. And for general information on a broad range of local government issues, see Commerce's Local Government Portal.[75]

[72] https://ecology.wa.gov/Water-Shorelines/Wetlands/Tools-resources/Contacts-by-subject-region
[73] http://www.commerce.wa.gov/serving-communities/growth-management/growth-management-topics/development-rights/
[74] https://deptofcommerce.app.box.com/s/pbi8qhqijcv6jn6u5raztdw028htjimc
[75] https://www.commerce.wa.gov/serving-communities/local-government/

References

This publication is part of a significant agency action under RCW 34-05-272. To meet the requirements of the law, the sources of information used to support this action are identified. The required 11 types of sources are listed below by number. Each reference is followed by a bracketed number that indicates the source.

1. Independent peer review: Review is overseen by an independent third party.
2. Internal peer review: Review by staff internal to the Department of Ecology.
3. External peer review: Review by persons that are external to and selected by the Department of Ecology.
4. Open review: Documented open public review process that is not limited to invited organizations or individuals.
5. Federal and state statutes.
6. Court and hearings board decisions.
7. Federal and state administrative rules and regulations.
8. Policy and regulatory documents adopted by local governments.
9. Data from primary research, monitoring activities, or other sources, but that has not been incorporated as part of documents reviewed under the processes described in numbers 1, 2, or 3 of this list.
10. Records of best professional judgment of Department of Ecology employees or other individuals.
11. Other: Sources of information that do not fit into one of the other categories listed.

Bunten, D., Mraz, R., Driscoll, L., & Yahnke, A. (2016a). *Wetland Guidance for CAO Updates: Western Washington Version* (Ecology Publication #16-06-001). Washington State Department of Ecology. https://apps.ecology.wa.gov/publications/summarypages/1606001.html [2]

Bunten, D., Mraz, R., Driscoll, L., & Yahnke, A. (2016b). *Wetland Guidance for CAO Updates: Eastern Washington Version* (Ecology Publication #16-06-002). Washington State Department of Ecology. https://apps.ecology.wa.gov/publications/summarypages/1606002.html [2}

Commerce. See Washington State Department of Commerce.

Compensatory Mitigation for Losses of Aquatic Resources; Final Rule, 33 CFR Sections 325 and 332 and 40 CFR Section 230 (2008). https://www.epa.gov/cwa-404/compensatory-mitigation-losses-aquatic-resources-under-cwa-section-404-final-rule [7]

Corps. See U.S. Army Corps of Engineers.

Ecology. See Washington State Department of Ecology.

Federal Geographic Data Committee. (2013). *Classification of wetlands and deepwater habitats of the United States* (2nd ed.) (FGDC-STD-004-2013). Wetlands Subcommittee, Federal Geographic Data Committee and U.S. Fish and Wildlife Service. https://www.fgdc.gov/standards/projects/FGDC-standards-projects/wetlands/nvcs-2013 [4]

Federal Mitigation Rule. See Compensatory Mitigation for Losses of Aquatic Resources; Final Rule. 2008. [7]

Granger, T., Hruby, T., McMillan, A., Peters, D., Rubey, J., Sheldon, D., Stanley, S., & Stockdale, E. (2005). *Wetlands in Washington State - Volume 2: Guidance for Protecting and Managing Wetlands* (Ecology Publication #05-06-008). Washington State Department of Ecology. https://apps.ecology.wa.gov/publications/summarypages/0506008.html [4]

Hruby, T., Bunten, D., Yahnke, A., & Franklin, J. (2017). *Characterizing Wetland Buffers in Washington State*. (Ecology Publication #17-06-008). Washington State Department of Ecology. https://apps.ecology.wa.gov/publications/SummaryPages/1706008.html [4]

Hruby, T., Harper, K., & Stanley, S. (2009). *Selecting Wetland Mitigation Sites Using a Watershed Approach (Western Washington)* (Ecology Publication #09-06-032). Washington State Department of Ecology. https://apps.ecology.wa.gov/publications/SummaryPages/0906032.html [4]

Hruby, T., Harper, K., & Stanley, S. (2010). *Selecting Wetland Mitigation Sites Using a Watershed Approach (Eastern Washington)* (Ecology Publication #10-06-007). Washington State Department of Ecology. https://apps.ecology.wa.gov/publications/SummaryPages/1006007.html [4]

Hruby, T. (2012a). *Calculating Credits and Debits for Compensatory Mitigation in Wetlands of Western Washington* (Ecology Publication #10-06-011). Washington State Department of Ecology. https://apps.ecology.wa.gov/publications/summarypages/1006011.html [4]

Hruby, T. (2012b). *Calculating Credits and Debits for Compensatory Mitigation in Wetlands of Eastern Washington* (Ecology Publication #11-06-015). Washington State Department of Ecology. https://apps.ecology.wa.gov/publications/summarypages/1106015.html [4]

Hruby, T. (2013). *Update on Wetland Buffers: The State of the Science, Final Report* (Ecology Publication #13-06-11). Washington State Department of Ecology. https://apps.ecology.wa.gov/publications/SummaryPages/1306011.html [4]

Hruby, T. (2014a). *Washington State Wetland Rating System for Western Washington–2014 Update* (Ecology Publication #14-06-029). Washington State Department of Ecology. https://apps.ecology.wa.gov/publications/SummaryPages/1406029.html [4]

Hruby, T. (2014b). *Washington State Wetland Rating System for Eastern Washington–2014 Update* (Ecology Publication #14-06-030). Washington State Department of Ecology. https://apps.ecology.wa.gov/publications/SummaryPages/1406030.html [4]

Sheldon, D., Hruby, T., Johnson, P., Harper, K., McMillan, A., Stanley, S., & Stockdale, E. (2005). *Wetlands in Washington State–Volume 1: A Synthesis of the Science* (Ecology Publication #05-06-006). Washington State Department of Ecology. https://apps.ecology.wa.gov/publications/summarypages/0506006.html [4]

U.S. Army Corps of Engineers. (1987). *Corps of Engineers Wetlands Delineation Manual* (Technical Report Y-87-1 [online edition]). U.S. Army Corps of Engineers Waterways Experiment Station. https://usace.contentdm.oclc.org/digital/collection/p266001coll1/id/4530 [4]

U.S. Army Corps of Engineers. (2008). *Regional Supplement to the Corps of Engineers Wetland Delineation Manual: Arid West Region (Version 2.0)* (J. S. Wakeley, R. W. Lichvar, & C. V. Noble Eds.). U.S. Army Engineer Research and Development Center. https://usace.contentdm.oclc.org/utils/getfile/collection/p266001coll1/id/7627 [4]

U.S. Army Corps of Engineers. (2010). *Regional Supplement to the Corps of Engineers Wetland Delineation Manual: Western Mountains, Valleys, and Coast Region (Version 2.0)* (J. S. Wakeley, R. W. Lichvar, & C. V. Noble Eds.). U.S. Army Engineer Research and Development Center. https://usace.contentdm.oclc.org/utils/getfile/collection/p266001coll1/id/7646 [4]

Washington State Department of Commerce. (2018). Critical Areas Handbook: A Handbook for Reviewing Critical Areas Regulations. https://deptofcommerce.box.com/shared/static/3s5d5or3tdn21i7lhf9y22v8hgoqoodu.pdf [4]

Washington State Department of Ecology, U.S. Army Corps of Engineers Seattle District, and U.S. Environmental Protection Agency Region 10. (2006). *Wetland Mitigation in Washington State – Part 2: Developing Mitigation Plans (Version 1)*. (Ecology Publication #06-06-011b). Washington State Department of Ecology. https://apps.ecology.wa.gov/publications/summarypages/0606011b.html [4]

Washington State Department of Ecology, U.S. Army Corps of Engineers Seattle District, and U.S. Environmental Protection Agency Region 10. (2021). *Wetland Mitigation in Washington State–Part 1: Agency Policies and Guidance (Version 2)*. (Ecology Publication #21-06-003). Washington State Department of Ecology. https://apps.ecology.wa.gov/publications/summarypages/2106003.html [4]

Appendix A. Sample Wetland Regulations

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Subchapter 100
(individual numbering will vary)
Wetlands

Sections

010 Purpose

020 Identification and Rating

030 Regulated Activities

040 Exemptions and Allowed Uses

050 Buffers

060 Critical Area Reports

070 Compensatory Mitigation

080 Unauthorized Alterations and Enforcement

010 Purpose

The purposes of this Chapter are to:

010.A. Recognize and protect the beneficial functions performed by many wetlands, which include, but are not limited to, providing food, breeding, nesting and/or rearing habitat for fish and wildlife; recharging and discharging ground water; contributing to stream flow during low flow periods; stabilizing stream banks and shorelines; storing storm and flood waters to reduce flooding and erosion; carbon sequestration; thermal refugia, and improving water quality through biofiltration, adsorption, retention, and transformation of sediments, nutrients, and toxicants.

010.B. Regulate land use to avoid adverse effects on wetlands and maintain the functions and values of wetlands throughout [City/County].

010.C. Establish review procedures for development proposals in and adjacent to wetlands.

1. Compliance with the provisions of this Chapter does not necessarily constitute compliance with other federal, state, and local regulations and permit requirements that may be required (for example, Shoreline permits, Hydraulic Project Approval permits, Clean Water Act Section 404 permits and 401 certifications, Ecology Administrative Orders, or NPDES permits). The applicant

is responsible for complying with these requirements, apart from the processes established in this Chapter.

020 Identification, Delineation, and Rating

020.A. Identification and Delineation. Identification of wetlands and delineation of their boundaries pursuant to this Chapter shall be done in accordance with the approved federal wetland delineation manual and applicable regional supplement. All areas within the [City/County] meeting the wetland definition and designation criteria in that procedure are hereby designated critical areas and are subject to the provisions of this Chapter. Wetland delineations are valid for five years; after such date the [City/County] shall determine whether a revision or additional assessment is necessary. Wetland delineations will be documented on a ground-verified map using either professional surveying methods or an equivalent professional method using GPS with sub-meter accuracy.

020.B. Rating. Wetlands shall be rated according to the Washington State Wetland Rating System for [Eastern or Western] Washington: 2014 Update (Ecology Publication [14-06-030 or 14-06-029] or as revised). Wetland ratings are valid for five years; after such date the [City/County] shall determine whether a revision or additional rating is necessary.

020.C. Illegal modifications. Wetland rating categories shall not change due to illegal modifications made to the wetland.

030 Regulated Activities

030.A. For any proposed regulated activity, a critical area report may be required to support the requested activity (see Section 060 of this Chapter).

030.B. The following activities are regulated if they occur in a wetland or its buffer:

1. The removal, excavation, grading, or dredging of soil, sand, gravel, minerals, organic matter, or material of any kind
2. The dumping of, discharging of, or filling with any material
3. The draining, flooding, or disturbing of the water level or water table
4. Pile driving
5. The placing of obstructions
6. The construction, reconstruction, demolition, or expansion of any structure
7. The destruction or alteration of wetland vegetation through clearing, harvesting, shading, intentional burning, or planting of vegetation that would alter the character of a wetland

8. Class IV General Forest Practices under the authority of the 1992 Washington State Forest Practices Act Rules and Regulations, WAC 222-12-030, or as thereafter amended

9. Activities that result in:

   a. A significant change of water temperature

   b. A significant change of physical or chemical characteristics of the sources of water to the wetland

   c. A significant change in the timing, frequency, depth, or duration of water entering or within the wetland

   d. The introduction of pollutants

030.C. Subdivisions. The subdivision and/or short subdivision of land where wetlands and/or associated buffers are present are subject to the following:

1. Land that is located wholly within a wetland and/or wetland buffer may not be subdivided

2. Land that is located partially within a wetland and/or wetland buffer may be subdivided provided that an accessible and contiguous portion of each new lot is:

   a. Located outside of the wetland and buffer; and

   b. Meets the minimum lot size requirements of [the zoning code]

040 Exemptions and Allowed Uses in Wetlands

040.A. Wetlands that meet the following criteria are not subject to the avoidance and minimization requirements of the mitigation sequence (Chapter 070.A.1 and 070.A.2) in accordance with the following provisions, and they may be filled if the impacts are fully mitigated based on the remaining actions in Chapter 070.A.3 through 6. Impacts should be mitigated through the purchase of credits from a mitigation bank or in-lieu fee program, if available, consistent with the terms and conditions of the bank or program. In order to verify whether the following criteria are met, it is essential that a critical area report for wetlands meeting the requirements in Chapter 060 be submitted.

1. All Category IV wetlands less than 4,000 square feet that:

   a. Are located in the areas covered by the Regional Supplement to the Corps of Engineers Wetland Delineation Manual: Western Mountains, Valleys, and Coast Region (U.S. Army Corps of Engineers, 2010)

   b. Are not associated with riparian areas or their buffers

   c. Are not associated with shorelines of the state or their associated buffers

d. Are not part of a wetland mosaic

e. Do not score 6 or more points for habitat function based on the Washington State Wetland Rating System for [Western or Eastern] Washington: 2014 Update (Ecology Publication [#14-06-029 or #14-06-030]), or as revised by Ecology)

f. Do not contain a Priority Habitat or a Priority Area for a Priority Species identified by the Washington Department of Fish and Wildlife and do not contain state or federally listed species or their critical habitat or species of local importance identified in the [City/County] code [if there is a locally adopted regulation]

2. Wetlands less than 1,000 square feet that meet the above criteria are exempt from the buffer provisions contained in this Chapter.

040.B. Activities Allowed in Wetlands. The activities listed below are allowed in wetlands. These activities do not require submission of a critical area report, except where such activities have the potential to result in a loss of the functions, values or area of a wetland or wetland buffer. These activities include:

1. [For counties enrolled in the VSP] Agricultural activities in and around critical areas that are addressed by the implementation of the VSP work plan, or

   [For counties not enrolled in the VSP, and all cities/towns] Existing and ongoing agricultural activities, provided they implement applicable Best Management Practices (BMPs) contained in the latest edition of the USDA Natural Resources Conservation Service (NRCS) Field Office Technical Guide (FOTG); or develop a farm conservation plan in coordination with [the local conservation district]. BMPs and/or farm plans should address potential impacts to wetlands from livestock, nutrients, chemicals, soil erosion, sediment control, and agricultural drainage infrastructure. BMPs and/or farm plans should ensure that ongoing agricultural activities minimize their effects on wetlands, water quality, riparian ecology, salmonid populations, and wildlife habitat.

2. Those activities and uses conducted pursuant to the Washington State Forest Practices Act and its rules and regulations, WAC 222-12-030, where state law specifically exempts local authority, except those developments requiring local approval for a Class IV General Forest Practice Permit (conversions) as defined in Chapter 76.09 RCW and Chapter 222-12 WAC, provided conditions of that permit are met.

3. Conservation or preservation of soil, water, vegetation, fish, shellfish, and/or other wildlife that does not entail changing the structure or functions of the existing wetland.

4. The harvesting of wild crops in a manner that is not injurious to natural reproduction of such crops and provided the harvesting does not require tilling

of soil, planting of crops, chemical applications, or alteration of the wetland by changing existing topography, water conditions, or water sources.

5. Drilling for utilities/utility corridors under a wetland, with entrance/exit portals located completely outside of the wetland buffer, provided that the drilling does not alter the ground water connection to the wetland or percolation of surface water down through the soil column. Specific studies by a hydrologist are necessary to determine whether the ground water connection to the wetland or percolation of surface water down through the soil column will be altered. Trenching is not allowed by this provision.
6. Enhancement of a wetland through the removal of non-native, invasive plant species. Removal shall be restricted to hand removal unless permits from the appropriate regulatory agencies have been obtained for approved biological or chemical treatments or mechanical methods. All removed plant material shall be taken away from the site and disposed of properly. Plants that are on the Washington State Noxious Weed Control Board list of noxious weeds should be handled and disposed of according to a noxious weed control plan appropriate to that species. Re-vegetation with appropriate native species to achieve natural densities is allowed and encouraged in conjunction with removal of invasive plants.
7. Educational and scientific research activities that do not result in altering the structure or functions of the wetland.
8. Normal and routine maintenance and repair of any existing, legally established public or private facilities within an existing right-of-way, provided that the maintenance or repair does not expand the footprint of the facility or right-of-way and has no adverse effect on the wetland or buffer.
9. Stormwater management facilities. A wetland or its buffer can be physically or hydrologically altered to meet the requirements of a Low Impact Development (LID) methodology or Flow Control BMP if **ALL** of the following criteria are met:

   a. The wetland is classified as a Category IV or a Category III wetland with a habitat score of 3-5 points.

   b. There will be no net loss of functions and values of the wetland.

   c. The wetland does not contain a breeding population of any native amphibian species.

   d. The hydrologic functions of the wetland can be improved as outlined in questions 3, 4, and 5 of Chart 4 and questions 2, 3, and 4 of Chart 5 in Selecting Mitigation Sites Using a Watershed Approach, [Western Washington or Eastern Washington] (Ecology Publication [#09-06-032 or #10-06-007], or as revised); or the wetland is part of a restoration plan intended to achieve restoration goals identified in a shoreline master program or a local or regional watershed plan.

e. The wetland lies in the natural routing of the runoff, and the discharge follows the natural routing.

f. All regulations regarding stormwater and wetland management are followed, including but not limited to local and state wetland and stormwater codes, manuals, and permits.

g. Modifications that alter the structure of a wetland or its soils will require permits. Existing functions and values that are lost will need to be compensated.

Stormwater LID BMPs required as part of new and redevelopment projects may potentially be authorized within wetlands and their buffers. However, these areas may contain features that render LID BMPs infeasible. A site-specific characterization is required to determine whether an LID BMP is feasible at the project site.

040.C. Exceptions. If the application of these regulations would prohibit public facilities such as utilities within a wetland and/or buffer due to a specific service provision or design constraint, the agency or utility may apply for an exception. Exceptions applications must address mitigation sequencing, and include information meeting the review criteria according to the following: [or those found in variance provisions if applicable]

1. There is no other practical alternative to the proposed development with less impact on the critical areas;
2. The application of the critical area regulations would unreasonably restrict the ability to provide utility services to the public;
3. The proposal does not pose an unreasonable threat to the public health, safety, or welfare on or off the development proposal site;
4. The proposal attempts to protect and mitigate impacts to the critical area functions and values consistent with best available science; and
5. The proposal is consistent with other applicable regulations and standards.

040.D. Emergencies. Emergencies are those activities necessary to prevent an immediate threat to public health, safety, or welfare, or that pose an immediate risk of damage to private property and that require remedial or preventive action in a timeframe too short to allow for compliance with the requirements of the critical areas regulations. Emergency actions are required to use reasonable methods to address the emergency with the least possible impact to the critical area. The [Administrator] will require review of the action to determine whether it was beyond the scope of the exemption and may require permits after the fact, which may include restoration or compensatory mitigation.

050 Wetland Buffers

050.A. Buffer Requirements. The buffer tables have been established in accordance with the best available science. They are based on the category of wetland and the habitat score [for options 1 and 2] as determined by a qualified wetland professional using the Washington State Wetland Rating System for [Western or Eastern] Washington: 2014 Update (Ecology Publication [#14-06-029 or #14-06-030], or as revised). Unless otherwise noted, the level of impact from adjacent land use is assumed to be high.

1. Buffer Width Tables.

> See Appendix C (western) or Appendix D (eastern) for buffer approaches and insert the selected buffer table option here.

2. Increased Wetland Buffer Width. Buffer widths shall be increased on a case-by-case basis as determined by the [Administrator] when a wider buffer is necessary to protect wetland functions and values. This determination shall be supported by appropriate documentation showing that it is reasonably related to protection of the functions and values of the wetland. The documentation shall include but not be limited to the following criteria:

   a. The wetland is used by a state or federally listed plant or animal species. These species would be those listed under WAC 220-610-010, 50 CFR 17-11, 50 CFR 17-12, or other state or federal regulations.

   b. The wetland has critical habitat; or a priority area for a priority species as defined by WDFW; or Wetlands of High Conservation Value as defined by the Washington Department of Natural Resources' Natural Heritage Program.

   c. The adjacent land is susceptible to severe erosion, and erosion-control measures will not effectively prevent adverse wetland impacts.

   d. The adjacent land has minimal vegetative cover.

   e. The land has slopes greater than 30 percent.

3. Buffer averaging to improve wetland protection may be permitted when all of the following conditions are met:

   a. The wetland has significant differences in characteristics that affect its habitat functions, such as a wetland with a forested component adjacent to a degraded emergent component or a dual-rated wetland with a Category I area adjacent to a lower-rated area.

   b. The buffer is increased adjacent to the higher-functioning area of habitat or more-sensitive portion of the wetland and decreased adjacent to the lower-

functioning or less-sensitive portion as demonstrated by a critical area report from a qualified wetland professional.

c. The total area of the buffer after averaging is equal to the area required without averaging.

d. The buffer at its narrowest point is never less than either 75 percent of the required width or 75 feet for Category I and II, 50 feet for Category III, and 25 feet for Category IV, whichever is greater.

4. Averaging to allow reasonable use of a parcel may be permitted when all of the following are met:

a. No feasible alternatives to the site design could be accomplished without buffer averaging.

b. The averaged buffer will not result in degradation of the wetland's functions and values as demonstrated by a critical area report from a qualified wetland professional.

c. The total buffer area after averaging is equal to the area required without averaging.

d. The buffer at its narrowest point is never less than either 75 percent of the required width or 75 feet for Category I and II, 50 feet for Category III, and 25 feet for Category IV, whichever is greater.

050.B. Allowed Buffer Uses. The following uses may be allowed within a wetland buffer in accordance with the review procedures of this Chapter, provided they are not prohibited by any other applicable law, and they are conducted in a manner so as to minimize impacts to the buffer and adjacent wetland:

1. Conservation or restoration activities aimed at protecting the soil, water, vegetation, or wildlife.

2. Passive recreation facilities designed in accordance with an approved critical area report, including:

a. Walkways and trails, provided that they are limited to minor crossings having no adverse impact on water quality. They should be generally parallel to the perimeter of the wetland, located only in the outer twenty-five percent (25%) of the wetland buffer area, and located to avoid removal of significant [as defined in ordinance], old growth, or mature trees. They should be limited to pervious surfaces no more than five (5) feet in width and designed for pedestrian use only. Raised boardwalks utilizing non-treated pilings may be acceptable.

b. Wildlife-viewing structures.

3. Educational and scientific research activities.

4. Normal and routine maintenance and repair of any existing public or private facilities within an existing right-of-way, provided that the maintenance or repair does not increase the footprint or use of the facility or right-of-way.

5. The harvesting of wild crops in a manner that is not injurious to natural reproduction of such crops and provided the harvesting does not require tilling of soil, planting of crops, chemical applications, or alteration of the wetland by changing existing topography, water conditions, or water sources.

6. Drilling for utilities/utility corridors under a buffer, with entrance/exit portals located completely outside of the wetland buffer boundary, provided that the drilling does not alter the ground water connection to the wetland or percolation of surface water down through the soil column. Specific studies by a hydrologist are necessary to determine whether the ground water connection to the wetland or percolation of surface water down through the soil column would be disturbed.

7. Enhancement of a wetland buffer through the removal of non-native, invasive plant species. Removal of invasive plant species shall be restricted to hand removal. All removed plant material shall be taken away from the site and appropriately disposed of. Plants that appear on the Washington State Noxious Weed Control Board list of noxious weeds should be handled and disposed of according to a noxious weed control plan appropriate to that species. Revegetation with appropriate native species at natural densities is allowed in conjunction with removal of invasive plant species.

8. Repair and maintenance of legally established non-conforming uses or structures, provided they do not increase the degree of nonconformity.

050.C. Measurement of Wetland Buffers. All buffers shall be measured perpendicular from the wetland boundary as delineated in the field.

050.D. Functionally Disconnected Buffer Area. Buffers may exclude areas that are functionally and effectively disconnected from the wetland by an existing public or private road or legally established development, as determined by the [Administrator]. Functionally and effectively disconnected means that the road or other significant development blocks the protective measures provided by a buffer.

Significant developments shall include built public infrastructure such as roads and railroads, and private developments such as homes or commercial structures. The [Administrator] shall evaluate whether the interruption will affect the entirety of the buffer. Individual structures may not fully interrupt buffer function. In such cases, the allowable buffer exclusion should be limited in scope to just the portion of the buffer that is affected. Where questions exist regarding whether a development functionally disconnects the buffer, or the extent of that

impact, the [Administrator] may require a critical area report to analyze and document the buffer functionality.

050.E. Signs and Fencing:

1. Temporary markers. The outer perimeter of the wetland buffer and the clearing limits identified by an approved permit or authorization shall be marked in the field with temporary high-visibility fencing in such a way as to ensure that no unauthorized intrusion will occur. The marking is subject to inspection by the [Administrator] prior to the commencement of permitted activities. This temporary marking shall be maintained throughout construction and shall not be removed until permanent signs, if required, are in place.

2. Permanent signs. As a condition of any permit or authorization issued pursuant to this Chapter, the [Administrator] may require the applicant to install permanent signs along the boundary of a wetland or buffer.

   a. Permanent signs shall be made of an enamel-coated metal face attached to a metal post or another non-treated material of equal durability. Signs shall be posted at an interval of one (1) every fifty (50) feet, or one (1) per lot if the lot is less than fifty (50) feet wide, and shall be maintained by the property owner in perpetuity. The signs shall be worded as follows or with alternative language approved by the [Administrator]:

Protected Wetland Area
Do Not Disturb
Contact [Local Jurisdiction]
Regarding Uses, Restrictions,
and Opportunities for Stewardship

   b. The provisions of Subsection (a) may be modified as necessary to assure protection of sensitive features or wildlife.

3. Fencing

   a. The applicant shall be required to install a permanent fence along the boundary of the wetland buffer when adjacent activities could degrade the wetland or its buffer. Examples include domestic animal grazing, unauthorized access by humans or pets, etc.

   b. Fencing installed as part of a proposed activity or as required in this Subsection shall be designed so as to not interfere with species migration, including fish runs, and shall be constructed in a manner that minimizes impacts to the wetland and associated habitat.

050.F. Buffer Maintenance. Except as otherwise specified or allowed in accordance with this Chapter, wetland buffers shall be retained in an undisturbed or enhanced

condition. In the case of compensatory mitigation sites, removal of invasive, non-native weeds is required for the duration of the mitigation bond (Section 070.J.2.a.x).

050.G. Impacts to Buffers**.** Requirements for the compensation for impacts to buffers are outlined in Section 070.K of this Chapter*.*

050.H. Overlapping Critical Area Buffers. If buffers for two critical areas overlap (such as buffers for a stream and a wetland), the wider buffer applies.

060 Critical Area Report for Wetlands

060.A. If the [Administrator] determines that the site of a proposed development includes, is likely to include, or is adjacent to a wetland or wetland buffer, a wetland report, prepared by a qualified wetland professional, shall be required. The expense of preparing the wetland report shall be borne by the applicant.

060.B. Minimum Standards for Wetland Reports. The written report and the accompanying plan sheets shall contain the following information, at a minimum:

1. The written report shall include at a minimum:

   a. The name and contact information of the applicant; the name, qualifications, and contact information of the primary author(s) of the report; a description of the proposal; identification of all the local, state, and/or federal wetland-related permit(s) required for the project; and a vicinity map for the project.

   b. A statement specifying the accuracy of the report and all assumptions made and relied upon.

   c. Documentation of any fieldwork performed on the site, including field data sheets for delineations, rating system forms, baseline hydrologic data, etc.

   d. A description of the methodologies used to conduct the wetland delineations, wetland ratings, and impact analyses, including references.

   e. Identification and characterization of all critical areas, water bodies, shorelines, floodplains, and buffers on or adjacent to the proposed project area. For areas off the project site, estimate conditions within 300 feet of the project boundaries using all reliable available information.

   f. For each wetland identified on site and within 300 feet of the project boundary, provide the completed wetland rating, per Section 020.B of this Chapter; required buffers; hydrogeomorphic classification; wetland area based on the field delineation (area for on-site portion and estimate entire wetland area including off-site portions); Cowardin classifications; habitat elements; soil conditions based on site assessment and/or soil survey information; and to the extent possible, hydrologic information such as

location and condition of inlets/outlets, estimated water depths within the wetland, and estimated hydroperiod patterns based on visual cues (e.g., algal mats, drift lines, flood debris, etc.). Provide area estimates, classifications, and ratings based on entire wetland units, not only the portion present on the proposed project site.

g. A description of the proposed actions, including an estimation of area of impacts to wetlands and buffers based on the field delineation, and an analysis of site development alternatives, including a no-development alternative.

h. An assessment of the probable cumulative impacts to the wetlands and buffers resulting from the proposed development, considering past development and potential future development.

i. A description of how mitigation sequencing has been followed, pursuant to Section 070.A, Mitigation Sequencing, of this Chapter.

j. An evaluation of the functions of the wetland and its buffer, including references for the method used and data sheets.

k. A discussion of the potential impacts to the wetland(s) associated with any anticipated hydroperiod alterations from the project.

2. The site plan sheet(s) shall include, at a minimum:

a. Maps (to scale) depicting delineated and mapped wetlands and required buffers on site, including buffers for off-site wetlands that extend onto the project site; the development proposal; other critical areas and their buffers; grading and clearing limits; and areas of proposed impacts to wetlands and/or buffers (include square footage or acreage).

b. A depiction of the proposed stormwater management facilities and outlets (to scale) for the development, including estimated areas of intrusion into wetland buffers.

070 Compensatory Mitigation

070.A. Mitigation Sequencing. Before being authorized to impact any wetland or its buffer, an applicant must demonstrate that they have implemented mitigation in the following order:

1. Avoid impacts altogether by not taking a certain action or parts of an action.

2. Minimize impacts by limiting the degree or magnitude of the action and its implementation, by using appropriate technology, or by taking affirmative steps to avoid or reduce impacts.

3. Rectify impacts by repairing, rehabilitating, or restoring the affected environment.

4. Reduce or eliminate impacts over time by preservation and maintenance operations.

5. Compensate for impacts by replacing, enhancing, or providing substitute resources or environments.

6. Monitor required compensation and take remedial or corrective measures when necessary.

070.B. Requirements for Compensatory Mitigation:

1. Compensatory mitigation for alterations to wetlands shall be used only for impacts that cannot be avoided or minimized and shall achieve equivalent or greater functions. Compensatory mitigation plans shall be consistent with Wetland Mitigation in Washington State–Part 2: Developing Mitigation Plans—Version 1 (Ecology Publication #06-06-011b, or as revised), and Selecting Wetland Mitigation Sites Using a Watershed Approach [Western Washington (Ecology Publication #09-06-32) or Eastern Washington, (Ecology Publication #10-06-007), or as revised].

2. Mitigation ratios, if used, shall be consistent with Subsection H of this Chapter.

3. Mitigation requirements may be determined using the Credit-Debit Method described in Calculating Credits and Debits for Compensatory Mitigation in Wetlands of [Western Washington (Ecology Publication #10-06-011) or Eastern Washington (Ecology Publication #10-06-015), or as revised] consistent with Subsection I of this Chapter.

4. Plantings used in mitigation actions shall be native species appropriate to the ecoregion.

5. The following areas within a proposed compensation site shall not contribute to satisfying the requirements for compensatory mitigation:

   a. Easements for utility corridors, stormwater facilities, rights-of-way, and streams conveyed underground

   b. Driveways

   c. Roads

   d. Any paved or graveled areas intended to convey vehicle or foot traffic.

6. Buffers on Wetland Mitigation Sites. All wetland mitigation sites shall have buffers consistent with the buffer requirements of this Chapter. Buffers shall be based on the expected or target category of the proposed wetland mitigation site and the expected level of impact from the adjacent land use.

Buffers need to be fully vegetated in order to be included in buffer area calculations. Lawns, walkways, driveways, paved areas, and mowed or developed areas will not be considered buffers or included in buffer area

calculations when assessing whether adequate compensatory mitigation buffers have been provided.

070.C. Compensating for Lost or Affected Functions. Compensatory mitigation shall address the functions affected by the proposed project, with an intention to achieve functional equivalency or improvement of functions. The goal shall be for the compensatory mitigation to provide similar wetland functions as those lost, except when either:

1. The lost wetland provides minimal functions, and the proposed compensatory mitigation action(s) will provide equal or greater functions or will provide functions shown to be limited within a watershed through an existing watershed plan or a local or regional study that characterizes watershed processes; or
2. Out-of-kind replacement of wetland type or functions will best meet watershed goals formally identified by a watershed plan, such as replacement of historically diminished wetland types.

070.D. Approaches to Compensatory Mitigation. Mitigation for lost or diminished wetland and buffer functions shall rely on the approaches listed below:

1. Wetland Mitigation Banks. Credits from a wetland mitigation bank certified under Chapter 173-700 WAC may be used to compensate for impacts located within the service area specified in the mitigation bank instrument if all the following are met:
   a. The [Administrator] determines that it would provide appropriate compensation for the proposed impacts; and
   b. The proposed use of credits is consistent with the terms and conditions of the mitigation bank instrument.
   c. Mitigation ratios are consistent with ratios specified in the mitigation bank instrument.
2. In-Lieu Fee (ILF) Mitigation: Credits from an approved in-lieu fee program may be used when all the following apply:
   a. The [Administrator] determines that it would provide appropriate compensation for the proposed impacts.
   b. The proposed use of credits is consistent with the terms and conditions of the approved ILF program instrument.
   c. Projects using ILF credits shall have debits associated with the proposed impacts calculated by the applicant's qualified wetland professional using the credit assessment method specified in the approved instrument for the ILF program.

d. The impacts are located within the service area specified in the approved ILF instrument.

3. Permittee-responsible, advance mitigation. Advance mitigation is a form of permittee-responsible mitigation implemented before a permitted impact takes place. It is designed to compensate for impacts expected to occur in the future. The applicant proposing the advance mitigation is the only one who can use the credits generated. Credits cannot be sold or transferred to another applicant. Advance mitigation proposals should be developed in accordance with state and federal rules and guidance on advance mitigation (Interagency Regulatory Guide: Advance Permittee-Responsible Mitigation, Ecology Publication #12-06-015, and Chapter 4.2 of Wetland Mitigation in Washington State–Part 1: Policies and Guidance—Version 2, Ecology Publication #21-06-003, or as revised).

4. Permittee-responsible, concurrent mitigation. Concurrent mitigation is a form of permittee-responsible mitigation implemented at the same time permitted impacts are occurring. The permittee is responsible for implementation and success of the compensation. Concurrent mitigation may occur at the site of the permitted impacts or at an off-site location, usually within the same watershed. Permittee-responsible, concurrent mitigation shall be used only if the applicant's qualified wetland professional demonstrates to the [Administrator]'s satisfaction that the proposed approach is ecologically preferable to use of a bank or ILF program, consistent with the criteria in this Section.

070.E. Methods of Compensatory Mitigation. Mitigation for wetland and buffer impacts shall rely on a method listed below in order of preference. A lower-preference form of mitigation shall be used only if the applicant's qualified wetland professional demonstrates to the [Administrator]'s satisfaction that all higher-ranked types of mitigation are not viable, consistent with the criteria in this Section.

1. Restoration: The manipulation of the physical, chemical, or biological characteristics of a site with the goal of returning natural/historic functions and environmental processes to a former or degraded wetland. Restoration is divided into two categories:

a. Re-establishment: The manipulation of the physical, chemical, or biological characteristics of a site with the goal of returning natural/historic functions and environmental processes to a former wetland. Re-establishment results in rebuilding a former wetland and results in a gain in wetland area and functions. Example activities could include removing fill, plugging ditches, or breaking drain tiles to restore a wetland hydroperiod, which in turn will lead to restoring wetland biotic communities and environmental processes.

b. Rehabilitation: The manipulation of the physical, chemical, or biological characteristics of a site with the goal of repairing natural/historic functions and environmental processes to a degraded wetland. Rehabilitation results in a gain in wetland function but does **not** result in a gain in wetland area. The area already meets wetland criteria, but hydrological processes have been altered. Rehabilitation involves restoring historic hydrologic processes. Example activities could involve breaching a dike to reconnect wetlands to a floodplain or return tidal influence to a wetland.

2. Establishment (Creation): The manipulation of the physical, chemical, or biological characteristics of a site to develop a wetland on an upland where a wetland did not previously exist at an upland site. Establishment results in a gain in wetland area and functions. An example activity could involve excavation of upland soils to elevations that will produce a wetland hydroperiod and hydric soils by intercepting groundwater, and in turn supports the growth of hydrophytic plant species.

   a. If a site is not available for wetland restoration to compensate for expected wetland and/or buffer impacts, the [Administrator] may authorize establishment of a wetland and buffer upon demonstration by the applicant's qualified wetland professional that:

      i. The hydrology and soil conditions at the proposed mitigation site are conducive for sustaining the proposed wetland and that establishment of a wetland at the site will not likely cause hydrologic problems elsewhere;

      ii. Adjacent land uses and site conditions do not jeopardize the viability of the proposed wetland and buffer (e.g., due to the presence of invasive plants or noxious weeds, stormwater runoff, noise, light, or other impacts); and

      iii. The proposed wetland and buffer will eventually be self-sustaining with little or no long-term maintenance.

      iv. The proposed wetland would not be established at the cost of another high-functioning habitat (i.e., ecologically important uplands).

3. Preservation (Protection/Maintenance). The removal of a threat to, or preventing the decline of, wetlands by an action in or near those wetlands. This term includes activities commonly associated with the protection and maintenance of wetlands through the implementation of appropriate legal and physical mechanisms such as recording conservation easements and providing structural protection like fences and signs. Preservation does not result in a gain of aquatic resource area or functions but may result in a gain in functions over the long term. Preservation of a wetland and associated buffer can be used only if:

a. The [Administrator] determines that the proposed preservation is the best mitigation option;

b. The proposed preservation site is under threat of undesirable ecological change due to permitted, planned, or likely actions that will not be adequately mitigated under existing regulations;

c. The area proposed for preservation is of high quality or critical for the health and ecological sustainability of the watershed or sub-basin. Some of the following features may be indicative of high-quality sites:

i. Category I or II wetland rating (per 020.B of this Section).

ii. Rare or irreplaceable wetland type [e.g, peatlands, mature forested wetland, estuaries, vernal pools, alkali wetlands] or aquatic habitat that is rare or a limited resource in the area.

iii. The presence of habitat for threatened or endangered species (state, federal, or both).

iv. Provides biological and/or hydrological connectivity to other habitats.

v. Priority sites identified in an adopted watershed plan.

d. Permanent preservation of the wetland and buffer shall be provided through a legal mechanism such as a conservation easement or tract held by an appropriate natural land resource manager/land trust.

e. The [Administrator] may approve another legal and administrative mechanism in lieu of a conservation easement if it is determined to be adequate to protect the site.

4. Enhancement. The manipulation of the physical, chemical, or biological characteristics of a wetland to heighten, intensify, or improve specific wetland function(s). Enhancement is undertaken for specified purposes such as water quality improvement, flood water retention, or wildlife habitat. Enhancement results in the gain of selected wetland function(s) but may also lead to a decline in other wetland function(s). Enhancement does not result in a gain in wetland area. Enhancement activities could include planting vegetation, controlling non-native or invasive species, and modifying site elevations to alter hydroperiods in existing wetlands.

Applicants proposing to enhance wetlands and/or associated buffers shall demonstrate how the proposed enhancement will increase the wetland and/or buffer functions, how this increase in function will adequately compensate for the impacts, and how existing wetland functions at the mitigation site will be protected.

5. Alternative Types of Mitigation/Resource Tradeoffs. The [Administrator] may approve alternative mitigation proposals that are based on best available science, such as priority restoration plans that achieve restoration goals

identified in the SMP. Alternative mitigation proposals shall provide an equivalent or better level of ecological functions and values than would be provided by standard mitigation approaches. Alternative mitigation approaches shall comply with all reporting, monitoring, and performance measures of this Section including adherence to mitigation sequencing. The [City/County] may consult with agencies with expertise and jurisdiction over the critical areas during the review to assist with analysis and identification of appropriate performance measures that adequately safeguard critical areas.

The [Administrator] will consider the following for approval of an alternative mitigation proposal:

a. Clear identification of how an alternative approach will achieve equal or better ecological benefit.

b. The proposal uses a watershed approach consistent with Selecting Wetland Mitigation Sites Using a Watershed Approach [Western Washington or Eastern Washington (Ecology Publication #09-06-32 or Publication #10-06-007), or as revised].

c. All impacts are identified, evaluated, and mitigated.

d. Methods to demonstrate ecological success are clear and measurable.

070.F. Location of Compensatory Mitigation. Permittee-responsible compensatory mitigation actions shall be conducted using a watershed approach and shall generally occur within the same sub-drainage basin. However, when the applicant can demonstrate that a mitigation site in a different sub-drainage basin is ecologically preferable, it should be used.

The following criteria will be evaluated when determining whether on-site or off-site compensatory mitigation is ecologically preferable. When considering the location of mitigation, preference should be given to using programmatic approaches, such as a mitigation bank or an ILF program.

1. No reasonable opportunities exist on site or within the sub-drainage basin or opportunities on site or within the sub-drainage basin do not have a high likelihood of success based on a determination of the capability of the site to compensate for the impacts. Considerations should include anticipated replacement ratios for wetland mitigation, buffer conditions and required widths, available water to maintain anticipated hydrogeomorphic class(es) of wetlands when restored, proposed flood storage capacity, and potential to mitigate riparian fish and wildlife impacts (such as connectivity);

2. On-site mitigation would require elimination of high-quality upland habitat;

3. Off-site mitigation has a greater likelihood of providing equal or improved wetland functions compared to the altered wetland.

4. Off-site locations shall be in the same sub-drainage basin unless:

   a. Watershed goals for water quality, flood storage or conveyance, habitat, or other wetland functions have been established by the [City/County] and strongly justify locating mitigation at another site;

   b. Credits from a state-certified wetland mitigation bank are used as compensation, and the use of credits is consistent with the terms of the certified bank instrument;

   c. Fees are paid to an approved ILF program to compensate for the impacts.

5. The design for the compensatory mitigation project needs to be appropriate for its position in the landscape. Therefore, compensatory mitigation should not result in the creation, restoration, or enhancement of an atypical wetland.

070.G. Timing of Compensatory Mitigation. It is preferred that compensatory mitigation projects be completed prior to activities that will impact wetlands. At the least, compensatory mitigation shall be completed immediately following wetland impacts and prior to use or occupancy of the action or development. Construction of mitigation projects shall be timed to reduce impacts to existing fisheries, wildlife, and flora.

1. The [Administrator] may authorize a one-time temporary delay in completing construction or installation of the compensatory mitigation when the applicant provides a written explanation from a qualified wetland professional as to the rationale for the delay. An appropriate rationale would include identification of the environmental conditions that could produce a high probability of failure or significant construction difficulties. For example, a project delay that creates conflicts with other regulatory requirements (fisheries, wildlife, stormwater, etc.) or installing plants should be delayed until the dormant season to ensure greater survival of installed materials. The delay shall not create or perpetuate hazardous conditions or environmental damage or degradation, and the delay shall not be injurious to the health, safety, or general welfare of the public. The request for the delay shall include a written justification that documents the environmental constraints that preclude timely implementation of the compensatory mitigation plan. The justification will be verified by the [City/County] who will issue a formal decision.

070.H. Wetland Mitigation Ratios.

> See Appendix E for mitigation ratio tables and insert the appropriate tables for your jurisdiction here.

070.I. Credit-Debit Method. To protect functions and values more fully, and as an alternative to the mitigation ratios found in Section 070.H of this Chapter, the [Administrator] may allow mitigation based on the Credit-Debit Method developed by the Department of Ecology in Calculating Credits and Debits for Compensatory Mitigation in Wetlands of [Western Washington (Ecology Publication # 10-06-011) or Eastern Washington (Ecology Publication #11-06-015), or as revised].

070.J. Mitigation Plan. When a project involves wetland and/or buffer impacts, a mitigation plan prepared by a qualified wetland professional shall be required, meeting the following minimum standards:

1. Wetland Critical Area Report. A critical area report for wetlands shall accompany or be included in the compensatory mitigation plan and include the minimum parameters described in Section 060.B of this Chapter, Minimum Standards for Wetland Reports.

2. Mitigation Plan and Plan Sheets. The report shall include a written plan and plan sheets that contain, at a minimum, the elements listed below. Full guidance can be found in Wetland Mitigation in Washington State–Part 2: Developing Mitigation Plans (Version 1) (Ecology Publication #06-06-011b, or as revised).

   a. The written report shall be prepared by a qualified wetland professional and contain, at a minimum:

      i. The name and contact information of the applicant; the name, qualifications, and contact information of the primary author(s) of the compensatory mitigation plan; a description of the development proposal; a summary of the impacts and proposed compensation concept; identification of all the local, state, and federal wetland-related permits required for the project; and a vicinity map for the project.

      ii. Description of how the development project has been designed to avoid, minimize, or reduce adverse impacts to wetlands.

      iii. Description of the existing wetland and buffer areas proposed to be altered. Include acreage or square footage, water regime, vegetation, soils, functions, landscape position, and surrounding land uses. Also describe impacts in terms of acreage by Cowardin classification, hydrogeomorphic classification, and wetland rating, based on Section 020.B of this Chapter, Wetland Ratings.

iv. Description of the compensatory mitigation site, including location and rationale for selection. Include an assessment of existing conditions, including acreage or square footage of wetlands and uplands, water regime, sources of water, vegetation, soils, functions, landscape position, and surrounding land uses. Estimate future conditions in this location if the compensation actions are not undertaken.

v. Surface and subsurface hydrologic conditions, including an analysis of existing and proposed hydrologic regimes for enhanced, established, or restored compensatory mitigation areas. Include illustrations of how data for existing hydrologic conditions were used to determine the estimates of future hydrologic conditions.

vi. A description of the proposed actions for compensation of wetland and buffer areas affected by the project. Include overall goals of the proposed mitigation, including a description of the targeted functions, hydrogeomorphic classification, and expected categories of wetlands.

vii. A description of the proposed mitigation construction activities and timing of activities.

viii. Performance standards (measurable standards for years post-installation) for wetland and buffer areas, a monitoring schedule, a maintenance schedule, and actions proposed by year.

ix. A discussion of ongoing management practices that will protect wetlands after the development project has been implemented, including proposed monitoring and maintenance programs (for remaining wetlands and compensatory mitigation wetlands).

x. A bond estimate for the entire compensatory mitigation project, including the following elements: site preparation, plant materials, construction materials, installation and oversight, maintenance at least twice per year for up to ten (10) years, annual monitoring field work and reporting, contingency actions for a maximum of the total required number of years for monitoring, and removal of all non-natural site implements (e.g., irrigation equipment, construction fencing, plant protectors, weed barrier fabric) by the end of the monitoring period.

xi. Proof of establishment of Notice on Title for the remaining wetlands and buffers on the development project site (if any) and a legal site protection mechanism for the compensatory mitigation areas.

b. The scaled plan sheets shall contain, at a minimum:

i. Mapped, ground-verified edges of the existing wetland and buffers, proposed areas of wetland and/or buffer impacts, and location of proposed wetland and/or buffer compensation actions.

ii. Existing topography, ground-verified, at two-foot contour intervals in the zone of the proposed compensation actions if any grading activity is proposed in the compensation area(s). Also include existing cross-sections (estimated one-foot intervals) of wetland areas on the development site that are proposed to be altered and of the proposed areas of wetland and buffer compensation.

iii. Conditions expected from the proposed actions on site, including future hydrogeomorphic classes, vegetation community types (e.g., Cowardin class), and future hydroperiods.

iv. Required wetland buffers for existing wetlands and proposed compensation areas. Also identify any zones where buffers are proposed to be reduced or enlarged outside of the standards identified in this Chapter.

v. A planting plan for the compensation area, including all species by proposed community type and hydroperiod, size and type of plant material to be installed, spacing of plants, typical clustering patterns, total number of each species by community type, and timing of installation.

070.K. Buffer Mitigation Ratios. Impacts to buffers shall be mitigated at a minimum 1:1 ratio. Compensatory buffer mitigation shall replace those buffer functions lost from development.

070.L. Protection of the Mitigation Site. The mitigation area and any associated buffer shall be protected by a legal mechanism such as a critical area tract or a conservation easement. The [Administrator] may approve another legal and administrative mechanism if it is determined to be adequate to protect the site.

070.M. Monitoring. Mitigation monitoring shall be required for a period necessary to establish that performance standards have been met, but not for a period less than five years. If a scrub-shrub or forested vegetation community is proposed, monitoring may be required for ten years or more. The mitigation plan shall include monitoring elements that ensure success for the wetland and buffer functions. If the mitigation goals are not attained within the initially established monitoring period, the applicant remains responsible for managing the mitigation project until the goals of the mitigation plan are achieved.

080 Unauthorized Alterations and Enforcement

080A. When a wetland or its buffer has been altered in violation of this Chapter, all ongoing development work shall stop, and the critical area shall be restored. The [Administrator] shall have the authority to issue a [stop-work] order to cease all ongoing development work and order restoration, rehabilitation, or replacement measures at the owner's or other responsible party's expense to compensate for violation of provisions of this Chapter.

080.B. Requirement for Restoration Plan. All development work shall remain stopped until a restoration plan is prepared and approved by the [Administrator]. Such a plan shall be prepared by a qualified wetland professional using currently accepted scientific principles and shall describe how the actions proposed meet the minimum requirements described in Subsection C below. The [Administrator] may, at the owner's or other responsible party's expense, seek expert advice in determining the adequacy of the plan. Inadequate plans shall be returned to the applicant or other responsible party for revision and re-submittal.

080.C. Minimum Performance Standards for Restoration. The following minimum performance standards shall be met for the restoration of a wetland, when the owner or other responsible party can demonstrate that greater functions and habitat values can be attained, these standards may be modified:

1. The pre-violation structure, functions, and values of the affected wetland shall be restored.
2. The pre-violation soil types and configuration shall be restored to the extent practicable.
3. The wetland and buffers shall be replanted with native vegetation that replicates the pre-violation vegetation in species types, sizes, and densities.
4. Information demonstrating compliance with other applicable provisions of this Chapter shall be submitted to the [Administrator].

080.D. Site Investigations. The [Administrator] is authorized to make site inspections and take such actions as are necessary to enforce this Chapter. The [Administrator] shall present proper credentials and make a reasonable effort to contact the property owner before entering onto private property.

080.E. Penalties. Any person, party, firm, corporation, or other legal entity convicted of violating any of the provisions of this Chapter shall be guilty of a [misdemeanor/civil infraction/etc.].

1. Each day or portion of a day during which a violation of this Chapter is committed or continued shall constitute a separate offense. Any development carried out contrary to the provisions of this Chapter shall constitute a public

nuisance and may be enjoined as provided by the statutes of the state of Washington. The [Administrator] may levy civil penalties against any person, party, firm, corporation, or other legal entity for violation of any of the provisions of this Chapter. The civil penalty shall be [as provided for in City/County code].

2. If the wetland affected cannot be restored, monies collected as penalties shall be deposited in a dedicated account for the preservation or restoration of landscape processes and functions in the watershed in which the affected wetland is located. The [Administrator] may coordinate preservation or restoration activities with other jurisdictions in the watershed to optimize the effectiveness of the restoration action.

Appendix B. Definitions

Agricultural activities, existing and ongoing: Those activities conducted on lands defined in RCW 84-34-020(2), and those activities involved in the production of crops and livestock, including but not limited to operation, maintenance and conservation measures of farm and stock ponds or drainage ditches, irrigation systems, changes between agricultural activities, and normal operation, maintenance or repair of existing serviceable structures, facilities or improved areas. Activities that bring an area into agricultural use are not part of an ongoing activity. An operation ceases to be ongoing when the area in which it was conducted is proposed for conversion to a nonagricultural use or has lain idle for a period of longer than five years, unless the idle land is registered in a federal or state soils conservation program.

Alkali wetlands: See *Wetlands with special characteristics.*

Alteration: Any human-induced change in an existing condition of a critical area or its buffer. Alterations include, but are not limited to, grading, filling, channelizing, dredging, clearing of vegetation, construction, compaction, excavation, or any other activity that changes the character of the critical area or its buffer.

Atypical wetland: A wetland whose "design" does not match the type of wetland that would be found in the geomorphic setting of the proposed site (i.e., the water source and hydroperiod proposed for the mitigation site are not typical for the geomorphic setting). Designs that provide exaggerated morphology or require a berm or other engineered structures to hold back water would also be considered atypical. Note: An atypical wetland resulting from an inappropriate hydrogeomorphic class is different from the "atypical situation" defined in the Corps 1987 wetland delineation manual.

Best available science (BAS): Current scientific information used in the process of designating, protecting, or restoring critical areas; that is, scientific information derived from a valid scientific process as defined by WAC 365-195-900 through 925.

Best management practices (BMPs): Conservation practices or systems of practices and management measures that:

(a) Control soil loss and reduce water quality degradation caused by high concentrations of nutrients, animal waste, toxics, or sediment;

(b) Minimize adverse impacts to surface water and ground water flow and circulation patterns and to the chemical, physical, and biological characteristics of wetlands;

(c) Protect trees, vegetation, and soils designated to be retained during and following site construction and use native plant species appropriate to the site for re-vegetation of disturbed areas; and

(d) Provide standards for proper use of chemical herbicides within critical areas.

Bog: See *Wetlands with special characteristics*.

Buffer or buffer area: Vegetated areas adjacent to wetlands or other aquatic resources that can reduce impacts from adjacent land uses through various physical, chemical, and/or biological processes.

Calcareous fens: See *Wetlands with special characteristics.*

Carbon sequestration: The process of capturing and storing atmospheric carbon dioxide through biologic, chemical, geologic, or physical processes (RCW 70A-45-010).

Clean Water Act (CWA): The federal law that establishes the basic structure for regulating discharges of pollutants into the waters of the United States and regulating quality standards for surface waters. Under the CWA, the U.S. Environmental Protection Agency (EPA) has implemented pollution control programs such as setting wastewater standards for industry. The EPA has also developed national water quality criteria recommendations for pollutants in surface waters.

Compensatory mitigation: The restoration (re-establishment or rehabilitation), establishment (creation), enhancement, and/or in certain circumstances preservation of wetlands for the purposes of offsetting unavoidable adverse impacts that remain after all appropriate and practicable avoidance and minimization has been achieved.

Cowardin classification. A commonly used classification system for wetlands. It was first developed in 1979 by the U.S. Fish and Wildlife Service and updated in 2013 (Federal Geographic Data Committee, 2013). The Cowardin system classifies wetlands based on water flow, substrate types, vegetation types, and dominant plant species. It is used for wetland classification in the National Wetland Inventory.

Credit-Debit Method: A tool to provide applicants and regulators a way to determine whether actions taken to mitigate an impact to wetlands will adequately replace

the functions and values lost. It is based on the Washington State Wetland Rating System.

Critical areas: Any of the following areas or ecosystems: (a) wetlands; (b) areas with a critical recharging effect on aquifers used for potable water; (c) fish and wildlife habitat conservation areas; (d) frequently flooded areas; and (e) geologically hazardous areas.

Critical habitat: A term defined and used in the Endangered Species Act. It is specific geographic areas that contain features essential to the conservation of an endangered or threatened species and may require special management and protection. Critical habitat may also include areas that are not currently occupied by the species but are needed for its recovery.

Creation: The manipulation of the physical, chemical, or biological characteristics present to develop a wetland that did not previously exist at an upland site. Creation results in a gain in wetland area and functions. A typical action is the excavation of upland soils to elevations that will produce a wetland hydroperiod and hydric soils, and support the growth of hydrophytic plant species.

Cumulative impacts: The combined, incremental effects of human activity on critical area functions and values. Cumulative impacts result when the effects of an action are added to or interact with the effects of other actions in a particular place and within a particular time. It is the combination of these effects, and any resulting environmental degradation, that should be the focus of cumulative impact analysis and changes to policies and permitting decisions.

Development: A land use consisting of the construction or exterior alteration of structures; grading, dredging, drilling, or dumping; filling; removal of sand, gravel, or minerals; bulkheading; driving of pilings; or any project of a temporary or permanent nature that modifies structures, land, wetlands, buffers, or shorelines and that does not fall within the allowable exemptions or exceptions contained in the [City/County] Code.

Emergencies: Those activities necessary to prevent an immediate threat to public health, safety, or welfare, or that pose an immediate risk of damage to private property and that require remedial or preventive action in a timeframe too short to allow for compliance with the requirements of the critical areas regulations.

Enhancement: The manipulation of the physical, chemical, or biological characteristics of a wetland to heighten, intensify, or improve specific function(s). Enhancement results in the gain of selected function(s), but may also lead to a decline in other function(s). Enhancement does not result in a gain in wetland area.

Establishment: See *Creation*.

Estuarine wetland: See *Wetlands with special characteristics.*

Forested wetlands: See *Wetlands with special characteristics.*

Functions and values: The ecosystem services provided by critical areas to society, including, but not limited to, improving and maintaining water quality, providing fish and wildlife habitat, supporting terrestrial and aquatic food chains, reducing flooding and erosive flows, wave attenuation, carbon sequestration, thermal refugia, historical or archaeological importance, cultural uses and significance, educational opportunities, and recreation.

Growth Management Act: Chapters 36-70A and 36-70B RCW, as amended.

Impervious surface: A surface area that either prevents or retards the entry of water into the soil or other substrate that would occur under natural conditions prior to development. A non-vegetated surface area that causes water to run off the surface in greater quantities or at an increased rate of flow from the flow present under pre-development or pre-developed conditions. Common impervious surfaces include, but are not limited to, rooftops; walkways; patios; driveways; parking lots; storage areas; concrete or asphalt paving; gravel roads; packed earthen materials; and oiled, macadam, or other surfaces that similarly impede the natural infiltration of stormwater.

In-lieu fee (ILF) program: An agreement between a regulatory agency (state, federal, or local) and a single sponsor, generally a public natural resource agency or non-profit organization. Under an in-lieu-fee agreement, the sponsor collects funds from individuals and/or entities required to conduct compensatory mitigation under a wetland regulatory program. The sponsor uses the funds pooled from multiple permittees to create one or more mitigation sites under the authority of the agreement to satisfy the permittees' required mitigation.

Infiltration: The downward entry of water into the soil.

Interdunal wetland: See *Wetlands with special characteristics*.

Low Impact Development (LID) methodology: A stormwater and land-use management strategy that tries to mimic natural hydrologic conditions by emphasizing the following techniques: conservation, use of on-site natural features, site planning, and distributed stormwater best management practices (BMPs) integrated into a project design.

Mitigation sequence: A prescribed order of steps taken to reduce the impacts of activities on wetlands. As defined in WAC 197-11-768, mitigation means:

(a) Avoiding the impact altogether by not taking a certain action or parts of an action;

(b) Minimizing impacts by limiting the degree or magnitude of the action and its implementation by using appropriate technology or by taking affirmative steps to avoid or reduce impacts;

(c) Rectifying the impact to wetlands, critical aquifer recharge areas, and habitat conservation areas by repairing, rehabilitating, or restoring the affected environment;

(d) Reducing or eliminating the impact or hazard over time by preservation and maintenance operations during the life of the action;

(e) Compensating for the impact by replacing, enhancing, or providing substitute resources or environments; and/or

(f) Monitoring the impact and taking remedial action when necessary.

Monitoring: Evaluating the impacts of development proposals on biological, hydrological, and geological elements of critical areas, and assessing the performance of required mitigation measures through the collection and analysis of data by various methods for the purpose of understanding and documenting changes in natural ecosystems and features. Monitoring includes gathering baseline data.

National Wetland Inventory (NWI): A publicly available resource provided by the U.S. Fish and Wildlife Service that provides detailed information and maps showing the abundance, characteristics, and distribution of wetlands in the U.S.

Native vegetation: Plant species that occur naturally in a particular region or environment and were present before European colonization.

Non-federally regulated wetland: A wetland that is not jurisdictional under the federal Clean Water Act. Sometimes referred to as “isolated wetlands,” these wetlands remain regulated under state and local laws and rules, whether or not they are protected by federal law.

Off-site compensatory mitigation: Replacement of critical areas away from the site on which a critical area has been impacted.

On-site compensatory mitigation: Replacement of critical areas at or adjacent to the site on which a critical area has been impacted.

Ordinary High Water Mark: Under the Shoreline Management Act, that mark which is found by examining the bed and banks of water bodies and ascertaining where

the presence and action of waters are so common and usual, and so long continued in all ordinary years, that the soil has a character distinct from that of the abutting upland in respect to vegetation.

Preservation: The removal of a threat to, or preventing the decline of, wetland conditions by an action in or near a wetland. This term includes activities commonly associated with the protection and maintenance of wetlands through the implementation of appropriate legal and physical mechanisms (such as recording conservation easements and providing structural protection like fences and signs). Preservation does not result in a gain of wetland area and functions (but may result in a gain in functions over the long term).

Prior Converted Croplands (PCC): Wetlands that, prior to December 23, 1985, were drained or otherwise manipulated to enable production of an agricultural commodity crop. Farmland must meet all the following criteria for it to be designated as Prior Converted Cropland:

(a) Cropped prior to December 23, 1985, with an agricultural commodity (an annually tilled crop such as corn);

(b) The land was cleared, drained or otherwise manipulated to make it possible to plant a crop;

(c) The land has continued to be used for agricultural purposes (cropping, haying or grazing); and

(d) The land does not flood or pond for more than 14 days during the growing season.

Priority area: Known limiting habitats (e.g., breeding areas) or areas that support a relatively high number of individuals (e.g., regular concentrations) identified in WDFW's Priority Habitats and Species List.

Priority habitats: As defined by WDFW, habitat types or elements with unique or significant value to a diverse assemblage of species. A priority habitat may consist of a unique vegetation type (e.g., shrub-steppe) or dominant plant species (e.g., juniper savannah), a described successional stage (e.g., old-growth forest), or a specific habitat feature (e.g., cliffs).

Priority species: As defined by WDFW, State Endangered, Threatened, Sensitive, and Candidate species; animal aggregations (e.g., heron colonies, bat colonies) considered vulnerable; and species of recreational, commercial, or tribal importance that are vulnerable.

Project area: All areas, including those within fifty (50) feet of the area, proposed to be disturbed, altered, or used by the proposed activity or the construction of any proposed structures. When the action binds the land, such as a subdivision, short subdivision, binding site plan, planned unit development, or rezone, the project area shall include the entire parcel, at a minimum.

Qualified wetland professional: A person with professional wetland experience that meets the following criteria:

(a) A Bachelor of Science or Bachelor of Arts or equivalent degree in hydrology, soil science, botany, ecology, resource management, or related field, or four years of full-time work experience as a wetland professional may substitute for a degree, and

(b) At least two additional years of full-time work experience as a wetland professional; including delineating wetlands, preparing wetland reports, conducting function assessments, and developing and implementing mitigation plans, and

(c) Completion of additional wetland-specific training programs. This could include a more comprehensive program such as the University of Washington Wetland Science and Management Certificate Program or individual workshops on topics such as wetland delineation, function assessment, mitigation design, hydrophytic plant or hydric soil identification.

A person certified as a Professional Wetland Scientist through the Society of Wetland Scientists professional certification program meets the above criteria.

Re-establishment: The manipulation of the physical, chemical, or biological characteristics of a site with the goal of returning natural/historic functions and environmental processes to a former wetland. Re-establishment results in rebuilding a former wetland and results in a gain in wetland area and functions.

Rehabilitation: The manipulation of the physical, chemical, or biological characteristics of a site with the goal of repairing natural/historic functions and environmental processes to a degraded wetland. Rehabilitation results in a gain in wetland function, but does not result in a gain in wetland acres.

Repair or maintenance: An activity that restores the character, scope, size, and design of a serviceable area, structure, or land use to its previously authorized and undamaged condition. Activities that change the character, size, or scope of a project beyond the original design and drain, dredge, fill, flood, or otherwise alter critical areas are not included in this definition.

Restoration: Measures taken to restore an altered or damaged natural feature, including:

(a) Active steps taken to restore damaged wetlands, streams, protected habitat, or their buffers to the functioning condition that existed prior to an unauthorized alteration; and

(b) Actions performed to re-establish structural and functional characteristics of a critical area that have been lost by alteration, past management activities, or catastrophic events.

Revised Code of Washington (RCW): A compilation of all permanent Washington state laws currently in force.

SEPA: Washington State Environmental Policy Act, Chapter 43-21C RCW.

Service area: The geographic area within which impacts can be mitigated at a specific mitigation bank or an in-lieu fee program, as designated in its instrument.

Shoreline Management Act (SMA): Chapter 90-58 RCW, which is the law that requires all counties, towns, and cities with shorelines to develop and implement shoreline master programs.

Soil survey: The most recent Natural Resources Conservation Service soil maps for the local area or county by the National Resources Conservation Service, U.S. Department of Agriculture.

Species, listed: Any species listed under the federal Endangered Species Act or state endangered, threatened, and sensitive, or priority lists (see WAC 220-610-110 or current "Priority Habitat and Species List," Washington Department of Fish and Wildlife).

Species of local importance: Those species of local concern designated by the [City/County] in Chapter [Section #] deemed to need additional or special consideration or protection due to their population status or their sensitivity to habitat manipulation.

Stream: An area where open surface water produces a defined channel or bed, not including irrigation ditches, canals, storm or surface water runoff devices, or other entirely artificial watercourses, unless they are used by salmonids or are used to convey a watercourse that was naturally occurring prior to construction. A channel or bed need not contain water year-round, provided there is evidence of at least intermittent flow during years of normal rainfall.

Temporal loss: The time lag between the loss of wetland functions caused by the permitted or unpermitted impacts and the replacement of wetland functions at the compensatory mitigation site.

Thermal refugia: Sites within a landscape that are relatively protected from temperature extremes and warming trends.

Unavoidable impacts: Adverse impacts that remain after all appropriate and practicable avoidance and minimization has been achieved.

Vernal pools: See *Wetlands with special characteristics*.

Voluntary Stewardship Program (VSP): The local program under the supervision of the Washington State Conservation Commission where counties and agricultural landowners can implement an incentive-based program to provide farm-friendly options for protecting and enhancing critical areas in places where agricultural activity is conducted.

Washington Administration Code (WAC): Administrative rules implementing state laws.

Watershed approach: A watershed approach means an analytical process for making compensatory mitigation decisions that support the sustainability or improvement of wetlands in a watershed. It involves consideration of watershed needs, and how locations and types of compensatory mitigation projects address those needs. A landscape perspective is used to identify the types and locations of compensatory mitigation projects that will benefit the watershed and offset losses of wetland functions and services caused by authorized activities. The watershed approach may involve consideration of landscape scale, historic and potential wetland conditions, past and projected wetland impacts in the watershed, and terrestrial connections between wetlands when determining compensatory mitigation requirements.

Watershed plan: A plan developed by federal, tribal, state, and/or local government agencies and/or appropriate non-governmental organizations, in consultation with relevant stakeholders, for the specific goal of aquatic resource restoration, establishment, enhancement, and preservation. A watershed plan addresses aquatic resource conditions in the watershed, multiple stakeholder interests, and land uses. Watershed plans may also identify priority sites for aquatic resource restoration and protection. Examples of watershed plans include special area management plans, advance identification programs, and wetland management plans.

Wetlands: Those areas that are inundated or saturated by surface or ground water at a frequency and duration sufficient to support, and that under normal

circumstances do support, a prevalence of vegetation adapted for life in saturated soil conditions. Wetlands generally include swamps, marshes, bogs, and similar areas. Wetlands do not include those artificial wetlands intentionally created from non-wetland sites, including, but not limited to, irrigation and drainage ditches, grass-lined swales, canals, detention facilities, wastewater treatment facilities, farm ponds, and landscape amenities, or those wetlands created after July 1, 1990, that were unintentionally created as a result of the construction of a road, street, or highway. Wetlands may include those artificial wetlands intentionally created from non-wetland areas to mitigate the conversion of wetlands.

Wetland delineation: The method used to establish the existence (location) and physical limits (size) of a wetland for purposes of federal, state, and local regulations.

Wetlands of High Conservation Value: See *Wetlands with special characteristics*.

Wetland mitigation bank: A site or suite of sites where resources are restored, created, enhanced, and/or preserved, for the purpose of providing compensatory mitigation for impacts. In general, a mitigation bank sells compensatory mitigation credits to permittees whose obligation to provide compensatory mitigation is then transferred to the mitigation bank sponsor. The operation and use of a mitigation bank are governed by a mitigation banking instrument.

Wetland mosaic: An area with a concentration of multiple small wetlands, in which each patch of wetland is less than one acre; patches are less than 100 feet from each other; and areas delineated as wetland are more than 50 percent of the total area of the entire mosaic, including uplands and open water.

Wetlands in coastal lagoons: See *Wetlands with special characteristics.*

Wetlands with special characteristics for eastern Washington: Alkali wetlands, bogs, calcareous fens, forested wetlands, vernal pools, and Wetlands of High Conservation Value. Detailed information about these individual wetland types is found in Washington State Wetland Rating System for Eastern Washington: 2014 Update (Ecology Publication #14-06-030), or as revised.

Wetlands with special characteristics for western Washington: Bogs, estuarine wetlands, forested wetlands, interdunal wetlands, wetlands in coastal lagoons, and Wetlands of High Conservation Value. Detailed information about these individual wetland types is found in the Washington State Wetland Rating System for Western Washington: 2014 Update (Ecology Publication #14-06-029), or as revised.

Appendix C. Buffer Approaches for Western Washington

Option 1

Table 1. Wetland buffer width requirements, in feet, if Table 2 is implemented and a habitat corridor is provided

Category of wetland	Habitat score 3-5 points (corridor not required)	Habitat score 6-7 points	Habitat score 8-9 points	Buffer width based on special characteristics
Category I or II: Based on rating of wetland functions (and not listed below)	75	110	225	NA
Category I: Bogs and Wetlands of High Conservation Value	NA	NA	225	190
Category I: Interdunal	NA	NA	225	NA
Category I: Forested	75	110	225	NA
Category I: Estuarine and wetlands in coastal lagoons	NA	NA	NA	150
Category II: Interdunal	NA	NA	NA	110
Category II: Estuarine and wetlands in coastal lagoons	NA	NA	NA	110
Category III: All types except interdunal	60	110	225	NA
Category III: Interdunal	NA	NA	NA	60
Category IV: All types	40	40	40	NA

Impact minimization measures

Developments that produce the listed disturbances and are requesting a buffer reduction are required to address the disturbance through the use of applicable minimization measures.

This is not a complete list of measures, nor is every example measure required. Though not every measure is required, all effort should be made to implement as many measures as possible. Regulatory staff should determine, in coordination with the applicant, which measures are applicable and practicable.

Table 2. Impact minimization measures

Examples of disturbance	Activities and uses that cause disturbances	Examples of measures to minimize impacts
Lights	• Parking lots • Commercial/Industrial • Residential • Recreation (e.g., athletic fields) • Agricultural buildings	• Direct lights away from wetland • Only use lighting where necessary for public safety and keep lights off when not needed • Use motion-activated lights • Use full cut-off filters to cover light bulbs and direct light only where needed • Limit use of blue-white colored lights in favor of red-amber hues • Use lower-intensity LED lighting • Dim light to the lowest acceptable intensity
Noise	• Commercial • Industrial • Recreation (e.g., athletic fields, bleachers, etc.) • Residential • Agriculture	• Locate activity that generates noise away from wetland • Construct a fence to reduce noise impacts on adjacent wetland and buffer • Plant a strip of dense shrub vegetation adjacent to wetland buffer
Toxic runoff	• Parking lots • Roads • Commercial/industrial • Residential areas • Application of pesticides • Landscaping • Agriculture	• Route all new, untreated runoff away from wetland while ensuring wetland is not dewatered • Establish covenants limiting use of pesticides within 150 ft. of wetland • Apply integrated pest management (These examples are not necessarily adequate for minimizing toxic runoff if threatened or endangered species are present at the site.)

Examples of disturbance	Activities and uses that cause disturbances	Examples of measures to minimize impacts
Stormwater runoff	• Parking lots • Roads • Residential areas • Commercial/industrial • Recreation • Landscaping/lawns • Other impermeable surfaces, compacted soil, etc.	• Retrofit stormwater detention and treatment for roads and existing adjacent development • Prevent channelized or sheet flow from lawns that directly enters the buffer • Infiltrate or treat, detain, and disperse new runoff from impervious surfaces and lawns
Pets and human disturbance	• Residential areas • Recreation	• Use privacy fencing • Plant dense native vegetation to delineate buffer edge and to discourage disturbance • Place wetland and its buffer in a separate tract • Place signs around the wetland buffer every 50-200 ft., and for subdivisions place signs at the back of each residential lot • When platting new subdivisions, locate greenbelts, stormwater facilities, and other lower-intensity uses adjacent to wetland buffers
Dust	• Tilled fields • Roads	• Use best management practices to control dust

Table 3. Wetland buffer width requirements, in feet, for applicants not providing a habitat corridor or implementing measures in Table 2

Category of wetland	Habitat score 3-5 points	Habitat score 6-7 points	Habitat score 8-9 points	Buffer width based on special characteristics
Category I & II: Based on rating of wetland functions (and not listed below)	100	150	300	NA
Category I: Bogs and Wetlands of High Conservation Value	NA	NA	300	250
Category I: Interdunal	NA	NA	300	NA
Category I: Forested	100	150	300	NA
Category I: Estuarine and wetlands in coastal lagoons	NA	NA	NA	200
Category II: Interdunal	NA	NA	NA	150
Category II: Estuarine and wetlands in coastal lagoons	NA	NA	NA	150
Category III: All types except interdunal	80	150	300	NA
Category III: Interdunal	NA	NA	NA	80
Category IV	NA	NA	NA	50

Conditions for implementing Tables 1, 2, and 3

1. Wetlands that score 6 points or more for habitat function: the buffers in Table 1 can be used only if all of the following criteria are met:

a. A relatively undisturbed, vegetated corridor at least 100 feet wide is protected between the wetland and:

i. A legally protected, relatively undisturbed and vegetated area (e.g., Priority Habitats, compensatory mitigation sites, wildlife areas/refuges, national, county, and state parks where they have management plans with identified areas designated as Natural, Natural Forest, or Natural Area Preserve, or

ii. An area that is the site of a Watershed Project identified within, and fully consistent with, a Watershed Plan as defined by RCW 89-08-460, or

iii. An area where development is prohibited according to the provisions of the local shoreline master program, or

iv. An area with equivalent habitat quality that has conservation status in perpetuity, in consultation with WDFW.

b. The corridor is permanently protected for the entire distance between the wetland and the shoreline or legally protected area by a conservation easement, deed restriction, or other legal site protection mechanisms.

c. Presence or absence of the shoreline or Priority Habitat must be confirmed by a qualified biologist or shoreline Administrator.

d. The measures in Table 2 are implemented, as applicable, to minimize the impacts of the adjacent land uses.

2. For wetlands that score 5 or fewer habitat points, only the measures in Table 2 are required for the use of the buffers in Table 1.

3. If an applicant does not apply the mitigation measures in Table 2 or is unable to provide a protected corridor, then the buffers in Table 3 shall be used.

4. The buffer widths in Tables 1 and 3 assume that the buffer is vegetated with a native plant community appropriate for the ecoregion. If the existing buffer is unvegetated, sparsely vegetated, or vegetated with invasive species that do not perform needed functions, the buffer must either be planted to create the appropriate native plant community or be widened to ensure that the buffer provides adequate functions to protect the wetland.

Note: An expanded table with graduated buffer widths based on habitat score is also outlined in the July 2018 Appendix 8-C[76] of *Wetlands in Washington State, Volume 2*. This is an approach that assigns unique buffer widths to each habitat score in seven increments. It is a gradual increase in buffer width with each point. Compared to Option 1, this avoids a marked increase in buffer width resulting from an increase of one point in the habitat score.

Option 2

Table 1. Width of buffers, in feet, needed to protect wetlands from impacts of proposed land uses (used with Table 2)

Category of wetland	Land use with low impact*	Land use with moderate impact*	Land use with high impact*
I	150	225	300
II	150	225	300
III	75	110	150
IV	25	40	50

*See Table 2 below for types of land uses that can result in low, moderate, and high levels of impacts to wetlands

Table 2. Levels of impacts from proposed land use types

[Local governments are encouraged to ensure the uses in this table match the uses specified in their development and land use regulations and are consistent with the principles in this example.]

Level of impact from proposed land use	Types of land use
High	• Commercial • Urban • Industrial • Institutional • Mixed-use developments • Residential (more than 1 unit/acre) • Roads: federal and state highways, including on-ramps and exits, state routes, and other roads associated with high-impact land uses • Railroads • Agriculture with high-intensity activities (dairies, nurseries, greenhouses, growing and harvesting crops requiring annual tilling, raising and maintaining animals, etc.)

[76] https://apps.ecology.wa.gov/publications/parts/0506008part3.pdf

Level of impact from proposed land use	Types of land use
	• Open/recreational space with high-intensity uses (golf courses, ball fields, etc.) • Solar farms (utility scale)
Moderate	• Residential (1 unit/acre or less) • Roads: Forest Service roads and roads associated with moderate-impact land uses • Open/recreational space with moderate-intensity uses (parks with paved trails or playgrounds, biking, jogging, etc.) • Agriculture with moderate-intensity uses (orchards, hay fields, light or rotational grazing, etc.) • Utility corridor or right-of-way used by one or more utilities and including access/maintenance road • Wind farm
Low	• Natural resource lands (forestry/silviculture–cutting of trees only, not land clearing and removing stumps) • Open/recreational space with low-intensity uses (unpaved trails, hiking, birdwatching, etc.) • Utility corridor without a maintenance road and little or no vegetation management • Cell tower

Option 3

Table 1. Wetland buffer width requirements, in feet, based solely on wetland category

Category of wetland	Buffer width
I	300
II	300
III	150
IV	50

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Appendix D. Buffer Approaches for Eastern Washington

Option 1

Table 1. Wetland buffer width requirements, in feet, if Table 2 is implemented and a habitat corridor is provided

Category of wetland	Habitat Score 3-5 points (corridor not required)	Habitat Score 6-7 points	Habitat Score 8-9 points	Buffer width based on special characteristics
Category I & II: Based on rating of wetland functions (and not listed below)	75	110	150	NA
Category I & II: Forested	75	110	150	NA
Category I: Bogs, calcareous fens, and Wetlands of High Conservation Value	NA	NA	NA	190
Category I: Alkali	NA	NA	NA	150
Category II: Vernal pool	NA	NA	NA	150
Category III	60	110	150	NA
Category IV	40	40	40	NA

Impact minimization measures

Developments that produce the listed disturbances and are requesting a buffer reduction are required to address the disturbance through the use of applicable minimization measures.

This is not a complete list of measures, nor is every example measure required. Though not every measure is required, all effort should be made to implement as many measures as possible. Regulatory staff should determine, in coordination with the applicant, which measures are applicable and practicable.

Table 2. Impact minimization measures

Examples of disturbance	Activities and uses that cause disturbances	Examples of measures to minimize impacts
Lights	• Parking lots • Commercial/Industrial • Residential • Recreation (e.g., athletic fields) • Agricultural buildings	• Direct lights away from wetland • Only use lighting where necessary for public safety and keep lights off when not needed • Use motion-activated lights • Use full cut-off filters to cover light bulbs and direct light only where needed • Limit use of blue-white colored lights in favor of red-amber hues • Use lower-intensity LED lighting • Dim light to the lowest acceptable intensity
Noise	• Commercial • Industrial • Recreation (e.g., athletic fields, bleachers, etc.) • Residential • Agriculture	• Locate activity that generates noise away from wetland • Construct a fence to reduce noise impacts on adjacent wetland and buffer • Plant a strip of dense shrub vegetation adjacent to wetland buffer
Toxic runoff	• Parking lots • Roads • Commercial/industrial • Residential areas • Application of pesticides • Landscaping • Agriculture	• Route all new, untreated runoff away from wetland while ensuring wetland is not dewatered • Establish covenants limiting use of pesticides within 150 ft. of wetland • Apply integrated pest management (Note: These examples are not necessarily adequate for minimizing toxic runoff if threatened or endangered species are present at the site.)

Examples of disturbance	Activities and uses that cause disturbances	Examples of measures to minimize impacts
Stormwater runoff	• Parking lots • Roads • Residential areas • Commercial/industrial • Recreation • Landscaping/lawns • Other impermeable surfaces, compacted soil, etc.	• Retrofit stormwater detention and treatment for roads and existing adjacent development • Prevent channelized or sheet flow from lawns that directly enters the buffer • Infiltrate or treat, detain, and disperse new runoff from impervious surfaces and lawns
Pets and human disturbance	• Residential areas • Recreation	• Use privacy fencing • Plant dense native vegetation to delineate buffer edge and to discourage disturbance • Place wetland and its buffer in a separate tract • Place signs around the wetland buffer every 50-200 ft., and for subdivisions place signs at the back of each residential lot • When platting new subdivisions, locate greenbelts, stormwater facilities, or other lower-intensity land uses adjacent to wetland buffers
Dust	• Tilled fields • Roads	• Use best management practices to control dust

Table 3. Wetland buffer width requirements, in feet, for applicants not providing a habitat corridor or implementing measures in Table 2

Category of wetland	Habitat score 3-5 points	Habitat score 6-7 points	Habitat score 8-9 points	Buffer width based on special characteristics
Category I & II: Based on rating of wetland functions (and not listed below)	100	150	200	NA
Category I & II: Forested	100	150	200	NA
Category I: Bogs, calcareous fens, and Wetlands of High Conservation Value	NA	NA	NA	250
Category I: Alkali	NA	NA	NA	200
Category II: Vernal pool	NA	NA	NA	200
Category III	80	150	200	NA
Category IV	50	50	50	NA

Conditions for implementing Tables 1, 2, and 3

1. Wetlands that score 6 points or more for habitat function: the buffers in Table 1 can be used only if all of the following criteria are met:

a. A relatively undisturbed, vegetated corridor at least 100 feet wide is protected between the wetland and:

i. A legally protected, relatively undisturbed and vegetated area (e.g., Priority Habitats, compensatory mitigation sites, wildlife areas/refuges, national, county, and state parks where they have management plans with identified areas designated as Natural, Natural Forest, or Natural Area Preserve, or

ii. An area that is the site of a Watershed Project identified within, and fully consistent with, a Watershed Plan as defined by RCW 89-08-460, or

iii. An area where development is prohibited according to the provisions of the local shoreline master program, or

iV. An area with equivalent habitat quality that has conservation status in perpetuity, in consultation with WDFW.

b. The corridor is permanently protected for the entire distance between the wetland and the shoreline or legally protected area by a conservation easement, deed restriction, or other legal means.

c. Presence or absence of the shoreline or Priority Habitat must be confirmed by a qualified biologist or shoreline Administrator.

d. The measures in Table 2 are implemented, as applicable, to minimize the impacts of the adjacent land uses.

2. For wetlands that score 5 or fewer habitat points, only the measures in Table 2 are required for the use of the buffers in Table 1.

3. If an applicant does not apply the mitigation measures in Table 2 or is unable to provide a protected corridor, then the buffers in Table 3 shall be used.

4. The buffer widths in Tables 1 and 3 assume that the buffer is vegetated with a native plant community appropriate for the ecoregion. If the existing buffer is un-vegetated, sparsely vegetated, or vegetated with invasive species that do not perform needed functions, the buffer must either be planted to create the appropriate native plant community or be widened to ensure that the buffer provides adequate functions to protect the wetland.

Note: An expanded table with graduated buffer widths based on habitat score is also outlined in the July 2018 Appendix 8-D[77] of *Wetlands in Washington State, Volume 2*. This is an approach that assigns unique buffer widths to each habitat score in seven increments. It is a gradual increase in buffer width with each point. Compared to Option 1, this avoids a marked increase in buffer width resulting from an increase of one point in the habitat score.

Option 2

Table 1. Width of buffers, in feet, needed to protect wetlands from impacts of proposed land uses (used with Table 2)

Category of wetland	Land use with low impact*	Land use with moderate impact*	Land use with high impact*
I	125	190	250
II	100	150	200
III	75	110	150
IV	25	40	50

*See Table 2 below for types of land uses that can result in low, moderate, and high impacts to wetlands

Table 2. Levels of impacts from proposed land use types

[Local governments are encouraged to ensure the uses in this table match the uses specified in their development and land use regulations and are consistent with the principles in this example.]

Level of impact from proposed land use	Types of land use
High	• Commercial • Urban • Industrial • Institutional • Mixed-use developments • Residential (more than 1 unit/acre) • Roads: federal and state highways, including on-ramps and exits, state routes, and other roads associated with high-impact land uses • Railroads • Agriculture with high-intensity activities (dairies, nurseries, greenhouses, growing and harvesting crops requiring annual tilling, raising and maintaining animals, etc.)

[77] https://apps.ecology.wa.gov/publications/parts/0506008part4.pdf

Level of impact from proposed land use	Types of land use
	• Open/recreational space with high-intensity uses (golf courses, ball fields, etc.) • Solar farms (utility scale)
Moderate	• Residential (1 unit/acre or less) • Roads: Forest Service roads and roads associated with moderate-impact land uses • Open/recreational space with moderate-intensity uses (parks with paved trails or playgrounds, biking, jogging, etc.) • Agriculture with moderate-intensity uses (orchards, hay fields, light or rotational grazing, etc.) • Utility corridor or right-of-way used by one or more utilities and including access/maintenance • Wind farm
Low	• Natural resource lands (forestry/silviculture–cutting of trees only, not land clearing and removing stumps) • Open/recreational space with low-intensity uses (unpaved trails, hiking, birdwatching, etc.) • Utility corridor without a maintenance road and little or no vegetation management • Cell tower

Option 3

Table 1. Wetland buffer width requirements, in feet, based solely on wetland category

Category of wetland	Buffer width
I	250
II	200
III	150
IV	50

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Appendix E. Mitigation Ratio Tables

Compensation ratios for permanent impacts (western and eastern Washington)

Table 1

Category of impacted wetland (based on score for function)	Re-establishment or creation	Rehabilitation	Preservation	Enhancement
Category I	4:1	8:1	16:1	16:1
Category II	3:1	6:1	12:1	12:1
Category III	2:1	4:1	8:1	8:1
Category IV	1.5:1	3:1	6:1	6:1

Notes:

- Ratios for rehabilitation, preservation, and enhancement may be reduced when combined with 1:1 replacement through re-establishment or creation. See Table 6B-2 in *Wetland Mitigation in Washington State – Part 1: Agency Policies and Guidance –Version 2* (Ecology et al., 2021 or as revised).
- All proposed preservation sites need to meet the preservation criteria listed in Chapter 070.3.E of Appendix A, Sample Wetland Regulations.
- The ratios provide in Table 1 are for permanent, direct impacts to wetlands. For recommended ratios for other types of impacts (e.g., long-term temporary, conversions), see Chapters 6B4.4 through 6B4.8 of *Wetland Mitigation in Washington State – Part 1: Agency Policies and Guidance –Version 2* (Ecology et al., 2021 or as revised).
- The category of impacted wetland is based on scores for functions. Compensation ratios in this table generally do not apply when impacts involve a wetland whose category is based on special characteristics. Compensation ratios for impacts to wetlands with special characteristics are provided in Table 2 below. Specific tables are provided for western and eastern Washington.

Compensation ratios for unavoidable permanent impacts to wetlands with special characteristics (western Washington)

Table 2. Western

Category of impacted wetland (based on special characteristics)	Re-establishment or creation	Rehabilitation	Preservation	Enhancement
Category I forested	6:1	12:1	24:1	24:1
Bogs	NA	NA	24:1	NA
Wetlands of High Conservation Value	Consult with WA DNR	Consult with WA DNR	24:1	Consult with WA DNR
Category I Estuarine wetlands	3:1 (re-establishment only)	6:1	12:1	Limited circumstances (case by case)
Category II Estuarine wetlands	4:1 (re-establishment only)	8:1	16:1	Limited circumstances (case by case)
Category I Interdunal wetlands	4:1	8:1 (limited circumstances)	16:1	Not considered an option
Category II Interdunal wetlands	2:1	4:1 (limited circumstances)	8:1	Not considered an option
Category III and IV Interdunal wetlands	1.5:1	3:1 (limited circumstances)	6:1	Not considered an option
Category I Wetlands in coastal lagoons	4:1 (re-establishment only)	8:1	16:1	Not considered an option
Category II Wetlands in coastal lagoons	3:1 (re-establishment only)	6:1	12:1	Not considered an option

Note: Methods of compensation are limited for certain wetlands with special characteristics. Some of these wetland types only occur naturally and have never been successfully created or rehabilitated. Some may take more than a lifetime to re-establish. Thus, avoidance is the best regulatory approach when addressing these wetlands. Refer to Chapter 6B.5 of Wetland Mitigation in Washington State – Part 1: Agency Policies and Guidance –Version 2 (Ecology et al., 2021 or as revised) for more information on methods of compensation and ratios for wetlands with special characteristics.

Compensation ratios for unavoidable permanent impacts to wetlands with special characteristics (eastern Washington)

Table 2. Eastern

Category of impacted wetland (based on special characteristics)	Re-establishment or creation	Rehabilitation	Preservation	Enhancement
Category I forested	6:1	12:1	24:1	24:1
Category II forested (eastern WA only)	4:1	8:1	16:1	16:1
Bogs and calcareous fens	NA	NA	24:1	NA
Wetlands of High Conservation Value	Consult with WA DNR	Consult with WA DNR	24:1	Consult with WA DNR
Alkali wetlands	NA	NA	24:1	NA
Vernal pools	Case by case or 3:1 for re-establishment of a seasonally ponded wetland	Case by case or 6:1 for re-establishment of a seasonally ponded wetland	16:1 (preservation of vernal pool complex)	16:1 (enhancement of both wetlands and uplands within a vernal pool complex)

Note: Methods of compensation are limited for certain wetlands with special characteristics. Some of these wetland types only occur naturally and have never been successfully created or rehabilitated. Some may take more than a lifetime to re-establish. Thus, avoidance is the best regulatory approach when addressing these wetlands. Refer to Chapter 6B.5 of *Wetland Mitigation in Washington State – Part 1: Agency Policies and Guidance –Version 2* (Ecology et al., 2021 or as revised) for more information on methods of compensation and ratios for wetlands with special characteristics.

An official website of the United States government Here's how you know

Southern Resident Killer Whale Priority Chinook Salmon Stocks - Questions and Answers

In July 2018, NOAA Fisheries issued a paper on priority Chinook salmon stocks for Southern Resident killer whales. The following questions and answers provide more information about the priority Chinook salmon stocks.

Q: Why is this list of priority Chinook salmon stocks important?

A: The paper, "Southern Resident killer whale priority Chinook stocks," describes a model that analyzes how much endangered Southern Resident killer whales likely depend on different West Coast Chinook salmon stocks. At the end of the paper is a list of West Coast Chinook salmon stocks, according to their importance to the Southern Resident killer whales. Several of these stocks are also listed as endangered or threatened under the federal Endangered Species Act (ESA).

One of the key actions in NOAA Fisheries' Species in the Spotlight Action Plan for Southern Resident killer whales is "target recovery of critical prey." Understanding the specific stocks of Chinook salmon that Southern Resident killer whales rely on for food will help NOAA Fisheries and our partners target recovery actions to provide the greatest benefit to both native West Coast salmon and steelhead and the Southern Resident killer whales.

Q: Who developed the model that produced the list?

A: NOAA Fisheries' West Coast Region and Northwest Fisheries Science Center worked with the Washington Department of Fish and Wildlife to develop the list and model using the best and latest research on Southern Resident killer whales and their prey. That research includes sampling of the whales' prey and scat to understand which types of fish they rely on during different times of the

year, as well as analyzing high-resolution aerial photographs that reveal their body weight and condition.

Salmon and whale biologists, managers, and recovery partners reviewed the model and initial list of the priority Chinook salmon stocks and discussed it at a recent workshop sponsored by the National Fish and Wildlife Foundation. The workshop included representatives of the Northwest Indian Fisheries Commission, Columbia River Inter-Tribal Fish Commission, Fisheries and Oceans Canada, Puget Sound Partnership, Long Live the Kings, and the Skagit River System Cooperative. We then shared the list with the working group that is looking for ways to improve the availability of prey for the killer whales as part of the Governor's Task Force for Southern Resident killer whale recovery.

Q: What factors affect where a Chinook salmon stock falls on the list?

A: NOAA Fisheries and Washington Department of Fish and Wildlife used their most current data and other relevant peer reviewed research to develop a model to identify which Chinook salmon runs are most important to these whales. The model weighs salmon stocks based on how much their ranges overlap with the Southern Resident killer whales. The model also incorporates the latest research identifying which salmon stocks the killer whales eat based on fecal samples and scraps of their prey collected by biologists. The model gives extra weight to salmon runs that support the Southern Resident killer whales when their access to food is limited, such as in winter when aerial photographs show some whales to have poorer body condition.

In summer, the whales feed mainly on Chinook salmon returning to the Fraser River in British Columbia and Puget Sound. In other months the whales expand their diet to include other types of salmon like chum, coho, and steelhead as well as small amounts of bottomfish including halibut and lingcod. Switching to other prey items may be an indicator that there is not enough of their preferred Chinook salmon. The framework and initial priority list were shared with state and tribal co-managers, stakeholders, and non-profit groups to get feedback and make improvements.

Q: Are salmon stocks that are not included on the list considered unimportant for the whales?

A: Southern Resident killer whales range from central California to Southeast Alaska and eat Chinook salmon from many different runs within this area. Southern Resident killer whales eat all year long and need access to a variety of salmon with different run timing and distribution. NOAA Fisheries is committed to recovery of all threatened and endangered West Coast salmon stocks. We jointly created the priority list to help scientists and managers understand where we can focus salmon recovery efforts that will also help Southern Resident killer whales. In addition, there are some Chinook salmon runs that were historically important to the Southern Resident killer whales, but have been significantly reduced or extirpated and are no longer available. While these runs are

not reflected in the priority list, they may provide potential for increasing the whales' prey though future recovery or reintroduction of these populations.

Q: Is the lack of prey the most significant threat to the recovery of Southern Resident killer whales?

A: The availability of prey is one of three main threats to Southern Resident killer whales. The Southern Resident killer whales are also adversely affected by vessel noise and traffic which can interfere with the whales' echolocation, making finding their prey harder. When prey is hard to find and they are not eating regularly, it causes the whales to dip into their blubber stores for energy. Often, that fat is contaminated because of pollution in coastal waters. This contamination in their tissues threatens the whales' long-term health and reproductive success. Given the myriad of threats, we've created a comprehensive recovery program for Southern Residents killer whales to address all of these threats.

Q: Will prioritizing Chinook salmon stocks for Southern Resident killer whales leave fewer for fishing?

A: The prioritization will inform recovery actions such as habitat restoration and perhaps production of fish at hatcheries, which are designed to increase the abundance of salmon overall. That will benefit salmon populations, killer whales, and fishing opportunities. Benefits of healthy habitat may well extend to other species of salmon and steelhead that support commercial and recreational fisheries. We assess all fisheries to make sure threatened and endangered salmon are protected, and in doing so also take into account their significance to Southern Resident killer whales.

Q: How will the list affect salmon recovery funding opportunities, such as the Pacific Salmon Coastal Recovery Fund?

A: The list can help inform funders in making decisions about a variety of salmon recovery actions and they may prioritize actions that benefit both salmon and Southern Resident killer whales. Connecting salmon recovery actions to recovery of Southern Resident killer whales could increase awareness and bring new partnerships and funding sources to the table. Already, the National Fish and Wildlife Foundation has dedicated more than $2 million in funding toward projects, including habitat restoration, that will benefit Southern Resident killer whales. That money has leveraged more than $2.75 million in matching grants, for a total of nearly $5 million worth of impact on the region, which in turn benefits the local economy.

Q: How will this list be used to help priority Chinook salmon stocks?

A: Identifying and implementing actions to improve abundance of the priority stocks requires consideration of various factors including:

- the feasibility of an action,
- recovery or growth potential of the salmon run, and
- climate and ecosystem impacts.

These considerations were not factored into the model and are not reflected in the list. However, we will be weighing these and other considerations as we identify and implement actions to benefit both the salmon stocks and Southern Resident killer whales.

Q: Will the list be used to increase hatchery production of Chinook salmon? How might this affect current efforts to reduce the impact of hatchery production on ESA-listed Chinook?

A: Adjustments to hatchery production of high priority salmon runs may increase the prey available to the Southern Resident killer whales. However, any increase in hatchery production of Chinook salmon stocks needs to carefully consider the impacts hatchery fish may have on threatened and endangered salmon runs. Hatchery fish can compete with and affect the genetics of natural-origin salmon, which may impact their recovery. Managing recovery of multiple species will require an ecosystem approach that considers food web interactions.

Q: How will we use this list to prioritize habitat restoration? Will current projects be halted or changed to address these new priority stocks?

A: NOAA Fisheries is committed to recovery of all threatened and endangered West Coast salmon stocks. Access to quality habitat is a limiting factor for most salmon runs. The priority list can help inform and garner support for salmon habitat projects that benefit both salmon and Southern Resident killer whales.

Q: Several of the priority Chinook salmon stocks are found in the Snake River. Does NOAA Fisheries now support removing those federal dams?

A: The U.S. Bureau of Reclamation, U.S. Army Corps of Engineers, and Bonneville Power Administration (the Action Agencies) are currently developing an Environmental Impact Statement (EIS) in accordance with the National Environmental Policy Act (NEPA) that will assess and update the approach for long-term Columbia River System operations, maintenance, and configuration, as well as evaluate measures to avoid, offset, or minimize impacts to resources affected by the

management of the Columbia River System. Based on scoping, the range of alternatives being considered is broad and will likely include evaluation of potential large-scale changes such as breaching the lower Snake River dams.

NOAA Fisheries is coordinating with the Action Agencies during the NEPA process and ultimately intends to complete ESA Section 7 consultation on the final preferred alternative to assist the Action Agencies in ensuring that their action is not likely to jeopardize the continued existence of ESA-listed species, including Southern Resident killer whales, or result in destruction or adverse modification of critical habitat. During the EIS and ESA Section 7 consultation processes, the federal agencies will consider the effects of operating the lower Snake River dams on prey species currently relied upon by Southern Resident killer whales and any associated measures to avoid, offset, or minimize those effects will be considered during that process.

Q: Can ESA-listed Chinook salmon stocks recover to the point where they can support the population of Southern Resident killer whales?

A: Since Southern Resident killer whales need a variety of Chinook salmon prey throughout their range throughout the year, they can obtain sufficient prey in many ways. Restoring habitat and recovering threatened and endangered Chinook salmon stocks to natural, abundant, and sustainable levels are important long-term goals which may take decades. In the near-term we can take actions that support prey for the current number of killer whales and allow for growth of both salmon and killer whale populations.

Q: Sea lions are feeding on ESA-listed Chinook salmon in the Columbia River, so how is NOAA Fisheries addressing that?

A: The growing abundance of California sea lion numbers along the West Coast has raised concern about predation on threatened and endangered salmon and steelhead in the Northwest. Sea lions are protected under the Marine Mammal Protection Act. Salmon is one of their favorite prey when they visit the Northwest, and some of the salmon runs they feed on are protected under the ESA. While balancing the competing laws is challenging, NOAA Fisheries has taken the step of authorizing Oregon, Washington, and Idaho to remove a small number of individually identifiable sea lions near the Columbia River's Bonneville Dam that have been spotted repeatedly preying on salmon. We are also evaluating another request for similar action in the Willamette River.

Q: What is the next step, now that you have the model and list? Are there new research questions/needs that would improve these?

A: The model remains a work in progress. It will be updated as we gather additional data and increase our knowledge of where Chinook salmon overlap with the Southern Resident killer whales, what Chinook salmon runs are important to the killer whales' diet, and where and when the killer whales are food limited. For example, we used a detailed analysis of available data of fall-run Chinook salmon distribution to inform the model. A study to analyze spring-run Chinook salmon movements is now underway. This new information will be included in future runs of the model to improve its accuracy. Another potential next step is to identify stocks that have been more historically important but are not currently reflected in the Southern Resident killer whales' diet and so may not be reflected on this current list.

More Information

- Southern Resident Killer Whales
- Food for the Southern Resident Killer Whales
- Chinook Salmon Species Profile

Last updated by West Coast Regional Office on 02/14/2020

SOUTHERN RESIDENT KILLER WHALE PRIORITY CHINOOK STOCKS REPORT

NOAA Fisheries West Coast Region

and

Washington Department of Fish and Wildlife

June 22, 2018

SOUTHERN RESIDENT KILLER WHALE PRIORITY CHINOOK STOCKS

Outline of Prey Prioritization Conceptual Model

NOAA Fisheries and Washington Department of Fish and Wildlife (WDFW) have developed a framework to identify Chinook salmon stocks that are important to Southern Resident killer whales (SRKW) to assist in prioritizing actions to increase critical prey for the whales. The framework currently includes three factors that contribute to the identification of priority Chinook salmon populations. Note, here "population" could mean management unit, stock, ESU, run, etc. Each of the three factors has a range of scores which affects its weight. For each Chinook population ranging from Southeastern Alaska to California, a total score is calculated by adding up the three individual factor scores. The Chinook salmon populations with the highest total scores are considered the highest priority to increase abundance to benefit the whales. Several sensitivity analyses provided initial help in understanding how the weighting/scoring affects the priority list. The conceptual model, factors, and scoring were reviewed at a workshop sponsored by the National Fish and Wildlife Foundation and modifications were made to incorporate feedback from participants. The factors, scoring and priority list can be adapted as new scientific information becomes available.

The three evaluation factors include:

FACTOR 1- Observed Part of SRKW Diet

Description and data sources: Prey tissues/scales and fecal samples have been collected from 2004 – present (Hanson et al. 2010, Ford et al. 2016, Hanson et al. in prep). From the prey tissues/scales collected, Genetic Stock Identification (GSI) were run to identify the Chinook stocks in the diet. The majority of samples have been collected in the summer months in inland waters of WA and British Columbia.

<u>Assumption</u>

- Chinook populations that have been observed in the diet will have higher priority than those that have not.

Caveat: There is currently no spatial correction factor for sample collection (stocks originating from near the sample locations are more likely to be collected), no correction factor for abundance (more abundant stocks are more likely to be identified in the diet), and no correction factor for potential whale selectivity (older, larger fish more likely to be recovered in scale samples).

FACTOR 2- Consumed During Reduced Body Condition or Diversified SRKW Diet

Description and data sources: For the second factor, "Consumed During Reduced Body Condition or Diverse Diet", stocks consumed during times of potential reduced body condition and increased diet diversity receive additional weight.

Since 2008, NOAA's SWFSC has used aerial photogrammetry to assess the body condition and health of SRKWs, initially in collaboration with the Center for Whale Research and, more recently, with the Vancouver Aquarium and SR^3. Photogrammetry data has been collected during seven field efforts in five years, including September 2008, 2013, and 2015, and May and September 2016 and 2017 (Durban et al. 2017; Fearnbach et al. 2018). The proportion of Chinook salmon consumed in whales' diet was estimated by season and region (inland vs coastal waters) using the data from prey tissues/scales and fecal samples (Hanson et al. 2010, Ford et al. 2016, Hanson et al. in prep).

Assumptions

- Reduced body condition and diverse diet occurs from Oct through May.
- Whales switch from preferred prey, Chinook salmon, to other salmonids or prey when Chinook are less available.

FACTOR 3- Degree of Spatial and Temporal Overlap

Description and data sources: Recent prey mapping from Shelton et al. in press (Coded Wire Tag data) was used to assess the overlap in time and space distribution of individual fall Chinook salmon stocks and SRKWs. The distribution/timing of all Chinook salmon stocks across the whales' range from California to Southwest Vancouver Island (and the inland waters of the Salish Sea) was divided into weighted spatial/temporal areas. Currently, Shelton et al. in press includes detailed information on fall runs. Available data for spring Chinook was included, but detailed analyses of data from spring runs are in progress and will be completed in the next two years, incorporating both recoveries in directed Chinook troll fisheries, and Chinook recovered as bycatch in fisheries not targeting Chinook.

For spring run Chinook we relied on reports from the Chinook Technical Committee of the Pacific Salmon Commission (PSC 2018a, 2018b) and published literature (e.g. Satterthwaite et al. 2013, Wahle et al. 1981, Weitkamp 2010) to assign approximate ocean distributions. For stocks with less information, we assumed that the risk to predation was low in seasons and regions that did not correspond to the return timing and origin of each stock (for example, Columbia spring Chinook are assumed to be most available to whales in winter and spring months near the mouth of the Columbia River, but because of their approximate ocean distribution, they are not available in other regions or seasons – particularly mid-summer to fall). Because of limited recoveries, we also assumed that for stocks returning to the Salish Sea

(Strait of Georgia, Puget Sound), the distribution was similar in the Salish Sea to Southwest Vancouver Island distributions.

The spatial/temporal Areas currently include: 1) Southwest Vancouver Island (WCVI); 2) Salish Sea; 3) Cape Falcon, Oregon north to British Columbia border; 4) Cape Falcon, OR south to Cape Mendocino (northern California); 5) Cape Mendocino, CA to Point Sur, CA. Seasons are defined as: Spring: April-May; Summer: June-July; Fall: Aug-Oct: Winter: November-March. These areas reflect the division of Chinook run timing (approximately), correspond to periods of coded wire tag recoveries in fisheries, and correspond to predictable patterns of SRKW movement. SRKW distribution data was assessed from multiple sources (e.g. Center for Whale Research, The Whale Museum, NWFSC satellite tagging, NWFSC coastal hydrophones, coastal spring/winter NWFSC cruises, other opportunistic observations).

Assumptions

- Chinook salmon stocks that overlap in space and time are potential prey.
- Chinook salmon stocks that have a higher degree of overlap in space and time have a higher priority than stocks that have a relatively lower degree of overlap.
- Weighted spatial/temporal areas accommodate variation in the distribution of SRKW and Chinook salmon

Caveat- Coded Wire Tag (CWT) model interpolates movement of stocks seasonally to account for gaps in fishing effort. Also, the hatchery releases going into the CWT model are not comprehensive, but rather model the distribution of major stock groupings. Within regions and run type (e.g. fall Puget Sound), the ocean distribution is assumed to be the same for all watersheds. Smaller release groups, such as those from the San Juan Islands (SJUA in RMIS) were not included in Shelton et al. because of the low recovery rates – though the ocean distribution of these fish is assumed to be similar to those populations originating from Puget Sound. In particular, ocean distributions of spring run stocks tend to be less well understood than fall stocks. We use the best information available but acknowledge that advances in estimates of ocean distribution of many stocks will improve with the completion of on-going research over the course of the next 1-3 years.

Weight and Scoring

FACTOR 1

If the Chinook stock was observed >=5% of the whales diet in summer or fall/winter/spring, the stock receives 1 point. If it was not observed in the diet, the stock receives 0 points. This prioritizes stocks observed in the diet compared to those that have not been observed.

FACTOR 2

Current data indicate that both reduced body condition and a diversified diet occur in non-summer months. If a stock is consumed during October through May, it receives 1 point. If it is consumed during June through September, the stock receives 0 points. This prioritizes stocks that are consumed during periods with a higher likelihood of food limitation or stress in the whales' health.

FACTOR 3

For each space/time area described above, if more than 25% of the Chinook stock is distributed in that area, the area receives a sub-score of 2. For areas that contain between 5% and 25% of the Chinook stock, the area receives a sub-score of 1. If an area contains less than 5% of the Chinook stock, it receives a sub-score of 0. The sub-scores for each area are multiplied by an importance weight for each area. The final score for the Chinook stock/population is the sum of the products of the scores and weight for each area normalized such that the highest possible score of a given stock is equal to 3.

Here are the seven space/time combinations included in Factor 3 and their associated weights.

1. WA coast in Winter/Spring; weight = 0.5
2. WA coast in Summer/Fall; weight = 0.5
3. Salish Sea in Winter/Spring; weight = 0.5
4. Salish Sea in Summer/Fall; weight = 0.5
5. OR / N.CA coast in Winter/Spring; weight = 0.25
6. CA coast in Winter/Spring ; weight = 0.25
7. West Coast of Vancouver Island in Winter/Spring; weight = 0.5

The Salish Sea and coastal waters off WA have a 0.5 weight. The areas off British Columbia, OR/North CA and CA have a 0.25 weight. This structure means that the areas of highest SRKW use – the Salish Sea and coastal WA – are treated as twice as important as the other areas.

References

Durban, J. W., H. Fearnbach, L. Barrett-Lennard, M. Groskreutz, W. Perryman, K. Balcomb, D. Ellifrit, M. Malleson, J. Cogan, J. Ford, and J. Towers. 2017. Photogrammetry and Body Condition. Availability of Prey for Southern Resident Killer Whales. Technical Workshop Proceedings. November 15-17, 2017.

Fearnbach, H., J. W. Durban, D. K. Ellifrit and K. C. Balcomb III. 2018. Using aerial photogrammetry to detect changes in body condition in endangered Southern Resident killer whales. Endangered Species Research. https://doi.org/10.3354/esr00883.

Ford, M. J., J. Hempelmann, M. B. Hanson, K. L. Ayres, R. W. Baird, C. K. Emmons, J. I. Lundin, G. S. Schorr, S. K. Wasser, and L. K. Park. 2016. Estimation of a killer whale (*Orcinus orca*) population's diet using sequencing analysis of DNA from feces. PLoS ONE. 11(1):e0144956. Doi:10.1371/journal.pone.0144956.

Hanson, M. B., R. W. Baird, J. K. B. Ford, J. Hempelmann-Halos, D. M. Van Doornik, J. R. Candy, C. K. Emmons, G. S. Schorr, B. Gisborne, K. L. Ayres, S. K. Wasser, K. C. Balcomb, K. Balcomb-Bartok, J. G. Sneva, and M. J. Ford. 2010. Species and stock identification of prey consumed by endangered southern resident killer whales in their summer range. Endang.Spec. Res. 11: 69-82.

Pacific Salmon Commission (PSC) Joint Chinook Technical Committee Report. 2018a. 2017 Exploitation Rate Analysis And Model Calibration Volume One. Available at: http://www.psc.org/publications/technical-reports/technical-committee-reports/chinook/

Pacific Salmon Commission (PSC) Joint Chinook Technical Committee Report. 2018b. 2017 Exploitation Rate Analysis And Model Calibration Volume Two: Appendix Supplement. Available at: http://www.psc.org/publications/technical-reports/technical-committee-reports/chinook/

Satterthwaite, W. H., M. S. Mohr, M. R. O'Farrell, and B. K. Wells. 2013. A comparison of temporal patterns in the ocean spatial distribution of California's Central Valley Chinook salmon runs. Canadian Journal of Fisheries and Aquatic Sciences 70:574–584.

Shelton, A.O., W.H. Satterthwaite, E.J. Ward, B.E. Feist, and B. Burke. In press. Using hierarchical models to estimate stock-specific and seasonal variation in ocean distribution, survivorship, and aggregate abundance of fall run Chinook salmon. Can. J. Fish. Aquat. Sci. DOI: 10.1139/cjfas-2017-0526.

Wahle, R.J., E. Chaney, and R.E. Pearson. 1981 Areal distribution of marked columbia river basin spring Chinook salmon recovered in fisheries and at parent hatcheries. Marine Fisheries Review 43:1-9.

Weitkamp, L. A. 2010. Marine distributions of Chinook salmon from the West Coast of North America determined by coded wire tag recoveries. Transactions of the American Fisheries Society 139:147–170

Priority Chinook Stocks Using Conceptual Model

ESU / Stock Group	Run Type	Rivers or Stocks in Group	Diet Contribution Score (0,1)	Killer Whale Reduced Body Condition or Diverse Diet Score (0,1)	Spatio-Temporal Overlap Score (0 - 3)	
			Avg. Factor 1 (see note)	Avg. Factor 2 (see note)	Avg. Factor 3	Total Score (sum of factors)
Northern Puget Sound	Fall	Nooksack, Elwha, Dungeness, Skagit, Stillaguamish, Snohomish	1	1	3.00	5.00
Southern Puget Sound	Fall	Nisqually, Puyallup, Green, Duwamish, Deschutes, Hood Canal systems	1	1	3.00	5.00
Lower Columbia	Fall	Fall Tules and Fall Brights (Cowlitz, Kalama, Clackamas, Lewis, others)	1	1	2.63	4.63
Strait of Georgia	Fall	Lower Strait (Cowichan, Nanaimo), Upper Strait (Klinaklini, Wakeman, others), Fraser (Harrison)	1	1	2.63	4.63
Upper Columbia & Snake Fall	Fall	Upriver Brights	1	1	2.25	4.25
Fraser	Spring	Spring 1.3 (upper Pitt, Birkenhead; Mid & Upper Fraser; North and South Thompson) and Spring 1.2 (Lower Thompson, Louis Creek, Bessette Creek)	1	1	2.25	4.25
Lower Columbia	Spring	Lewis, Cowlitz, Kalama, Big White Salmon	1	1	2.25	4.25
Middle Columbia	Fall	Fall Brights	1	1	2.06	4.06
Snake River	Spring-Summer	Snake, Salmon, Clearwater	1	1	1.88	3.88
Northern Puget Sound	Spring	Nooksack, Elwha, Dungeness, Skagit (Stillaguamish, Snohomish)	1	1	1.88	3.88
Washington Coast	Spring	Hoh, Queets, Quillayute, Grays Harbor	1	1	1.69	3.69
Washington Coast	Fall	Hoh, Queets, Quillayute, Grays Harbor	1	1	1.69	3.69
Central Valley	Spring	Sacramento and tributaries	1	1	1.50	3.50
Middle & Upper Columbia Spring	Spring	Columbia, Yakima, Wenatchee, Methow, Okanagan	1	1	1.31	3.31
Middle & Upper Columbia Summers	Summer		1	1	1.31	3.31

Fraser	Summer	Summer 0.3 (South Thompson & lower Fraser; Shuswap, Adams, Little River, S. Thompson mainstem, Maria Slough in Lower Fraser) and Summer 1.3 (Nechako, Chilko, Quesnel; Clearwater River in North Thompson)	1	0	1.88	2.88
Central Valley	Fall and Late Fall	Sacramento, San Joaquin	1	1	0.75	2.75
Klamath River	Fall	Upper Klamath and Trinity	1	1	0.75	2.75
Klamath River	Spring	Upper Klamath and Trinity	1	1	0.75	2.75
Upper Willamette	Spring	Willamette	0	0	2.25	2.25
Southern Puget Sound	Spring	Nisqually, Puyallup, Green, Duwamish, Deschutes, Hood Canal systems	0	0	1.88	1.88
Central Valley	Winter	Sacramento and tributaries	0	0	1.50	1.50
North & Central Oregon Coast	Fall	Northern (Siuslaw, Nehalem, Siletz) and Central (Coos, Elk, Coquille, Umpqua)	0	0	1.41	1.41
West Coast Vancouver Island	Fall	Robsertson Creek, WCVI Wild	1	0	0.38	1.38
Southern Oregon & Northern California Coastal	Fall	Rogue, Chetco, Smith, lower Klamath	0	0	0.75	0.75
Southern Oregon & Northern California Coastal	Spring	Rogue	0	0	0.75	0.75
California Coastal	Fall	Mad, Eel, Russian	0	0	0.75	0.75
California Coastal	Spring	Mad, Eel, Russian	0	0	0.75	0.75
Southeastern Alaska	Spring	Taku, Situk, Chilkat, Chickamin, Unuk, Alsek, Stikine	0	0	0.00	0.00
Northern BC	Spring	Yakoun, Skeena, Nass	0	0	0.00	0.00
Central BC	mostly Summer	Atnarko, Dean River, Rivers Inlet	0	0	0.00	0.00

Note: Factor 1 and 2 are not literal averages. If a major component of the rivers in the ESU / Stock group had 1 then this was scored a 1. If no major component was scored a 1, this was scored a 0

State of Washington
DEPARTMENT OF FISH AND WILDLIFE
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December 1, 2022

The Honorable Christine Rolfes
Chair, Senate Ways and Means
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The Honorable Timm Ormsby
Chair, House Appropriations
315 John L. O'Brien Building
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The Honorable Kevin Van De Wege
Chair, Senate Agriculture, Water
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212 John A. Cherberg Building
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The Honorable Mike Chapman
Chair, House Rural Development,
Natural Resources, and Parks
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Post Office Box 40600
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Dear Chairs Rolfes, Ormsby, Van De Wege, and Chapman,

During the 2022 Legislative session—through the proviso contained within Engrossed Substitute Senate Bill 5092—the Washington State Legislature directed the Washington Department of Fish and Wildlife (WDFW) to investigate a pathway for incorporating a Net Ecological Gain (NEG) standard into state law with the goal of improving endangered species recovery and ecological health statewide.

WDFW assessed opportunities for incorporating NEG into existing state law through a mix of research and engagement, with support from consultants and review and scientific input from the Washington State Academy of Sciences (WSAS). I am pleased to share our findings in the following report.

In our work to preserve, protect, and perpetuate Washington's fish, wildlife, and ecosystems, we see firsthand the need for bold polices that promote the rapid restoration of watersheds, wetlands, and other natural environments if we are to have a chance to recover threatened species. And equally important, to prevent further declines and state or federal endangered species listings.

In the face of such challenges, consulted experts largely agree that adopting NEG standards has merit and is an important step forward in advancing environmental protection in Washington state. However, NEG must build from the foundation of existing environmental policy in the state.

Washington currently has a No Net Loss (NNL) policy for development involving shorelines, wetlands, and certain other critical habitats. Despite significant investments in the recovery of salmon and other fish and wildlife species, scientific evidence of continued ecosystem decline in Washington indicates that NNL polices are not working or are not going far enough to protect our state's rich natural heritage.

In advancing NEG standards, the state must simultaneously address these issues and others tied to NNL. The Legislature must also identify a clear scope of NEG application, namely whether standards will apply to both private and public properties. Public projects should contribute to a higher environmental standard when conducting the public's business. If we are serious about restoring species such as Chinook salmon, Southern Resident orca whales, and sharp-tailed grouse, we should be investing in ecosystem restoration through each public works project, big or small.

We must protect what we currently have and restore ecological and watershed functions—through increased investments and actions at a greater scale and pace—if salmon and other threatened species are to have a chance for recovery in Washington, especially in the face of climate change and continued human population growth.

To be successful, this will require cooperation, innovation, increased investments, and bold leadership from our elected leaders, tribes, stakeholders, and local communities.

We have not lost the battle yet, but time is not on our side if threatened fish and wildlife species are to have a chance for recovery. Recovery of Pacific Northwest icons requires restoration at scale, and as this report indicates, Net Ecological Gain is one powerful tool for doing so.

If you have any questions about this report or the Department's efforts in this area, please feel free to contact Tom McBride, WDFW's Legislative Director, at (360) 480-1472.

Sincerely,

Kelly Susewind



Director

cc: Jeff Davis, WDFW Director of Conservation Policy
Ruth Musgrave, Senior Policy Advisor to Governor Jay Inslee



Washington Department of FISH and WILDLIFE

NET ECOLOGICAL GAIN STANDARD PROVISO SUMMARY REPORT

Washington Department of Fish and Wildlife (WDFW)

December 2022

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EXECUTIVE SUMMARY



During the 2021 Legislative session—through the proviso contained within Engrossed Substitute Senate Bill 5092—the Washington Legislature directed the Washington Department of Fish and Wildlife (WDFW) to **investigate a pathway for incorporating a Net Ecological Gain (NEG) standard into state law** with the goal of improving endangered species recovery and ecological health statewide. In summer and fall of 2022, WDFW assessed opportunities for incorporating NEG legislation into existing state law through a mix of secondary research and engagement, with support from consultants and review and scientific input from the Washington State Academy of Sciences (WSAS).

Key project initiatives included:

- **Review and expansion of the NEG definition and other key findings from the WSAS 2022 report**, "Report on Net Ecological Gain" (see full report in *Appendix D. WSAS Report on Net Ecological Gain*), which led to the following updated definition:

  Ecological functions and values, that support biodiversity and resiliency of native plant, animal and fungi species, water quality and quantity, air quality, and food security for all species, are improved over current conditions, at a cumulative scale that can be incrementally implemented through site-specific actions, with any short-term loss of those functions and values being more than offset by overall ecological gains.

- **Review and analysis of precedent** set by other communities based on national and international NEG research papers and legislation.

- **Analysis of existing Washington State environmental, development, or land use law or rule** where the existing standard—namely, No Net Loss (NNL)—is less protective of ecological integrity than the standard of Net Ecological Gain, to understand how these standards have operated within the state.

- **Robust engagement with local governments, state agencies, federally recognized tribes, and key stakeholder groups** across Washington State (henceforth referred to as "experts"). Engagement included a mix of one-on-one and small group interviews as well as large roundtable discussions.

Through these tasks, the project team identified several key themes for the legislature to consider when exploring the integration of NEG into Washington state policy. Key considerations, summarized throughout this report and detailed in Key Themes from Engagement below, include the following:

- Experts largely agree that adopting NEG standards has merit and is an important step forward in advancing environmental protection in Washington state. However, **NEG must build from the foundation of existing environmental policy** in the state.
- Evidence of ecosystem decline in Washington indicates that NNL is not working. However, **the true impact of existing NNL standards is largely unknown.** A pervasive lack of funding and resources available to state agencies and local jurisdictions has led to inconsistent implementation and enforcement of NNL standards and little to no monitoring and reporting of its impacts. Furthermore, there is not a consistent baseline of current conditions from which to monitor progress. In advancing NEG standards, the state must simultaneously address these issues and others tied to NNL.
- The legislature must **identify a clear scope of NEG application**, namely whether standards will apply to both private and public properties or just to public projects.[1]
- For NEG and NNL to succeed, the state needs to **significantly expand funding and resources** available to implementers. Stronger mandates, if insufficiently funded, will have little to no impact on rolling back ecological degradation and preserving the state's valuable natural resources.

The project culminated in the development of the following recommendations, detailed in Chapter 3: Recommendations.

NEG FRAMEWORK, METRICS, MONITORING, AND ENFORCEMENT

- Define policy frameworks that address NEG goals.
- Define scale and scope of NEG application (e.g., site specific or cumulative scale).
- Establish metrics that will be used for establishing targets and current conditions, and tracking progress.
- Establish the baseline conditions against which NNL and NEG can be quantitatively monitored.
- Identify existing information and gaps in monitoring data to ensure standardization across watersheds.
- Improve monitoring and compliance with existing and future environmental standards.



[1] This project primarily assessed NEG under the assumption that policy mandates would apply specifically to public projects and that private projects would continue to comply with a NNL standard. Experts both supported and disputed this stance through engagement and debate over the application of NEG persisted throughout the project. See Scope of Application of NEG legislation on Public and Private Projects for more details.

NEG & NNL IMPLEMENTATION

- Expand understanding of the successes and failures of NNL policies and improve implementation and oversight of NNL moving forward, to ensure that standards are upheld.
- Establish how to set up the tracking and reporting system and oversight for NEG.
- Convene an oversight body to develop an implementation framework for NEG to ensure cross-agency, cross-jurisdictional collaboration and assist with integration into local government planning.
- Ensure equitable and inclusive outcomes of a NEG standard.

NEG INCENTIVES & OTHER STRATEGIES

- Create NEG as a voluntary planning element under the Growth Management Act (GMA) and further incentivize local governments to participate in counties such as Whatcom, Snohomish, and King County.
- Strengthen and expand current incentives contributing to NEG for public projects and voluntary actions on private lands.
- Create new incentives to increase participation in programs and projects that benefit NEG.
- Understand opportunities and challenges in using incentives to achieve long-term benefits.
- Identify additional strategies for voluntarily achieving NEG on private property.

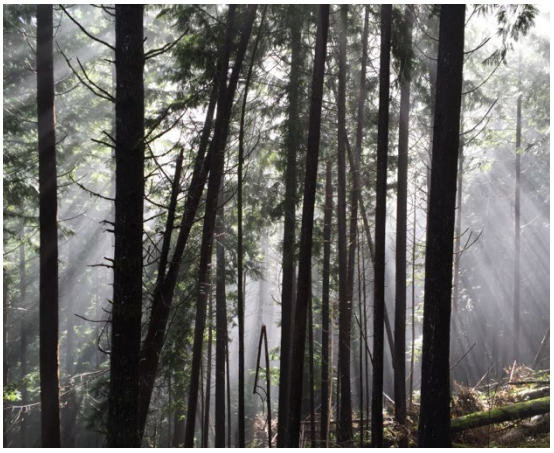
FUNDING NEG & NNL

- Ensure existing funding sources maximize ecological impact.
- Increase funding for implementing and monitoring NEG and NNL.
- Increase funding for local governments to increase staff capacity for long-range planning and compliance.
- Increase funding for local, state, and tribal monitoring programs.
- Provide funding for NEG and NNL multi-jurisdictional oversight.
- Maximize federal funding opportunities.
- Identify new funding opportunities.

EQUITABLE AND INCLUSIVE OUTCOMES AND COMMUNITY ENGAGEMENT

- Continue stakeholder and tribal engagement as early NEG elements move forward.
- Provide annual NEG status reports to the WA State Governor's Office and State Legislature.
- Enhance community engagement in developing an NEG program and continue to engage the community as standards are implemented.
- Review, utilize, or improve public engagement and education programs to support more extensive public awareness and engagement for NEG and NNL.

ACKNOWLEDGMENT OF TRIBAL ENGAGEMENT ON NET ECOLOGICAL GAIN REPORT



The Indigenous Peoples of the Pacific Northwest have resided throughout the lands known today as Washington state since time immemorial. For thousands of years, many generations of indigenous people have practiced stewardship and conservation. There are 29 federally recognized tribal governments that reside within Washington, of which 21 are treaty tribes and eight are executive order tribes (or recognized by Act of Congress). Further, three treaty tribes located outside of Washington have off-reservation treaty rights in the Columbia River and/or Blue Mountains regions in Washington.

The U.S. Constitution recognizes Native American tribes as distinct sovereign governments. Treaty tribes cooperatively manage fish in usual and accustomed areas reserved in their treaties. WDFW has a unique government-to-government relationship with Northwest tribes, with shared responsibilities in stewardship, conservation, and resource management. More information is available at: wdfw.wa.gov/about/state-tribal-coordination

In drafting this report to the Washington State Legislature on NEG policy considerations—and in accordance with the Legislature's direction—**WDFW sought to recognize the unique status of tribal nations and the standing of treaty tribes' roles in fish management**. WDFW invited federally recognized tribes as well as the Northwest Indian Fisheries Commission (NWIFC), Columbia River Inter-Tribal Fish Commission (CRITFC), and Upper Columbia United Tribes (UCUT) to provide input. WDFW engaged directly with leaders and staff of individual tribes and tribal commissions, including through one-on-one conversations, representative roundtables, and presentations to tribal commission meetings. WDFW provided opportunities to review the final report and recommendations prior to publication.



The following section was submitted by NWIFC. It was not written nor edited by WDFW.

NWIFC MEMBER TRIBES COMMENTS ON WASHINGTON DEPARTMENT OF FISH AND WILDLIFE'S REPORT TO THE WASHINGTON STATE LEGISLATURE ON NET ECOLOGICAL GAIN

DECEMBER 1ST, 2022

Since Washington State enacted the Shoreline Management Act (SMA) in 1971 and subsequently the Growth Management Act (GMA) in 1990 and implemented the mitigation standard of No Net Loss (NNL), there has been a steady decline in habitat and the associated ecosystem processes that are critical to sustaining salmon populations and supporting Endangered Species Act (ESA) listed salmon recovery efforts. It is the duty of Washington State to protect the treaty reserved rights of the 20 treaty tribes in western Washington. The tribes' treaty reserved rights are a property right which supersedes the property rights of the individual citizens of Washington State as the treaties were signed in 1855, 34 years before Washington became a member of the union and entered statehood. For Washington State to uphold the tribes' treaty reserved rights and resources guaranteed within the treaties, Washington State needs to protect and restore the habitat these resources depend on. It is imperative that Washington State act quickly and change its land use laws and regulations and the way that it manages growth and development to stave off ongoing and future impacts to the habitat necessary to sustain and recover salmon populations.

The SMA and GMA were intended to balance growth and development with its corresponding impacts to habitat in a way that results in a NNL of habitat function and the ecosystem processes that functional habitat provides. This is critically important as many ESA listed species, such as salmon and Orca, rely on this habitat and the inherent ecosystem processes that these habitats provide. However, due to the competing interests within the GMA and SMA and a deference to ensuring that private property owners can reasonably use their property, these two laws have failed to protect critical habitat for ESA listed species. The current laws and regulations give undue deference to private property owners right to use their property over habitat protection and conservation. This current system perpetuates declines in habitat function and the ecosystem processes that functional habitat provides, and in turn, salmon populations have and will continue to decline throughout Washington State.

The second chapter of the Washington State Academy of Science (WSAS) report, *Assessment of No Net Loss and Recommendations for Net Ecological Gain Metrics, Indicators, and Monitoring*, found that the current standard of NNL is not working. "When considering whether existing ecological standards, including NNL, have been sufficient in safeguarding ecological health and achieving endangered species recovery, the committee's consensus view is that NNL has not been an effective approach for ecosystem

or habitat management and protection nor for the maintenance of ecosystem services."[2] The report also states that there will continue to be a decline in habitat and ecosystem function if no changes are made to the State's land use laws and regulations. As a result of this continued loss of habitat and ecosystem function, the report concludes that species and habitat types will continue to go extinct in Washington State. Mitigation will never lead to recovery of ESA list species such as salmon, only the immediate protection and restoration of habitat critical for salmon such as riparian (freshwater & marine), wetlands, and estuaries, will enable ESA listed salmon to begin to recover.

For this report the Washington Department of Fish and Wildlife (WDFW) is proposing to only implement a Net Ecological Gain (NEG) standard for only publicly funded projects. While this is a good first step, it will not be sufficient to achieve the gains in habitat that are immediately needed to stop the continued decline of salmon populations and recover ESA listed salmon and the Orca that depend on them. Instead, a NEG standard with specific conservation metrics must established and applied to all public and private development projects in Washington State. Furthermore, the new standard of NEG will only apply to new development projects and does not address legacy impacts. Development that occurred before the adoption of GMA and SMA is exempt from mitigating the impacts to habitat that occurred from these projects. The ecological function that was lost from development that occurred before the GMA and SMA, also need to be recovered if Washington State is going to stop the decline of salmon populations and recover ESA listed species.

Tribes and salmon do not have the time to wait for WDFW to study how to implement a NEG standard and fix NNL to ensure that NNL is achieving its intended outcome on private development projects. Decades of evidence conclusively demonstrates that NNL is not working and as indicated by the WSAS report, will never work. Therefore, only the immediate protection and restoration of habitat critical for salmon will slow the decline of salmon populations and enable ESA listed species to begin to recover. The tribes constantly hear from organizations like the Washington Association of Counties and the Builders Industry Association of Washington that this will be too expensive and too difficult to achieve, but it will never be cheaper and more achievable than right now.

While the tribes commend the work that WDFW did for this report, their proposed recommendations do not go far enough and the lack the regulatory framework required to stop the decline of salmon populations and recover ESA listed species. The current system of laws and land use regulations in Washington State is failing to protect habitat, simply modifying the existing system will not be enough to lead to recovery of ESA listed species. Instead, the Washington State legislature must immediately enact stronger land use laws and regulations that require the immediate protection and restoration of habitat that is critical for salmon recovery, such as one Site Potential Tree Height riparian buffers, and require an enhanced standard that is more protective of habitat impacted by both public and private projects. This is the only way Washington State will be able to uphold its obligation to the tribes to protect the tribes' treaty-reserved rights and resources.

[2] Washington State Academy of Sciences. (2022). Assessment of No Net Loss and Recommendations for Net Ecological Gain Metrics, Indicators, and Monitoring. Seattle, WA: WSAS, 1-40.

LEGISLATIVE PROVISO

The proviso directed WDFW to assess how to improve statewide recovery of endangered and threatened species, species of concern, and ecological health by incorporating an NEG standard into state land use, development, and environmental laws and rules. The proviso required that this assessment include several specific actions. These requirements, and the process taken to address them, are detailed below.

Consult with the appropriate local governments, state agencies, federally recognized Indian tribes, and stakeholders with subject matter expertise on environmental, land use, and development laws.

Over the course of the project, the project team engaged with representatives from each of the groups outlined by the legislature. Engagement focused on gathering feedback on successes, failures, opportunities in the existing NNL standards, and challenges and opportunities in incorporating NEG. Engagement included one-on-one interviews and large roundtable discussions. The Engagement with Stakeholders and Tribes section of this report details these engagement activities.

Address each environmental, development, or land use law or rule where the existing standard is less protective of ecological integrity than the standard of net ecological gain.



The project team conducted a detailed regulatory review of how existing development and land use laws incorporate the current standards of NNL; findings are summarized in *Appendix B. Regulatory Review Memo.* These findings were then enhanced by engagement focused on understanding how laws are implemented and enforced to paint a more complete picture of how NNL operates within Washington.

The initial regulatory review focused on the following laws outlined by the legislature:

- Shoreline Management Act (chapter 90.58 RCW)
- Growth Management Act (chapter 36.70A RCW)
- Construction Projects in State Waters (chapter 77.55 RCW)
- Model Toxics Control Act (chapter 70A-305 RCW)

It also included the State Environmental Policy (chapter 43.21C RCW) and Forest Practices Act (chapter 76.09 RCW), identified as additional key pieces of legislation pertaining to NNL.

The analysis focused on how NNL standards operate within each of the state laws, regarding the following topics:

- How the law defines NNL (i.e., what metrics are used to determine whether NNL is achieved).
- How habitat prioritization/ranking systems are integrated in the law's mitigation requirements.
- Requirements for enforcement and oversight of NNL standards.
- How the law differentiates between on-site and compensatory mitigation approaches.

The Regulatory Review section provides the complete analysis of this legislative landscape.

Assess and compare opportunities and challenges, including legal issues and costs on state and local governments, to achievement of overall net ecological gain.

The project team conducted a detailed literature review of different planning documents, laws, and reports related to the development and application of NEG and NNL standards. Findings from this analysis, detailed in the Literature Review of NEG/NNL Legislative Precedent section, were presented, analyzed, and discussed through subsequent engagement to inform the final recommendations in this report.



The concerns over unconstitutional taking of private property that might arise from financial or other constraints imposed on private landowners as a result of NEG requirements are detailed in the Legal Considerations section.

Develop a definition, objectives, and goals for the standard of net ecological gain.

The WSAS 2022 report, "Report on Net Ecological Gain"—also developed in response to the same 2021 proviso within Senate Bill 5092—outlined a definition, objectives, and goals for the standard of NEG [1].

This project focused on assessing the WSAS conclusions through engagement and other analysis to identify any necessary revisions to the definitions, objectives, and goals outlined. Findings and subsequent recommendations are detailed in the Recommendations sections below.

The full WSAS report is included in *Appendix D. WSAS Report on Net Ecological Gain.*

Develop recommendations on funding, incentives, technical assistance, legal issues, monitoring, use of scientific data, and other applicable considerations to the integration of needs to assess progress made toward achieving net ecological gain into each environmental, development, and land use law or rule.

All project tasks, informed the final Recommendations outlined in this report. Ultimately, recommendations focused on key considerations, identified through engagement, for integrating NEG into existing state environmental, development, and land use laws as well as opportunities to improve the likelihood of meeting NNL standards.

Identify an enhanced approach to implementing and monitoring no net loss in existing environmental, development, and land use laws.

Through the literature review, detailed in the Literature Review of NEG/NNL Legislative Precedent section, the project team identified several consistent challenges that communities around the country and globe have faced in implementing and monitoring NNL standards. Engagement with policymakers, tribes, and subject matter experts, revealed that in its implementation of NNL standards to date, Washington state has faced several of these same challenges, including lack of resources, inconsistent data, fragmented enforcement, and lack of a baseline from which to monitor. The literature review and subsequent engagement also shed light on several opportunities and best practices to enhance the state's implementation and monitoring moving forward. More detailed findings and subsequent recommendations are detailed in the Recommendations section below.

Assess how applying a standard of net ecological gain in the context of each environmental, land use, or development law is likely to achieve substantial additional environmental or social co-benefits.



The literature review, detailed in the Literature Review of NEG/NNL Legislative Precedent section, provided a foundation for exploring the implications of NEG in achieving additional environmental and social co-benefits. These benefits include the cascading economic and social impacts of increased biodiversity and environmental resilience that NEG can achieve. Through engagement and additional secondary research, the project team built upon this foundation to identify the benefits most applicable to Washington state specifically. Additional findings and related recommendations are detailed in the Recommendations section below.

REPORT OVERVIEW

CHAPTER 1. INTRODUCTION

- **Background**—An overview of the NNL and NEG history in Washington policy.
- **Scope of NEG Legislation** —Details on the approach for assessing NEG standards on private projects.

CHAPTER 2. QUALITATIVE ANALYSIS

- **Engagement with stakeholders and tribes**—Overview of the project team's approach for assessing NEG and NNL through secondary research and engagement, and key findings from this engagement.
- **Secondary research**—Overview of secondary research conducted by the project team, including a literature review of NNL/NEG policy precedent set by other communities, and a comprehensive regulatory review of existing Washington state policies.

CHAPTER 3. RECOMMENDATIONS & NEXT STEPS

- **Revised NEG Definition**—The proposed updated NEG definition developed through engagement and secondary research.
- **Recommendations**—Final recommendations for the legislature to consider regarding integrating NEG standards into Washington policy and enhancing existing NNL standards.

APPENDICES

- **Appendix A. Literature Review Summary**—Detailed summary of the literature reviewed as part of the secondary research element of the project.
- **Appendix B. Regulatory Review Memo**—Detailed memo of the review of existing Washington state policies.
- **Appendix C. Interview Guide**—Complete interview guide and questions asked of experts as part of the one-on-one project interviews.
- **Appendix D. WSAS Report on Net Ecological Gain**—Full WSAS report developed in response the 2021 proviso within Senate Bill 5092.

CHAPTER 1: INTRODUCTION



BACKGROUND

Washington state has integrated NNL standards into environmental, development, and land use policy since 2013 with the adoption of the Shoreline Management Act, which outlined NNL requirements as part of the Shoreline Master Programs Guidelines [2]. At a high level, **NNL standards seek to limit the impacts from new development by adopting a mitigation hierarchy to avoid, minimize, remediate, and offset negative impacts on ecosystems** [3]. However, in the years since the introduction of NNL, Washington state has continued to face environmental degradation, indicating that the current NNL approach has been insufficient and that more rigorous standards, or more rigorous oversight of existing NNL requirements, are needed to adequately protect the state's many important species and habitats.

Fish, wildlife, and habitats are increasingly at risk in Washington. Population growth and climate change have been the driving factors for landscape changes affecting biodiversity. According to the State Wildlife Action Plan Washington is home to 268 Species of Greatest Conservation Need—from the wolverine, bull trout, and snowy plover to lynx, sharp-tailed grouse, and pinto abalone. Bold action is needed to avoid collapse of fish, wildlife, and ecosystems in Washington.

As our state's human population continues to grow, we must hold the line on habitat loss and vastly increase the scope and scale of recovery and restoration actions. Climate change is predicted to exacerbate these declines in Washington, with experts predicting dramatic impacts to biodiversity, including the erosion and loss of shoreline habitats from sea level rise, threats to salmon from warming streams and altered streamflow, and more frequent disruption to species and habitats from severe weather and wildfire [4].

One potential policy solution to addressing this ecological decline in Washington is implementing NEG standards into Washington land use, environmental, and development law. NEG exceeds NNL by not only requiring that impacts are avoided, but also requiring that projects improve the delivery of valued ecosystem functions by increasing biodiversity or resilience in the affected ecosystem [5]. However, according to many state representatives involved in NNL policy and other experts engaged in this project, there is evidence that the state has not successfully implemented, enforced, nor monitored existing NNL standards and that **in adopting new, more stringent standards, the state must simultaneously devote resources to improve NNL**.



This proviso summary report seeks to shed light on these and other pertinent questions related to NEG and NNL in Washington state. Engagement with experts with deep knowledge of the state's environmental, land use, and development laws informed the findings in this report as well as secondary research focused on the implementation of these environmental protection standards in Washington state and other communities around the country and globe. These findings are intended to guide the legislature's next steps in defining and implementing ecological preservation standards into the state's development and land use laws.

SCOPE OF NEG LEGISLATION



This project primarily assessed NEG assuming that policy mandates would apply specifically to public projects and that private projects would continue to comply with a NNL standard. Achieving NEG in private projects—at least in the short term—would continue to be achieved primarily through voluntary incentive programs promoted to private landowners.

This approach to assessing NEG aligns with the current legislative dialogue surrounding this policy in Washington. Considerations for applying NEG to private land have evolved since the legislature's original proviso in light of potential legal constraints (detailed in the Legal Considerations section below). The project team did not conduct a comprehensive legal analysis of NEG. However, many experts voiced concerns about imposing mandates on private projects. Experts asserted that imposing NEG mandates on private property was beyond the regulatory authority of state and federal agencies and that enforcement of NEG could, in some cases, amount to a regulatory taking (an unconstitutional acquisition of private property resulting from a government regulation). Experts also raised the concern that expanding mandates to private projects at this time could undermine the effort to successfully adopt any NEG standards in the state.

On the other hand, some experts voiced opposition to limiting the scope of NEG to public projects only, predicting that the state will not achieve NEG if mandates do not apply to both public and private projects. Some asserted that although public lands and projects could be held to a higher standard, there are not enough of those lands to address the current situation and low standards related to habitat impacts; therefore, limiting the scope of NEG to public lands will not result in enough recovery.

Given this feedback, this report's recommendations outline an approach for implementing a NEG standard on public projects, while still addressing ecosystem decline on private projects by incentivizing NEG and bolstering the implementation of NNL standards. Experts indicated that defining the scope of NEG implementation for private and public projects was a key first step in advancing the policy.

CHAPTER 2: QUALITATIVE ANALYSIS

This project interpreted its legislative charge as **outlining a roadmap for the future of Washington's ecological standards** by assessing the impact of the state's existing NNL standards, exploring opportunities for enhanced NEG standards and how these standards might interact with current laws, and understanding how various stakeholders, agencies, and tribes experience these policies.

To achieve these goals**, the project team took a multi-pronged qualitative approach** to information gathering through robust engagement with stakeholders and tribes, and secondary research. Findings from both are summarized below.

ENGAGEMENT WITH STAKEHOLDERS AND TRIBES

Per the proviso direction to **"Consult with the appropriate local governments, state agencies, federally recognized Indian tribes, and stakeholders with subject matter expertise on environmental, land use, and development laws,"** the project team engaged with these experts through interviews, roundtable discussions, and presentations at meetings focused on NEG.

Project engagement took place between September and November 2022. Engagement focused on gathering experts' unique perspectives and opinions based on their expertise in this subject matter to inform the final recommendations detailed it this report. **Engagement did not focus on coming to a single consensus on the final recommendations**.

ENGAGEMENT APPROACH

Engagement with experts included the following initiatives:

- **One-on-one interviews** related to NNL and NEG. Interviewers asked participants about current successes and challenges with NNL, opportunities and barriers related to NEG, and specific implementation questions for each of these policies. Interview questions are detailed in *Appendix C. Interview Guide.*

- **Roundtable discussions** focused on the same topics and questions discussed in the interviews, but with increased focus on understanding participants' specific recommendations for improving the implementation of existing NNL standards, whether and how to integrate NEG into state law, and other key considerations for the legislature.

  - The roundtables were attended by tribal representatives, representatives from state agencies and local governments, as well as stakeholders from the real estate and building industries, agricultural and forestry sectors, and state environmental groups.

- **Participation in external meetings** related to NEG policy hosted by the Northwest Indian Fisheries Commission and the Puget Sound Partnership.

KEY THEMES FROM ENGAGEMENT



Feedback from engagement was the driving force for developing the Recommendations presented in this report. While all feedback was considered and used to inform recommendations, several key themes emerged that ultimately directed the final set of recommendations.

- As indicated by the WSAS in its 2022 report, overall ecosystem loss in the state indicates that NNL is not working [1]. However, according to experts, there is also evidence that **lack of funding and oversight have barred NNL from being properly implemented and monitored**, and therefore the true impacts (or potential impacts) of NNL policy on mitigating ecological impacts from developments are largely unknown. Additionally, variances and exceptions in permitting requirements, as well as the approach of implementing NNL at a site-specific rather than cumulative scale, have limited the effectiveness of NNL and led to overall ecosystem decline.
- **Issues with the implementation of NNL may carry over to NEG unless they are identified and addressed**. Experts consistently shared that to successfully implement NEG, the state must complete a more robust assessment of NNL to identify and address the current issues with NNL standard implementation.
- **NEG policy must clearly define the scope and scale of the implementation of NEG standards.** Experts expressed that NEG policy must clearly define which projects are required to comply with NEG and at what scale NEG will be measured (e.g., whether implementation will be at the site-specific and/or cumulative scale or if NEG will eventually apply to private properties and projects).
- **NEG policy should include a robust decision-making framework and clearly defined goals.** The framework should outline how NEG implementers will achieve the defined goals and clearly define the implementation responsibilities and roles of state agencies and local governments.
- Currently, there is insufficient technical capacity and funding to implement, monitor, and enforce NNL and future NEG standards. Experts shared that **investment in the development of technical parameters and methodologies to measure ecological health** will be key to successfully implementing NEG. This investment should include developing a monitoring plan, defining baseline conditions, and establishing metrics to measure ecological health.
- Experts expressed frustration with underfunded government mandates, highlighting the need for NEG policy to also outline a plan for allocating **sufficient resources and funding for NEG**

implementation in projects, particularly to local jurisdictions to support planning, monitoring, and enforcement.

- **NEG and NNL policy must also outline an enforcement protocol** that ensures compliance with NNL and NEG standards. Experts also expressed that compliance could be achieved through offering incentives for NEG implementation.
- In order to ensure community buy-in, **there is a need for consistent and broad community engagement** as NEG policy is developed and executed.

SECONDARY RESEARCH

Secondary research included a **regulatory review** of existing Washington state environmental, development, and land use law, as well as a comprehensive **literature review** of policies, existing research, and evidence from other communities that have implemented NEG and NNL.

REGULATORY REVIEW

In response to the proviso direction to ***"Address each environmental, development, or land use law or rule where the existing standard is less protective of ecological integrity than the standard of net ecological gain,"*** secondary research included a regulatory review of existing environmental and land use laws with NNL standards.



The regulatory review analyzed existing Washington State environmental, development, or land use laws or rules where the existing standard, namely NNL or a similar standard, is mentioned to understand how these standards have operated within the state. The laws and rules assessed were those named within the proviso as well as two additional laws identified by the project team.

The analysis focused on the four primary laws outlined in the proviso—the Shoreline Management Act (SMA) (chapter 90.58 RCW), the Growth Management Act (GMA) (chapter 36.70A RCW), Construction Projects in State Waters (CPSW) (chapter 77.55 RCW), and the Model Toxics Control Act (MTCA) (chapter 70A-305 RCW)—as well as two additional statutes identified as key pieces of Washington legislation pertaining to NNL by the project team: the State Environmental Policy Act (SEPA) (chapter 43.21C RCW) and Forest Practices Act (FPA) (chapter 76.09 RCW).

REGULATORY REVIEW - KEY FINDINGS

The legislative review was bolstered by engagement with representatives from state agencies and local governments whose day-to-day work interacts with NNL implementation or oversight and others with

intricate knowledge of how NNL standards operate within the state. **The review of these regulations and subsequent engagement revealed several key themes in how NNL has operated in Washington** that ultimately informed the subsequent recommendations for how to enhance NNL standards moving forward. These themes are summarized below. For a more detailed synopsis of these regulations, see *Appendix B. Regulatory Review Memo.*

NNL DEFINITION AND INTEGRATION IN WASHINGTON STATE

The state uses a variety of terms to refer to NNL, including "no adverse impacts," "conservation," and "protection," and terminology varies across legislation. This **inconsistency in language, experts indicated through engagement, may create confusion** around what NNL encompasses, leading to inconsistent application of standards. Furthermore, uncertainty has been exacerbated by the introduction of an entire new set of potential standards under NEG.

Through engagement, **experts also highlighted a general lack of data and technical capacity to properly implement NNL standards**, including a lack of technical understanding of the ecosystem impacts that NNL seeks to mitigate. Experts also voiced concern that NNL standards have been defined and integrated into the state largely based around political and social needs (e.g., related to development), rather than maintaining ecosystem functions and biodiversity.

On the other hand, **experts also indicated that in other respects NNL has been defined and integrated successfully into Washington legislation**. In particular, some experts noted that the standards are written in a manner that allow for flexibility for growth and development while also providing a framework for mitigating impacts from development, and that the standards are within the scope of regulatory authority and adhere to federal and state law. However, according to other experts, these characteristics—namely, the flexibility of existing standards—have been a primary reason why the state has not successfully achieved NNL.



ENFORCEMENT, TRACKING, AND MONITORING

In the regulations analyzed, **requirements for monitoring the cumulative impacts of NNL** and/or documenting that regulations with NNL standards are achieving NNL **were inconsistent and minimal**, or in some cases nonexistent. Similarly, while each rule or act did include some details on enforcement of NNL standards, requirements were similarly inconsistent, with few or no specifics on penalties for violations.

Experts also expressed concern over enforcement, oversight, and monitoring of NNL in Washington throughout engagement, noting that local government and state agencies tasked with the enforcement and monitoring lacked financial support and other resources needed to adequately carry out these responsibilities and that enforcement of permit conditions left to the jurisdiction of local governments results in checkered enforcement processes and varying standards, which exacerbate lack of compliance.

Additional gaps related to enforcement, tracking, and monitoring identified in the regulatory review included the following:

- No requirement was found to require compensatory mitigation for temporal loss of ecological function after violations or inadvertent impacts are discovered.
- Mitigation required by local and state agencies does not have a long-term requirement beyond the initial monitoring period, meaning that when properties are sold, the new owners can degrade the mitigation.
- Permitting and SEPA exemptions, which most of the reviewed laws and rules allowed for in some capacity, complicate NNL tracking because the impacts of these exemptions are not always thoroughly accounted for in NNL assessments.
- Within the FPA, there is a need for measuring the cumulative impact of forest practices on ecological functions and values for all critical areas, not just the listed fish or riparian-dependent species that are the focus of the act.
- There is a lack of oversight of emergency permitting actions, which are often held to different ecological function standards. No requirement was found requiring compensatory mitigation for ecological function loss, including temporal loss, should it have occurred as a result of the emergency action(s), and there was no system for measuring the impacts of emergency permitted activities.

Experts echoed these same gaps through engagement. The decline in ecosystem function and biodiversity in the state indicates that **NNL is not being achieved**, experts said. However, **this failure is tied to a lack of proper implementation of the standards and other key gaps in the policy, including:**



- The baseline for which impacts are measured against is undefined or inconsistent, and there are not clear metrics for monitoring success or failure through time.
- There is not enough scientific understanding around site specific ecosystem function degradation and whether offsite (and especially out-of-kind) mitigation is equal to or outperforms the site-specific degradation.
- Overall, there is insufficient monitoring of NNL standards.
- There has been a persistent lack of accountability and enforcement, which exacerbates noncompliance.
- The state has not properly monitored the cumulative impacts of legacy development, variances and exceptions, and illegal development.

LITERATURE REVIEW OF NEG/NNL LEGISLATIVE PRECEDENT

In response to the proviso direction to ***"Assess and compare opportunities and challenges, including legal issues and costs on state and local governments, to achievement of overall net ecological gain,"*** the project team conducted a comprehensive literature review of policy documents, laws, and other research and reports related to NEG and NNL policy and implementation.



The literature review focused on key considerations identified by WDFW staff, as well as requirements outlined in the proviso. The review focused primarily on benefits achieved through NEG implementation, implementation strategies, economic implications, and barriers or challenges of implementing NEG policy.

The review included documents that focused primarily on the implementation of NEG, but also included details related to NNL. Sources represented different geographic scales, including global, national (United Kingdom), regional (Lake Tahoe), and statewide (Washington state). Findings from the review guided subsequent engagement with Washington experts and ultimately informed many of the final recommendations detailed in this report. The section below provides a summary of the key findings from the literature review. See *Appendix A. Literature Review Summary* for a more comprehensive summary of findings.

LITERATURE REVIEW - KEY FINDINGS



TRANSITIONING TO NEG AND IMPROVING NNL

The assessment of NNL and NEG implementation and policy standards found that NNL has not always been effective in producing successful outcomes and protecting ecosystem services and habitats [6], indicating a potential opportunity for implementing NEG and improving outcomes. However, **there are challenges that hinder progress in achieving NNL that the state must address to build from these standards to achieve NEG**. These challenges include establishing appropriate current baseline conditions, identifying appropriate targets and metrics, coordinating regionally between multiple levels of government, and securing funding for successfully implementing, enforcing, and monitoring NNL policy [1] [7] [8] [9]. After addressing these issues with NNL, experts indicated that the state must then

determine what level of gain is required in each geographic area to achieve NEG, and then apply NEG to all public projects within that area.

Despite these challenges, NEG is becoming increasingly more established in international policy and corporate practice [10].

POLICY DEVELOPMENT

The assessment revealed **key principles for successful design and development of NEG policies and plans**, including the following:

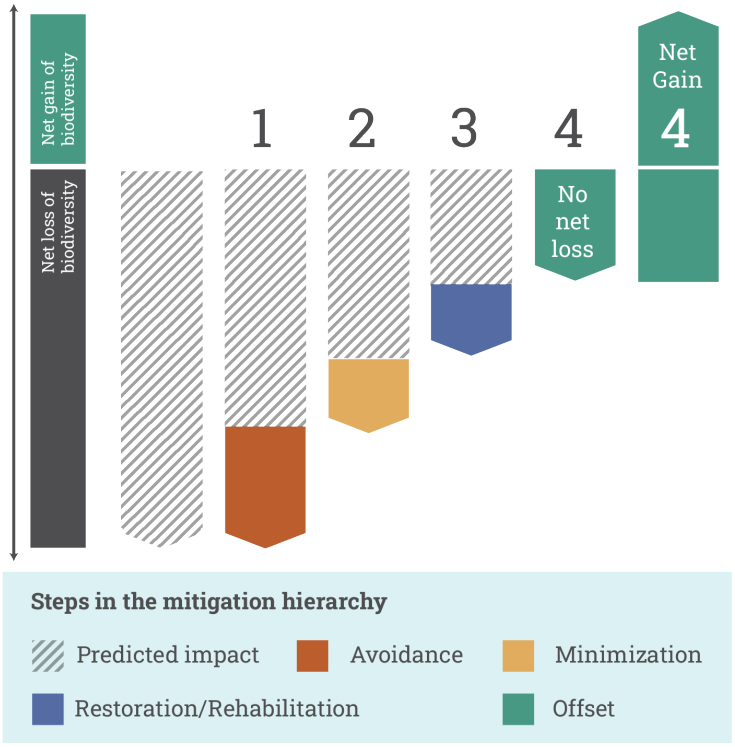
- **Address risk and uncertainty related to NEG, ensure additionality of ecosystem offsets** (i.e., ensure that NEG offsets are unique and not undermined through potential double counting of existing habitat restoration or conservation obligations) that exceed existing obligations.
- **Identify and classify baselines and metrics**, and ensure NEG generates long-term benefits [7] [8] [11] [12] [13] [14].

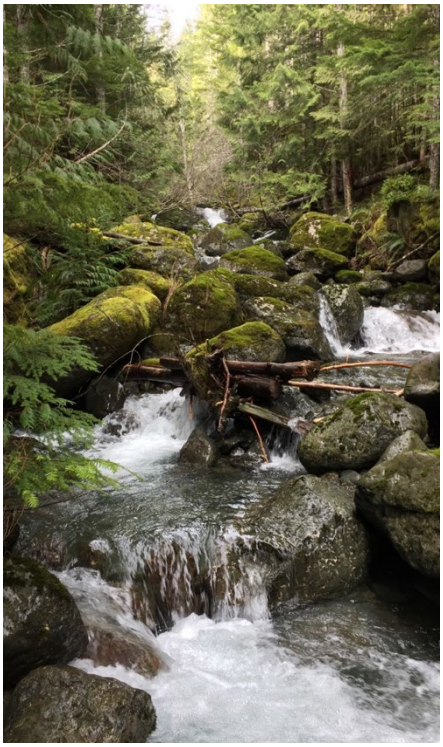
Interviewees also discussed these principles and established the importance of studies and assessments as important solutions to NEG policy barriers.

Successful design of NEG policies and plans also depend on adherence to the mitigation hierarchy (Figure 1) to avoid, minimize, remediate, and offset [12] [13]. Offsets must focus on providing benefit above and beyond avoided loss, and policies should adopt a no down-trading policy that states mitigation offsets in lower quality habitats cannot be applied to higher quality habitat impacts [8] [14]. Sources mainly described achieving NNL and NEG within this mitigation hierarchy via developers directly offsetting their project impact on site or off site, without relying on third parties. Other mitigation strategies that were mentioned for achieving mitigation offsets included:

- **Habitat banking** - A market mechanism where credits from actions with beneficial biodiversity outcomes can be purchased to offset the debit from environmental damage [11].
- **In-lieu fee program/compensation fund** - Accept payments in exchange for credits. Habitat creation and restoration projects are carried out once enough funds have been collected [11, 13].

Figure 1. Mitigation hierarchy for net gains [11].





Source: Adapted from Bennet et al., 2017

OVERSIGHT, MONITORING, AND METRICS

Robust monitoring, assessment, and accountability are critical to successful implementation of both the existing NNL and a new NEG policy. Monitoring strategies include enabling and incentivizing cross-agency and cross-disciplinary communication and collaboration and providing funding for long-term monitoring and maintenance of NEG outcomes.

It is also critical to manage a database of monitoring data to establish a baseline to measure gains or declines in ecosystem function and biodiversity from NEG. Proper data management and an established and justified baseline are key factors in successfully implementing and measuring NEG [13].

COST AND FUNDING CONSIDERATIONS

It is important for authorities to allocate sufficient funds to implement NNL and NEG long term. **Policymakers should plan for a range of costs**, including capital investment, management contingency costs, legal fees, administrative costs, ongoing costs for monitoring and reporting, risk mitigation, insurance, and inflation. Policymakers should also account for potential negative financial impacts to income that result from NEG requirements [8], as well as the positive economic implications of restoring ecosystem services from clean air and water, reduced heat island effects, improved native pollination, recovered salmon stocks, and reduced flood damages.

LEGAL CONSIDERATIONS



NEG policy mandates could constitute a regulatory taking due to the property constraints and/or financial burdens imposed on landowners. Specifically, a regulatory action such as NEG will amount to a taking if it deprives the property of all value or depreciates the value of the land to an extent that it meaningfully alters the expected future uses of the property. The character of the government's actions is also considered, namely whether there is substantial public interest at stake and whether the government could achieve the same objective through less intrusive means**. To ensure that a taking of private property is constitutional, the government must prove that the burden imposed on the landowner is reasonable and proportionable to the identified problem**. In the case of NEG, the government must demonstrate that the burden imposed on private landowners and developers mitigates the adverse impacts of the proposed development [15].

INCLUSIVITY AND EQUITY

Policymakers must intentionally consider inclusivity and equity in the design, implementation, monitoring, and evaluation approach of NEG policy to avoid inequitable outcomes. Policymakers should involve stakeholders and partners early in the process, balance on-site and off-site benefit delivery, and more explicitly incorporate social considerations into NEG initiatives [13] [16]. Experts proposed related solutions of ensuring broad engagement and input related to developing a potential NEG policy and integrating tribal sovereignty and climate equity into NEG policy and endpoint.

NEG IMPLEMENTATION IN OTHER COMMUNITIES

The project team also reviewed examples of NEG implementation in other communities, including Lake Tahoe and the United Kingdom. Findings from this review are detailed below.

LAKE TAHOE CASE STUDY

The Lake Tahoe Basin in the southwest United States is located in portions of both California and Nevada. As part of a regional and national effort to protect and enhance environmental conditions throughout the basin, a Bi-State Compact was developed in 1980 to **set environmental thresholds focused on establishing shared goals for restoration and environmental quality in the region**. These thresholds include a variety of environmental conditions, such as water clarity, water quality, air quality, vegetative cover, and habitat availability. Some of the thresholds are aimed at maintaining current environmental conditions, whereas others (e.g., water clarity) target improvements and restoration over time. Regional policymakers also developed a Tahoe Regional Plan to implement goals, policies, and regulations focused on meeting the threshold standards and balancing the natural and built environment [17]. There are **several components of the Regional Plan that could inform NEG in Washington**:

- The Plan leverages **private-public partnerships and creates incentives for property owners** to make improvements to their land and developments.

- The Plan promotes **environmentally friendly redevelopment** of aging built environment.
- Continued **monitoring and reporting of environmental conditions** helps track progress in meeting the thresholds.
- An **environmental evaluation report is prepared every four years** and assessed to determine if the Regional Plan needs to adapt to changing needs, circumstances, and emerging threats.

UNITED KINGDOM CASE STUDY

In the United Kingdom (UK), current NEG policy (referred to as biodiversity net gain or BNG) includes **explicit requirements to minimize impacts on biodiversity and provide net gains in biodiversity** as part of the government's commitment to halt biodiversity decline. The policy framework also includes "a presumption in favor of sustainable development" to emphasize support for and encourage sustainable development. This standard incentivizes developers by expediting or favoring sustainable development plans [18].

In the UK, NEG policy is on track to become mandatory by November 2023 and will require a minimum 10% gain of direct footprint losses from development, with gains maintained over a minimum of 30 years [19].

There are several **aspects of the UK policy development and implementation that could inform policy development in Washington**:

- The UK identified a need for **expanded funding to support local authorities** to enforce, monitor, and administer an NEG standard [19].
- The UK identified a need for **expanded funding to support local authorities** to enforce, monitor, and administer an NEG standard [19]. To measure the impact of NEG, the UK developed **a consistent biodiversity metric** to provide ecologists, developers, planners, and other interested parties in the UK with a means of assessing changes in biodiversity value (losses or gains) brought about by development or changes in land management [7].
- The UK has also partnered with local environmental record centers (LERCs) to **manage and retain data on changes to the natural environment**. These databases have been key to establishing the baseline ecological conditions to compare against and generally track NEG impacts over time [12].

CHAPTER 3: RECOMMENDATIONS

REVISED NEG DEFINITION

In response to the proviso direction to **"*Develop definition, objectives, and goals for the standard of net ecological gain,"*** the project team used findings from engagement and secondary research to develop the following updated definition of NEG.

> *Ecological functions and values, that support biodiversity and resiliency of native plant, animal and fungi species, water quality and quantity, air quality, and food security for all species, are improved over current conditions, at a cumulative scale that can be incrementally implemented through site-specific actions, with any short-term loss of those functions and values being more than offset by overall ecological gains.*

RECOMMENDATIONS

Ultimately, all project tasks focused on responding to the proviso direction to **"*Develop recommendations on funding, incentives, technical assistance, legal issues, monitoring, use of scientific data, and other applicable considerations to the integration of needs to assess progress made toward achieving net ecological gain into each environmental, development, and land use law or rule."***

Considerations related to the proviso direction to ***"Identify an enhanced approach to implementing and monitoring no net loss in existing environmental, development, and land use laws,"*** are also woven throughout the recommendations.

The regulatory review of existing environmental and land use laws, comprehensive literature review of policies, and engagement with experts culminated in the following set of 15 recommendations across six categories, each with a series of supporting actions needed to achieve that goal. **Recommendations relate to both NNL and NEG,** and, as noted above, were developed with the assumption that NEG will be required for public projects and that any net gain on private lands would be achieved through voluntary incentive program participation.



Throughout this section we have indicated where actions are recommended for **Near Term Action** ( ) as well as where actions **Require Legislative Action to Complete** ( ).

Action	Recommended for Near Term Action	Legislative Action Needed
Confirm that NEG would be required for public projects and voluntary for private projects/land.	✓	✓
Establish the metrics that will be used for establishing targets and current conditions and to track progress.	✓	
Clearly define what additional gains are needed beyond the existing NNL standards and scope, with appropriate sequencing.	✓	
Establish the baseline conditions against which NNL and NEG can be quantitatively monitored.	✓	
Fund and prioritize compliance with local jurisdictional environmental standards that are designed to achieve NNL.	✓	
Create a robust and cooperative monitoring program that tracks NEG and NNL implementation and enforces compliance.	✓	
Develop an oversight program that will work with local jurisdictions to set a protocol for compliance enforcement and penalties.	✓	
Establish how to set up the tracking and reporting system and oversight for NEG.	✓	
Convene an oversight body to develop an implementation framework for NEG to ensure cross-agency, cross-jurisdictional collaboration and assist with integration into local government planning.	✓	✓
Convey understanding of the current problem with the implementation of NNL, focusing on ecosystem function decline and why NNL is not working.	✓	
Clearly define performance metrics, such as quantifiable habitat functions, connectivity, refugia, downstream metrics.	✓	
Significantly increase investment in incentive programs on private property with measurable NEG. Consider funding incentives through fees imposed on activities that generate net ecological losses, thereby disincentivizing activities counter to NEG.	✓	
Increase funding for local governments to increase staff capacity for long-range planning and compliance.	✓	✓
Maximize state-level matching of federal funding sources (e.g., CREP) to ensure Washington is maximizing returns.	✓	
Incorporate inclusivity and equity in the design, implementation, monitoring, and evaluation approach of NEG policy by integrating input from communities that are disproportionately impacted by ecologically degraded environments.	✓	

NEG FRAMEWORK, METRICS, MONITORING, AND ENFORCEMENT

Define policy frameworks that address NEG goals.

- Confirm that NEG would be required for public projects and voluntary for private projects/land.
- Identify opportunities to address NEG through existing state, federal, and local laws and policies that improve habitat or decrease impacts of existing and future development.
- Identify challenges and limitations in existing laws that would need to be addressed for a more robust policy framework to achieve NEG.
- Identify opportunities to further NEG on public lands and use public funds to achieve NEG at relevant ecosystem scales.
- Identify existing information and gaps in the monitoring data to ensure standardization across watersheds.

Define scale and scope of NEG application (e.g., site specific or cumulative scale) and the metrics that will be used to track progress and establish a baseline.

- Establish the metrics that will be used for establishing targets and current conditions and to track progress.
- Clearly define what additional gains are needed beyond the existing NNL standards and scope, with appropriate sequencing.
- Establish the baseline conditions against which NNL and NEG can be quantitatively monitored.3
- Identify existing information and gaps in monitoring data to ensure standardization across watersheds.[4]
- Launch multi-scale NEG pilot projects to inform goals, baseline, and metrics that build upon findings from case studies focused on the implementation of NEG in other communities.
- Explore opportunities for developing and implementing coordinated monitoring requirements at the state level to reduce the burden on local jurisdictions and increase compliance with permit requirements.

3 For guidance on establishing this baseline, see the Time Scale and Baseline Measurements section on page 8 of the WSAS "Net Ecological Gain, Definition, Goals, and Objectives" chapter in *Appendix D. WSAS 2022 Report on Net Ecological Gain*.
4 WSAS has outlined guidance on how to navigate the process of selecting metrics/indicators and tracking progress toward NEG on page 15-16 of the "Assessment of No Net Loss and Recommendations for Net Ecological Gain Metrics, Indicators, and Monitoring" chapter in *Appendix D. WSAS 2022 Report on Net Ecological Gain*. Additional guidance related to choosing and ranking indictors is also detailed on page 20 of this chapter.

- Conduct a comprehensive cost/benefit analysis of local jurisdictions currently tracking and monitoring NNL standards to inform the funding approach for NEG.

Improve monitoring and enforcement of existing and future environmental standards.

- Fund and prioritize compliance with local jurisdictional environmental standards that are designed to achieve NNL.
- Create a robust and cooperative monitoring program that tracks NEG and NNL implementation and enforces compliance.5
- Develop an oversight program that will work with local jurisdictions to set a protocol for compliance enforcement and penalties.
  - Allocate significant funding toward enforcement, oversight, long-range planning, monitoring, and compliance to ensure local governments have capacity to monitor post-permitting outcomes.
  - Address existing barriers to voluntary implementation and monitoring, such as limitations in using Conservation Reserve Enhancement Program (CREP) data because of privacy concerns for private landowners.

- Create and manage central repositories for data and information to monitor NNL and NEG. NNL databases should include data related to specific actions implemented as well as violations and emergency actions, and any variances that don't achieve NNL—including temporally. NEG databases should include data that track metrics and indicators signaling NEG in the environment.[6]
  - Fund a database to monitor successful implementation milestones tied to funding incentives and adaptively manage when metrics/indicators show inadequate progress. Funding should cover database creation, long-term maintenance, analysis, and reporting.[7]

- Consult with existing successful programs that utilize a suite of approaches for monitoring and complying with requirements—such as municipal stormwater permit structural controls under the Clean Water Act and local development regulations that trigger improvements on public

[5] WSAS has proposed a potential NEG monitoring system on pages 20-21 of the "Assessment of No Net Loss and Recommendations for Net Ecological Gain Metrics, Indicators, and Monitoring" chapter in *Appendix D. WSAS 2022 Report on Net Ecological Gain.*

[6] WSAS has outlined an approach for data collection and monitoring on pages 26-27 of the "Assessment of No Net Loss and Recommendations for Net Ecological Gain Metrics, Indicators, and Monitoring" chapter in *Appendix D. WSAS 2022 Report on Net Ecological Gain*.

[7] For guidance on using scientific tools such as modeling or decision-making structures to reduce uncertainty, see pages 6-7 of the WSAS report chapter "Assessment of No Net Loss and Recommendations for Net Ecological Gain Metrics, Indicators, and Monitoring" in *Appendix D. WSAS 2022 Report on Net Ecological Gain*. According to WSAS, these tools can inform understanding of how an action could impact ecological functions, the kind of indicators necessary to monitor the impact, and how long it might take to see a response.

rights-of-way to meet transportation requirements—when developing the NEG and NNL monitoring framework.[8]

NEG & NNL IMPLEMENTATION

Expand understanding of the successes and failures of NNL policies and improve oversight of NNL moving forward to ensure that standards are upheld.[9]

- Establish how to set up the tracking and reporting system and oversight for NEG.
- Convene an oversight body to develop an implementation framework for NEG to ensure cross-agency, cross-jurisdictional collaboration and assist with integration into local government planning.
- Conduct a NNL assessment within a representative sample of counties to analyze the performance outcomes of implementing NNL policies, what programs counties currently use to implement NNL, and how standards for NNL were implemented within these communities.
- Convey understanding of the current problem with the implementation of NNL, focusing on ecosystem function decline and why NNL is not working.
- Identify and evaluate other agencies' programs and actions that may result in NNL and/or NEG through implementation of those specific programs (such as capping or reducing water use, chemical/pesticide use, pollution from stormwater treatment, etc.). Cross-jurisdictional coordination has been employed successfully in the Puget Sound region, which uses a suite of Vital Sign indicators for identification and tracking of implementation.
  - Identify existing programs that contribute to NEG and/or NNL and identify what initiatives are making the greatest impact. The goal of this assessment is to account for existing programs that already work toward NNL and/or NEG, and synergize efforts to increase the pace of recovery.
  - Address gaps in existing programs where NNL and/or NEG are known to fail currently, including:
    - Impacts of legacy development properties and practices in sensitive areas (e.g., development that would not be allowed under current regs or that would require changes in approaches)
    - Legal constructs that preclude future restoration options (e.g., development behind a levee that makes future removal more costly)

[8] WSAS has outlined additional examples of monitoring programs on pages 22-26 and page 27 of the "Assessment of No Net Loss and Recommendations for Net Ecological Gain Metrics, Indicators, and Monitoring" chapter in *Appendix D. WSAS 2022 Report on Net Ecological Gain*.The chapter also details a process for monitoring NEG, including considerations for community engagement, on pages 27-28.

[9] To review the WSAS assessment of NNL, see pages 4-5 of the "Assessment of No Net Loss and Recommendations for Net Ecological Gain Metrics, Indicators, and Monitoring" chapter in *Appendix D. WSAS 2022 Report on Net Ecological Gain*.

  - Cumulative permitted development outside of urban growth areas (UGAs) that eventually hits a threshold where it impacts hydrology through stormwater, impervious area, etc.

- Assess the cost of not achieving NNL. Evaluate the cost of ecological decline of function/loss/services compared to what could be achieved through successful NNL or NEG implementation.

Develop the implementation framework for NEG.[10]

- Clearly define performance metrics, such as quantifiable habitat functions, connectivity, refugia, downstream metrics.
- Develop a funding strategy for NEG implementation.
- Audit use of funding allocated to protect investments in NEG.
- Define responsibilities and roles between agencies with a focus on who has authority; establish interagency coordination, shared timelines, and standards.
- Identify opportunities to advance NNL, and barriers that conflict with NNL, within existing or developing state legislation.
- Develop accountability and enforcement metrics and monitoring requirements for NEG.
- Ensure equitable and inclusive outcomes of a NEG standard.

NEG INCENTIVES & OTHER STRATEGIES[11]

Strengthen and expand current incentives contributing to NEG.

- Create NEG as a voluntary planning element under the Growth Management Act (GMA) and further incentivize local governments.
- Conduct case studies that represent different geographic scales to understand what incentive programs have been implemented and how they have performed.
  - Determine the effectiveness of incentives and key design considerations—including non-financial incentives, such as streamlined permitting—for different types of redevelopment and development (i.e., those motivated to adhere to NEG early on versus those that require additional incentives to comply).
  - Analyze what co-benefits/tangential financial benefits developers gained from NEG (e.g., competitive advantages, increased financial property value, secured efficiencies) and how

[10] WSAS has outlined a planning and implementation framework for NEG in sections III and IV of the "Assessment of No Net Loss and Recommendations for Net Ecological Gain Metrics, Indicators, and Monitoring" chapter in *Appendix D. WSAS 2022 Report on Net Ecological Gain*. The framework includes implementation considerations and approaches for developing criteria and indicators for NEG.
[11] WSAS noted that incentive programs must be based on social science research and need substantial strategic planning; the WSAS Committee recommends defining a more inclusive NEG process.

those benefits can be highlighted and maximized to improve participation and private investment in NEG.

- Ensure equitable access to incentive programs, particularly with respect to local businesses and low-income, minority, overburdened, and other historically marginalized groups.
- Integrate performance incentives into projects tied to monitoring requirements at the start of projects (e.g., performance-based payments where managers are paid once biodiversity NNL/NEG and the associated social outcomes can be demonstrated).

Create new incentives to increase participation in programs that benefit NEG.

- Significantly increase investment in incentive programs on private property with measurable NEG. Consider funding incentives through fees imposed on activities that generate net ecological losses, thereby disincentivizing activities counter to NEG.
- Create and/or maximize incentives to avoid development on the most biodiverse sites.
- Certify projects that meet NEG standards as nature positive, and support advertising and publication of certification for market premium benefits.
- Develop expedited permitting pathways for projects that meet or exceed NEG standards.
- Plan for and conduct a strategic social marketing study to aid in targeting incentives.
- Provide incentives for early adopters/pilots to provide demonstration to other potential investors, and reduce outcome uncertainty.

Understand opportunities and challenges in using incentives to achieve long-term benefits.

- Apply incentives beyond the implementation minimum and pair incentives with strong monitoring.
- Consider how gains earned from status quo are accounted for, and whether credits are counted toward NEG.
  - Consider accounting for gains using a structure similar to NOAA's nearshore conservation calculator.
- Design incentives to complement existing incentives such as marketing benefits to developers and ecosystem service benefits, to close the cost gap and nudge as many NEG projects forward at the lowest cost possible.

Identify additional strategies for achieving NEG on private property.

- Adjust acquisition fund application to permit the use of market values as opposed to assessed values in particularly ecologically sensitive areas to avoid further development. Ensure acquisition program is nimble and able to respond to urgent acquisitions of key sensitive areas.

- Explore alternative mitigation strategies for achieving gains on private lands; ensure that impacts from these alternatives are adequately tracked in future monitoring systems to ensure that they are achieving the intended gains.
- Investigate the potential implications of NEG on affordability issues for private properties—particularly with respect to housing—or onerous permitting.
- Study how NEG implementation can coexist with the current local and federal permitting systems with an emphasis on private property rights.

FUNDING NEG & NNL

Ensure existing funding sources maximize positive ecological impact.

- Compile existing funding programs that relate to NNL and/or NEG, including restoration grant funds.
- Develop a framework for comparing ecological benefits and costs across existing restoration grant programs, with specific measurement that compare a range of activities such as:
  - Preserving current habitat such as through land acquisition.
  - Restoring degraded habitat.
  - Regulating new developments.
  - Regulating legacy developments that do not comply with current standards.

Increase funding for implementing and monitoring NEG and NNL.

- Increase funding for local governments to increase staff capacity for long-range planning and compliance.



- Increase funding for local, state, and tribal monitoring programs.
- Provide funding for NEG and NNL multi-jurisdictional oversight.
- Assess the adequacy of existing funding for implementation, monitoring, and enforcement for NNL and identify additional funding if implementing NEG.
- Assess and fully fund existing programs that contribute to NEG outcomes.
  - Determine requirements for securing ongoing fundings. If requirements are conditional, consider whether they might deter participation.
  - Allocate resources toward local code enforcement programs.
  - Support organizational capacity to access matching funds, educational resources, and technical assistance.

- Identify state-level funding sources that could require a fixed amount of funds to go toward ecological restoration projects.
- Allocate funding to local jurisdictions and agencies to assist with NEG planning and implementation by updating guidance documents (e.g., Ecology Shoreline Planner handbook, Comprehensive Plan updates) and increase capacity for local implementers.
  - Target funding for greatest benefit per dollar spent, potentially through coordination with incentive design.

Maximize federal funding opportunities.

- Maximize state-level matching of federal funding sources (e.g., CREP) to ensure Washington is maximizing returns.
- Increase resources to promote federal funding opportunities to local jurisdictions and state agencies, and support jurisdictions and agencies in securing funding.

Identify new funding sources.

- Assess opportunities for new funding for projects that achieve ecological gains at a regional, watershed, or connectivity scales.
- Identify funding sources targeting co-benefits of NEG that can be stacked.
- Explore options for integrating a conservation impact fee, similar to school and transportation impact fees, into NNL requirements to support/offset some costs for NNL implementation.

EQUITABLE AND INCLUSIVE OUTCOMES AND COMMUNITY ENGAGEMENT

Ensure equitable and inclusive outcomes of a NEG standard.

- Continue stakeholder and tribal engagement as early NEG elements move forward.
- Provide annual NEG status reports to the WA State Governor's Office and State Legislature.
- Enhance community engagement in developing an NEG program and continue to engage the community as standards are implemented.
- Review, utilize, or improve public engagement and education programs to support more extensive public awareness and engagement for NEG and NNL.
- Incorporate inclusivity and equity in the design, implementation, monitoring, and evaluation approach of NEG policy by integrating input from communities that are disproportionately impacted by ecologically degraded environments.

- Incorporate social considerations in NEG initiatives by including a human and health well-being element to the mitigation hierarchy that will aid in efforts to reduce negative local impacts [12].
- Develop engagement dashboard to track ongoing community engagement efforts related to NEG to help identify and address inequities.

Enhance community engagement in developing an NEG standard and continue to engage the community as standards are implemented.

- Ensure broad engagement and input related to developing potential NEG policy, especially with regards to communities disproportionately impacted by degraded ecological conditions.
- Collaborate with experts in the development process of an NEG standard to better understand how existing policies can better protect and restore ecological function.[13]

ANTICIPATED CO-BENEFITS

In response to the proviso direction to ***"Assess how applying a standard of net ecological gain in the context of each environmental, land use, or development law is likely to achieve substantial additional environmental or social co-benefits,"*** the project team analyzed the anticipated co-benefits of advancing NEG legislation.

Projects that generate NEG will likely generate other direct and indirect ecological co-benefits, as well as social and economic impacts through improved public health, quality of life, economic growth, and climate resiliency.

Direct ecological benefits include aesthetic and recreational improvements and positive impacts to various ecosystem services, such as stormwater management and net reduction of greenhouse gas emissions from increased carbon sequestration and storage capacity [20]. **Indirect ecological benefits** include reduced erosion, pollination and natural pest predation, reduced threatened and endangered species listings and the regulatory complexity that such listings create, and increased fish and wildlife for fishing, hunting, and wildlife viewing.

The ecological improvements under NEG policy can produce a range of additional positive social and economic impacts [21] [22] [23]. Companies and individuals can benefit financially in the form of

[12] WSAS incorporated human and health elements into its report and recommendations, which can be found in *Appendix D. WSAS 2022 Report on Net Ecological Gain*. The WSAS Committee discusses the importance of the human dimension to the success of NEG throughout report, including pages 9-10 of the "Definition, Goals, and Objectives" chapter and pages 27-28 of the "Assessment of No Net Loss and Recommendations for Net Ecological Gain Metrics, Indicators, and Monitoring" chapter. WSAS suggested that this set of recommendations emphasize the socio-economic and ecological dimensions of NEG.

[13] WSAS recommended that this collaboration include establishing an ongoing process to ensure that existing and emerging scientific knowledge is a core part of NEG implementation. A more detailed explanation on WSAS's recommendations related to collaboration with experts can be found on pages 28-29 of the "Assessment of No Net Loss and Recommendations for Net Ecological Gain Metrics, Indicators, and Monitoring" chapter in *Appendix D. WSAS 2022 Report on Net Ecological Gain*.

increased property value and reductions in other expenses (i.e., avoided costs). Communities benefit through enhanced well-being, enhanced climate resiliency, improved public health, and efforts to foster equity in communities through public services. For example, NEG in coastal ecosystems can create climate resiliency benefits by protecting against flooding and rising sea levels [24]. These benefits can, in turn, reduce the cost of restoration from climate change impacts.

Existing literature and methods provide a basis for categorization, measurement, and valuation of co-benefits that arise from NEG. Several tools are also available for measuring and valuing ecological improvements across geographies, including through the Millennium Ecosystem Assessment, a comprehensive assessment of the consequences of ecosystem change for human well-being [25].

These co-benefits are important drivers and motivators for advancing funding and incentives to provide NEG. Accounting for co-benefits allows for a more accurate valuation of NEG, thus better aligning costs and benefits of ecological improvement. Co-benefits can also serve as the basis for identifying partnering opportunities by stacking benefits to draw in more organizations and identify financial sources of support. For example, NEG projects might access secondary funding sources by simultaneously providing water quality/stormwater, habitat, air quality, recreation, carbon sequestration, emissions reduction, and wildfire risk reduction benefits.

NEXT STEPS

Through this proviso summary report the project team aimed to shed light on the most pertinent considerations for the legislature in defining and implementing the next phase of ecological preservation standards in Washington state. This report is one of several critical steps in developing and implementing NEG policy as well as enhancing the implementation and oversight of existing NNL standards. Currently, WDFW is exploring the following immediate next steps in advancing NEG:

1. Create an oversight body to develop metrics, monitoring, and reporting for future standards.
2. Create NEG as a "voluntary planning element" under GMA to encourage a few counties to partner with the organizing body to develop and implement the initial NEG program along with NNL improvements.
3. Confirm that NEG applies to public projects only, while encouraging voluntary gains on private properties.
4. Increase funding incentives for participating local governments (staff capacity, planning funding, and public project funding).
5. Develop a reporting framework for the oversight body to report progress to the governor and legislature.

Considering the ecological decline already documented in Washington and the expected advancement of this decline in the face of climate change, expediently advancing these protection standards is now more important than ever.

Washington Department of FISH and WILDLIFE

APPENDICES



APPENDIX A. LITERATURE REVIEW SUMMARY

METHODOLOGY

In September 2022, Cascadia Consulting Group conducted a literature review regarding key considerations related to net ecological gain (NEG) and no net loss (NNL) policy and implementation. The review focused on several key considerations identified by Washington Department of Fish and Wildlife (WDFW) staff, as well as requirements outlined in the state legislature's 2021 proviso contained within Engrossed Substitute Senate Bill 5092. Specifically, this review focused on benefits achieved through NEG implementation, implementation strategies, economic implications, and barriers or challenges of implementing NEG policy.

To conduct the literature review, the project team collected resources provided by WDFW. To ensure we captured the most relevant literature in our review, WDFW prioritized each document as low, medium, and high. A total of 13 documents were identified as a high priority. We also identified six additional source materials during the literature review research and added these to our review.

Overall, the sources reviewed represent a variety of document types relating to the policy standard of NNL and NEG and are representative of implementation at different geographic scales, including global, national (United Kingdom), regional (Lake Tahoe), and statewide (Washington state) policy implementation.

This review and assessment step will be important to ensure we are building upon existing foundational knowledge, both in Washington and other regions, and identifying potential middle ground options worth discussing. This step will also inform how we engage stakeholders and tribal representatives, especially those experiencing frustration or fatigue around these topics.

KEY FINDINGS FROM LITERATURE REVIEW

The following summarizes key themes identified related to the concept and implementation of a NEG policy that were emphasized in one or more documents. The numbers list in brackets following findings refer to the numbered items in the bibliography.

NO NET LOSS (NNL) AND NET ECOLOGICAL GAIN (NEG) DEFINITIONS

NNL policy is a tool that has been implemented by governments around the world in response to ecosystem function decline driven by built infrastructure development [6]. In concept, **NNL seeks to neutralize impacts of human infrastructure on the environment**, typically by applying some form of the mitigation hierarchy criteria—sequentially avoid, minimize, remediate, and offset biodiversity impacts from new development [26] [10].

Where NNL policy seeks to neutralize development impact to ecosystem function, NEG policy seeks to result in an **increase** in biodiversity or resilience that improves the delivery of valued ecosystem functions in the affected ecosystem following development [1]. NEG implementation also follows the

mitigation hierarchy to avoid, minimize, remediate, and/or offset negative impacts on ecosystems **and the net benefits they provide**.

TRANSITIONING FROM A NNL TO NEG POLICY PRESENTS OPPORTUNITIES AND CHALLENGES

NNL and NEG are key principles in conservation policy that seek to address the ongoing decline in ecosystem function and biodiversity loss caused by the impact of built infrastructure [10]. While NNL is well established in international policy, NEG is gaining popularity as a superior goal that will achieve better outcomes for the environment [10]. Additionally, there is scientific consensus that "NNL has not been an effective approach for ecosystem or habitat management and protection nor for the maintenance of ecosystem services" [26]. In a global review of NNL outcomes, researchers found that successful NNL outcomes were limited, and a key reason cited for success appeared to be due to the implementation of high offset ratios, i.e., large offsets relative to the impacted area [6].

If NNL policy is not working currently, **shifting from a NNL policy in favor of a NEG policy could be a solution** to reduce ecosystem decline; however, transitioning between these two policies can be difficult due to persisting barriers affecting both policy frameworks.

Challenges identified in NNL that will persist in NEG include the following:

- Establishing appropriate baseline conditions [26].
- Uneven distribution of impact and mitigation. On average, assessments of habitat quality tended to find that the quality of offset sites was lower than that at impact sites [6, 26].
- Identification of appropriate targets, indicators, and metrics, as well as the determination of the appropriate spatial and temporal scales for monitoring [10, 1, 7, 8].
- Funding and infrastructure, incorporation of climate change science, monitoring, assessment accuracy, and community buy in [10, 1, 7, 8].
- Regional coordination between multiple levels of government with the potential for conflicting internal rules and policies (compliance and enforcement) [9].

  "Ecological uncertainties make it difficult to know where the threshold between no net loss and net gain lies and to specify how large gains should be." [7]

- Transitioning from NNL to NEG policy will therefore need to address these challenges in addition to determining what constitutes sufficient gain [1, 7]. Because NNL success often requires overcompensating for losses, **determining how large gains should be to achieve NEG goals is not straightforward** [10].

INSIGHTS FROM ESTABLISHED NEG POLICY: IMPLEMENTATION GUIDELINES AND SUPPORT

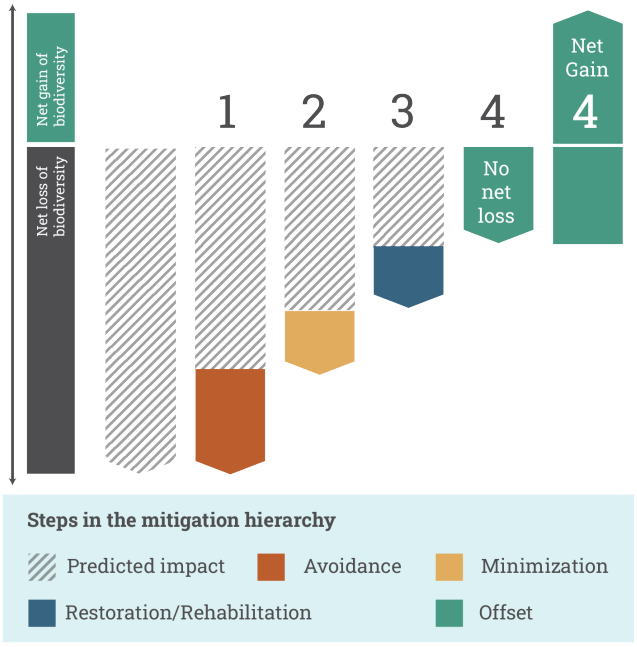
Despite the challenges successful implementation may present, **NEG is increasingly well established in international policy and corporate practice** [10]. In the United Kingdom (UK) current NEG policy (referred to as biodiversity net gain or BNG) includes explicit requirements to minimize impacts on biodiversity and provide net gains in biodiversity as part of the government's commitment to halt biodiversity decline [18]. The policy framework also includes "a presumption in favor of sustainable development" to emphasize support and encouragement of sustainable development [18]. This favor creates an incentive for developers by expediting or favoring sustainable development plans.

In the UK, NEG policy is on track to become mandatory by November 2023 and will require a minimum of 10% gain related to direct footprint losses due to development to be secured for at least 30 years [11]. Due to the mandatory implementation of NEG, the UK has produced resources providing insight and guidance on best practices when implementing NEG policies. In addition, implementation of NNL policy from Lake Tahoe, CA and Washington state provide **insights on how successful implementation of an NEG policy could look**. We summarize the main takeaways of these policies below.

DEVELOPING NEG POLICY AND PLANS

Key principles identified for the **successful design of NEG policies and plans** include the following:

Adhere to the mitigation hierarchy (Figure 1) to avoid, minimize, remediate, and offset [12, 13]. Offsets must focus on providing benefit above and beyond avoided loss [14]. Additionally, policies should adopt a no down-trading policy that states mitigation offsets in lower quality habitats cannot be applied to higher quality habitat impacts [8].



Source: Adapted from Bennet et al., 2017

The first and most important step of the mitigation hierarchy is to avoid adverse impacts, including the consideration of project alternatives. The second step consists of measures to reduce impacts that cannot be avoided, followed by work to restore, or rehabilitate damaged ecosystems or species populations on the site of the development (Step 3). Offsets (Step 4) can be used as a measure of the last resort if and when it can be demonstrated that appropriate efforts have been made, through other steps in the mitigation hierarchy, to minimize residual impacts. Offsets can either be on site or off site. They can be used to achieve either a no net loss objective or a net gain in biodiversity following the development.

Figure 2. Mitigation hierarchy for net gains [11].

- **Identify and classify baselines and metrics** needed to measure ecological impact [7, 11, 14].
- **Be inclusive and equitable in policy/program development.** Engage stakeholders early, and involve them in designing, implementing, monitoring, and evaluating the approach to Net Gain. Achieve NEG in partnership with stakeholders where possible and share the benefits fairly among stakeholders [12].
- **Ensure additionality of ecosystem offsets** that exceed existing obligations [12, 14].
- **Use robust, credible evidence and local knowledge** to make clearly justified choices when considering the following policy elements [12]:
  - Delivering compensation that is ecologically equivalent in type, amount and condition, and that accounts for the location and timing of biodiversity losses.
  - Compensating for losses of one type of biodiversity by providing a different type that delivers greater benefits for nature conservation.
  - Achieving NEG locally to the development while also contributing towards nature conservation priorities at local, regional, and national levels.
  - Enhancing existing or creating new habitat.
  - Enhancing ecological connectivity by creating more, bigger, better, and joined areas for biodiversity.
- **Ensure NEG generates long-term benefits** (benefits delivered in perpetuity) by planning for adaptive management, securing and dedicating funding for monitoring, incorporating resiliency

to external factors such as climate change and other land uses, and supporting local level management of NEG activities [8, 12, 13, 14].

- **Address risk and uncertainty** related to achieving NEG [12].

NEG IMPLEMENTATION STRATEGIES TO ADDRESS UNCERTAINTY

It is critical to evaluative uncertainties that exist in NEG policy to implement it successfully and determine the best path forward for developing robust plans that will lead to long term ecological gains [26]. There are risks to delivering NEG by creating or enhancing habitat, and climate change poses a significant level of uncertainty for all ecosystems [26]. However, there are suggested strategies that can be incorporated into program design that are important for NEG success, including the following:

Incorporate an adaptive management process. For example, in Lake Tahoe, CA an adaptive management system is used to ensure the region is meeting threshold standard goals related to environmental conditions such as water quality. The adaptive management system is described as a systematic approach for improving resource management by learning from management outcomes [9]. Figure 2 provides a visual for adaptive management flow. In terms of Lake Tahoe's adaptive management system, "the threshold standards and the Regional Plan represent the 'plan' function. The long-term goals (threshold standards) are set and kept up to date through periodic review and amendment as needed. Completion of public and private projects, programs, and proposals corresponds to the 'do' function. The 'check' function is carried-out through monitoring and reporting which is then used on an ongoing basis to 'adjust' by making changes to the 'plan." [9]

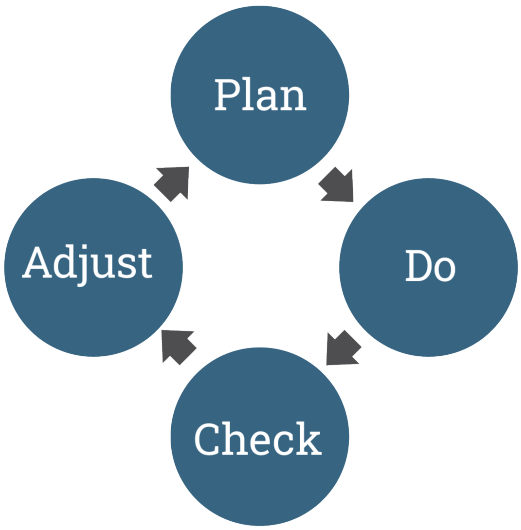


Figure 3. The adaptive management or continuous improvement "plan-do-check-adjust" approach used by Lake Tahoe's threshold and Regional Plan system [9].

- **Establish consistent biodiversity metrics.** Provide data on anticipated losses and gains related to ecosystem function or biodiversity in a standardized format that can be easily collected [7]. In the UK, the Department for Environment, Food & Rural Affairs (Defra) proposed a "Defra Biodiversity Metric" designed to provide ecologists, developers, planners, and other

interested parties with a means of assessing changes in biodiversity value (losses or gains) brought about by development or changes in land management. The metric is a habitat-based approach to determining a proxy biodiversity value. This metric will be used to measure Biodiversity Net Gain under the UK's mandatory policy [19, 27].

- **Establish consistent biodiversity metrics.** Provide data on anticipated losses and gains related to ecosystem function or biodiversity in a standardized format that can be easily collected [7]. In the UK, the Department for Environment, Food & Rural Affairs (Defra) proposed a "Defra Biodiversity Metric" designed to provide ecologists, developers, planners, and other interested parties with a means of assessing changes in biodiversity value (losses or gains) brought about by development or changes in land management. The metric is a habitat-based approach to determining a proxy biodiversity value. This metric will be used to measure Biodiversity Net Gain under the UK's mandatory policy [19, 27].
- **Manage a database of monitoring data.** Authorities can partner with organizations that manage data on the natural environment. In the UK, local environmental record centers (LERCs) are an important partner in establishing NEG within local planning associations. LERCs have the expertise to manage and retain databases and can aid in creating robust datasets that are available to others [13].
  - Monitoring data collection can be used to **establish a baseline** to which environmental improvement will be referenced.
  - Proper data management addresses the issue of double counting.
- **Make NEG mandatory** for all new developments. Making NEG mandatory will provide private investor confidence in the approach and in offsetting. This is vital to creating a 'Restoration Economy' through habitat banking, net gain, and corporate natural capital accounting [14]. In the US, regulatory certainty surrounding NNL policies led to significant economies of scale leading to the start of large, multisite habitat banking entities that can buffer risks [11].

MEASURING NEG

Achieving measurable net gains in biodiversity and ecosystem function is essential to the success of NEG. A 2019 guidance document out of the UK summarized the key points on measuring NEG as follows [13]:

- Justify the methods used to measure NEG.
- Use the same methods consistently throughout a project's life cycle (quantify outcomes from avoidance, minimization, and compensation measures that show additional gains).
- Establish and justify a baseline.
- Be transparent on metrics used and how NEG outcomes were determined.
- Use qualitative and quantitative assessments to be used in design, implementation, and maintenance/monitoring of NEG to capture all aspect of biodiversity/ecosystem function.
- Incorporate uncertainties into calculations by adding contingency to increase the amount of ecosystem function or biodiversity needed to achieve net gain. Contingency should account for the time-lag between losses occurring and the gains being realized.

- Do not aggregate all features together into a single summed number for a project.
- Carefully consider what constitutes net gain; it is important to consider metric accuracy compared to the goal of net gains.
- Present quantifiable evidence that demonstrates measurable net gains. This will typically mean monitoring data over a timeframe that is commensurate with the specific feature of the net gain design.

MONITORING IS ESSENTIAL FOR COMPLIANCE AND ENFORCEMENT OF NEG POLICY

- **Robust monitoring, assessment, and accountability are critical to successful implementation of NEG policy** [26]. Without monitoring and reporting plans in place, compliance could lapse, and enforcement or accountability triggers would fail. However, funding, authority, scale of mitigation, and the establishment of universal metrics all present challenges for creating monitoring plans related to NEG [28]. This section provides insights on key factors to consider when designing a monitoring program related to NEG and highlights legal considerations specific to Washington state.
- **Enable and incentivize cross-agency and cross-disciplinary communication and collaboration** on NEG-related issues [26]. This would decrease the potential for conflicting internal rules and policies between multiple levels of government [9].
  - If NNL or NEG are only applied to a subsection of impacts, then even if project-scale mitigation is achieved, the policy will inevitably oversee landscape-scale declines in biodiversity. "There are two main sources of unmitigated infrastructural impacts: (1) deliberate policy choices that leave particular sets of impacts either entirely unaddressed or granted special exemptions from regulation and (2) illegal, noncompliant, or unreported impacts." [13]
- **Funding for long-term monitoring and maintenance of NEG outcomes.** In the UK, additional funding to support local authorities to enforce, monitor, and administer a NEG standard has been identified as a need [28]. Overall, it is important for authorities to ensure sufficient funds have been allocated to deliver management long-term, anticipating costs such as capital works, negative impacts to income, potential need for management cost contingency, legal, administration, monitoring, reporting, foreseeable risks, insurance, and inflation [8].

LEGAL ISSUES IN WASHINGTON STATE

There is concern that mandatory enforcement of NEG policy could lead to a regulatory taking on private lands [15]. A taking is described as a "regulatory action that deprives property of all value […]. Where there is less than a complete deprivation of all value, a court will evaluate whether a taking has occurred by considering the economic impact in relation to at least two other factors: (1) the extent to which the government's action impacts legitimate and long-standing expectations about the use of the property; and (2) the character of the government's actions—is there an important interest at stake and has the government tended to use the least intrusive means to achieve that objective?" [15].

In an advisory memorandum related to actions to avoid unconstitutional takings of private property [15], the Office of the Attorney General stated that when a regulation requires a private property owner to dedicate land to public use, the dedication or financial obligation that is required from the landowner must be reasonable and proportional- i.e., specifically designed to mitigate adverse impacts of a proposed development. Ultimately, the government must demonstrate that it acted reasonably, and that its actions are proportionate to an identifiable problem.

ALTERNATIVE MITIGATION STRATEGIES

Sources mainly described achieving NNL and NEG within the mitigation hierarchy via developers directly offsetting their project impact on site or off site, without relying on third parties. Other mitigation strategies that were mentioned for achieving mitigation offsets included:

- **Habitat banking** - A market mechanism where credits from actions with beneficial biodiversity outcomes can be purchased to offset the debit from environmental damage [11].
- **In-lieu fee program/compensation fund** - Accept payments in exchange for credits. Habitat creation and restoration projects are carried out once enough funds have been collected [11, 13].

EQUITABLE AND INCLUSIVE OUTCOMES OF NEG POLICY ARE NOT A GUARANTEE AND SHOULD BE INTENTIONAL IN PLANNING

There is an opportunity to ensure NEG policy is more equitable and inclusive in its outcomes compared to NNL policy. Currently, social issues are often not well considered by those designing and implementing strategies to mitigate biodiversity loss and social impacts of changes in biodiversity are often overlooked [7, 16]. As a result, there is evidence that underserved groups are most affected by ecological loss, while wealthier members of the same community disproportionately benefit through mitigation actions [1].

> *"NNL is not equitable and NEG processes must learn from NNL's downfalls and create more equitable stakeholder engagement practices." [26]*

To address these inequities, **policymakers must consider inclusivity and equity in the design, implementation, monitoring, and evaluation approach of NEG policy**. Engaging and involving stakeholders and other partners early in the process will support successful NEG outcomes and promote community trust and buy-in [26, 13, 16]. Previous NNL and NEG implementation have also demonstrated the importance of balancing on-site and off-site benefit delivery. Although operating under the mitigation hierarchy first seeks to avoid significant adverse impacts and encourages on-site mitigation, there are often local constraints such as disturbance and lack of available space that make it a challenge to deliver social benefits where the impacts are observed [7, 14]. In the UK, it is typical for 80% of NEG to be delivered off-site which has raised concerns that some communities will experience most of the adverse impacts of development while others will receive the benefits [14].

Moving forward, **NEG initiatives can incorporate social considerations more explicitly**. Ecosystem services are often tied to community well-being, and as such, policies to mitigate ecosystem decline

should incorporate local values and impact [16]. In practice, incorporating these considerations is challenging because NEG is most effectively achieved at scale [14]. However, including a well-being framework to the mitigation hierarchy will aid in efforts to reduce negative local impacts [16].

ENVIRONMENTAL AND SOCIAL CO-BENEFITS

Successful implementation of NEG will increase biodiversity or resilience that improves the delivery of valued ecosystem functions in the affected ecosystem following development [1]. Strengthening ecosystem function and health has a cascading effect of positive environmental and social outcomes. In addition to providing increased climate resiliency, NEG environmental and social co-benefits include:

Protection of critical ecosystem function while ensuring sustainable development. Global development will continue to meet residential population and commercial enterprise demand [6, 26]. NEG will be an essential component of supporting this growth to continue in a sustainable way that leads to positive ecological outcomes.

Increased human health and well-being. Promoting sustainable development results in economic, social, and environmental benefits. By increasing biodiversity and ecosystem function through development, homes, and the people who live in them can benefit from clean water and air. Sustainable development has also been cited as increasing the value of a new home [13] and flood protection [7].

POTENTIAL INCENTIVES TO PROMOTE NEG

Incentivizing NEG for developers and private landowners will be a key component of moving the needle on NEG implementation. We summarize incentives included in the literature below.

- **Performance Incentives**. Monitoring requirements should be budgeted for at the start of the project. Where feasible, these requirements should link to financial incentives at the project level—such as withholding of project finance until monitoring data are submitted—or the individual level—such as performance-based payments where managers are paid once biodiversity NNL/NEG and the associated social outcomes can be demonstrated [29].
- **Create incentives for on-site mitigation** or off-set close to the mitigation site [11].
  - Incentivize the use of local habitat compensation schemes and encourage on-site enhancement [28].
- **Incentivize environmental principles within the development itself.** This would mean that built developments which were designed sustainably, utilizing sustainable building materials, or incorporating renewable energy, would score positively in a NEG approach [28].
- **Create incentives to avoid the most biodiverse sites for development** by recognizing biodiversity costs and benefits [28].

In addition to regulatory incentives, sources state that developers can gain a competitive advantage, increase financial value, and secure efficiencies by adopting good practice principles for NEG [13]. These advantages include the following:

- **Competitive advantage**—developers that implement NEG ensure a smooth transition when aligning project and operations with requirements to deliver NEG; help companies improve site selection; improve stakeholder relations by providing a collaborative basis to work from; demonstrate sustainability leadership, which can benefit company reputation.
- **Increased financial value**—developers that implement NEG can create more desirable areas due to the creation of sustainable building, public parks and other spaces that enhance people's wellbeing and quality of life. This can create increased investment and demand in the area.
- **Secured efficiencies**—applying the mitigation hierarchy can minimize the risk of delay and costs related to potential effects on the environment earlier in the process.

APPENDIX B. REGULATORY REVIEW MEMO

During the 2021 Legislative session, the Washington legislature directed Washington Department of Fish and Wildlife (WDFW) to investigate a pathway for incorporating a Net Ecological Gain (NEG) standard into state law with the goal of improving endangered species recovery and ecological health statewide.

One of the key project initiatives required by the legislative proviso includes an analysis of existing Washington State environmental, development, or land use laws or rules where the existing standard—namely NNL or a similar standard—is mentioned to understand how these standards have operated within the state. These include the Shoreline Management Act (SMA) (chapter 90.58 RCW), the Growth Management Act (GMA) (chapter 36.70A RCW), Construction Projects in State Waters (CPSW) (chapter 77.55 RCW), and the Model Toxics Control Act (MTCA) (chapter 70A.305 RCW).

This memo summarizes the NNL standards, mitigation, and enforcement requirements within the laws and associated rules named by the proviso above as well as within the State Environmental Policy Act (SEPA) (chapter 43.21C RCW) and the Forest Practices Act (FPA) (chapter 76.09 RCW)—identified as other key pieces of Washington legislation pertaining to NNL. Throughout this memo, laws and rules are linked when first referenced.

Table 1 summarizes the key legislative details outlined in this memo.

METHODOLOGY

The laws and rules assessed were those named within the proviso. SEPA was also included because of the law's requirements to review governmental decision making regarding environmental impacts and mitigation sequencing.

This memo is limited to review of the Revised Code of Washington (RCW) and Washington Administrative Code (WAC) language and relevant guidance documents produced by the Washington Department of Commerce (Commerce), Washington Department of Ecology (Ecology) and WDFW. Table 1 summarizes the key legislative details outlined in this memo.

This memo is not a literature review nor assessment of regulatory effectiveness of these laws, regulations, or guidelines. These details were gathered primarily through engagement with experts.

SUMMARY OF LEGISLATION REVIEWED

SHORELINE MANAGEMENT ACT (CHAPTER 90.58 RCW)

The SMA rules were the first rules to include NNL explicitly. The rules require local jurisdictions to develop and implement Shoreline Master Programs that protect shorelines of the state from NNL through land use zoning designations, with associated permitted uses and development standards, such as buffers and setbacks. Mitigation sequencing is applied to all projects with "avoidance" of impacts to ecological functions and values being the highest priority. Compensatory mitigation is an option if impacts cannot be avoided, minimized, rectified, reduced, or eliminated. Local governments oversee permit implementation and enforcement [30].

GROWTH MANAGEMENT ACT (CHAPTER 36.70A RCW)

The intent of GMA is to provide for growth while protecting natural resource lands and critical areas. Counties and cities are required to designate agricultural lands, forest lands, mineral resource lands, and critical areas where appropriate and develop protective regulations. The implementing guidance for protection of critical areas states that if development regulations allow harm to critical areas, that cannot be mitigated otherwise through appropriate mitigation sequencing, compensatory mitigation is required to avoid a net loss of critical areas. Local governments are responsible for permit implementation and enforcement [31].

CONSTRUCTION PROJECTS IN STATE WATERS (CHAPTER 77.55 RCW)

This regulation defines when a hydraulic project approval (HPA) is required for projects that might contribute to the decline of aquatic ecosystem function in or near state waters. HPAs are issued by WDFW and are designed to protect fish and their aquatic habitats. The law outlines the application requirement, review and approval procedures, and remediation actions required. WDFW may only deny or provision a HPA on the grounds of fish life protection, including habitat impacts. WDFW is responsible for enforcement of permit implementation and monitoring of violations [32].

MODEL TOXICS CONTROL ACT (CHAPTER 70A-305 RCW)

The Model Toxics Control Act (MTCA) directs the investigation, cleanup, and prevention of future contamination of sites that are contaminated by hazardous substances. The law directs the Department of Ecology to investigate any releases or threatened releases of hazardous substances, including but not limited to inspecting, sampling, or testing to determine the nature or extent of any release or threatened release of a hazardous material. The MTCA includes MTCA Cleanup Regulations, Sediment Management Standards and Remedial Action Grants and Loans. The law adopts the standard of "no adverse effects", which is defined as "no acute or chronic adverse effects to biological resources as measured by a statistically and biologically significant response relative to reference or control." Ecology is responsible for the enforcement of monitoring plan and mitigation standards [33].

STATE ENVIRONMENTAL POLICY ACT (CHAPTER 43.21C RCW)

The State Environmental Policy Act (SEPA) is intended to ensure that state and local agencies consider environmental values during decision making for proposed planning documents (non-project) or project actions. A threshold determination is made based on the standard of whether the project will result in "adverse environmental impacts," which then triggers further actions based on the level of impact expected, including the need for mitigation and or advanced review with an Environmental Impact Statement. The threshold determination is subjective and based, in part, on the physical setting, including, but not limited to, the sensitivity and value of the location as well as the magnitude and duration of the impact. The determination also considers proposed mitigation activities and input from stakeholders and other permit requirements. SEPA is a required planning tool used in conjunction with many environmental decisions to arrive at a determination of significance which then triggers mitigation sequencing and other planning actions. SEPA processes are led by lead agencies determined by the nature, intent, or location of the project on a project-by-project basis. SEPA standards are enforced by the state or local agency that issued the original permit for the project in question [34].

FOREST PRACTICES ACT (CHAPTER 76.09 RCW)

The Forest Practices Act (FPA) regulates forest practice activities on state-owned and public forest lands. FPA rules ensure the protection of federally listed fish and riparian-dependent species while maintaining commercial forest management as an economically viable use of forestlands. Forest practice rules focus on riparian and instream habitats by regulating activities such as timber harvesting, road construction, and road maintenance plans. Protection standards extend to protecting associated lands that affect habitat, such as operations on or around steep and unstable slopes and wetlands, as well as water quality. Incidental take of focus species and habitat impacts are monitored through regular assessments, monitoring and adaptive management programs. Washington Department of Natural Resources implement and enforce forest practice permits [35].

THEMES IDENTIFIED ACROSS LEGISLATION

THE DEFINITION OF NNL VARIES ACROSS WASHINGTON LEGISLATION

NNL is clearly defined as a requirement in the SMA guidance (chapter 173-26 WAC) and as a requirement for HPA (chapter 77.55 RCW) approval. It is defined as a goal in guidance for implementation of the GMA but not defined explicitly in the GMA (chapter 36.70A RCW).

SEPA (chapter 43.21C RCW) is widely used to assess environmental impacts of projects and determine if impacts will occur that require mitigation, but is not required for all land-use projects and decisions.

The MTCA cleanup regulations (chapter 173-340 WAC) and Sediment Management Standards (chapter 173-204 WAC) use the standard of "no adverse effects" which is defined as "no acute or chronic adverse effects to biological resources."

MITIGATION REQUIREMENTS VARY ACROSS LEGISLATION

Mitigation sequencing is explicitly stated in the SMA, SMA guidelines, and GMA guidelines. Mitigation for actions approved by CPSW is less well-defined but is suggested. Compensatory mitigation is consistently the least favored action. Commerce's 2018 Critical Area Handbook recommends local governments direct mitigation, including compensatory and compensatory mitigation, towards salmon recovery priorities in the basin when developing regulations for critical areas [31].

Mitigation plans (chapter 90.74 RCW) are an alternative process to standard on-site mitigation; in-kind mitigation can be approved by Ecology or WDFW and are initiated by the project proponent seeking a permit. Neither Ecology nor WDFW can limit the scope of options within a mitigation plan on, or adjacent to, site of impact, or to habitat types of the same type that will be impacted. They are not required to approve mitigation plans that do not provide equal or better ecological functions and values within the watershed or bay (chapter 90.74.020 RCW).

The MTCA does not appear to involve mitigation sequencing or procedures. If violations are found and "adverse impacts" are discovered then a cleanup process is initiated and permits revised.

THERE ARE CONSISTENT GAPS OR NEEDS ACROSS LEGISLATION WHERE THERE IS NOT STRONG GUIDANCE NOR STANDARDS

The following is a very high-level assessment of potential gaps and needs that were identified during this summary effort but is in no way comprehensive nor is this assessment vetted by legal staff or policy implementers. It is possible that these gaps and needs are addressed by different laws and rules not reviewed for this memo.

NEEDS

A consistent application of a standard would provide clarity of intent regarding goals to not lose any ecological function or values as a result of land use decisions and actions. The variety of terms used to address NNL ("no adverse impacts," "conservation," "protection") may be leading to confusion and inconsistent protections.

Fiscal and capacity support for local governmental enforcement and monitoring would enable comprehensive monitoring of permit implementation and violation investigations. Enforcement of permit conditions left to the jurisdiction of local governments results in a variety of enforcement processes and varying standards. Without enforcement and permit implementation review being required, NNL may be occurring, which in turn impacts the current conditions inventory during periodic updates. The baseline of NNL that is determined by inventories is negatively impacted, leading to incremental loss.

Forest practice actions should be included in any NNL assessment. Not achieving a NNL standard, when the entire forest ecology is considered, should not be considered a failure of forest practices. The FPA law and rules were designed to prevent impacts to, and incidental take of, a limited number of endangered species and federal and state water quality standards, while maintaining a viable timber industry. The law and rules were not designed to achieve NNL across the broad watershed landscape for all ecological functions and values. While the management practices required by the FPA have resulted in habitat improvements over historical forest practices, any assessment of NNL should also include forest lands under the FPA given the focus on fish and riparian-dependent species to ensure a cumulative picture of the amount of NNL across the state.

GAPS

- Most of the reviewed laws and rules include permitting and SEPA exemptions for different types of proposals. The impact of these exemptions may be considered during cumulative impacts analyses and NNL assessments conducted by local governments or state agencies, when required for periodic updates. However, any proposal action exempt from permit review, or held to different review standards under programs that do not undergo periodic updates, may not be accounted for in NNL assessments.
- Guidance for completing periodic updates does not include an assessment of ecological functions that may have been lost due to unpermitted activities or permitted activities with unexpected impacts. Nor is an assessment of potential ecological functions gained due to voluntary measures required during periodic updates. The current requirements of the cumulative impacts analysis are forward looking in time and only account for existing

conditions and proposed actions. SMPs are required to have Restoration Plans but not required to implement the proposed actions or assess any progress during periodic updates.

- During periodic updates under GMA and SMA, local governments are not required to "show their work" as to how they are achieving NNL or if they are achieving the standard. Monitoring and tracking are not required.
- During SMA periodic updates, local governments are not required to document progress made on implementing actions recommended in restoration plans. Restoration plan actions are voluntary. However, restoration is recognized as necessary in conjunction with protective regulations to achieve NNL. Therefore, an assessment of implementation progress of restoration plans would inform the overall state of NNL.
- No requirement was found to require compensatory mitigation for temporal loss of ecological function after violations or inadvertent impacts are discovered. Restoring lost habitat does not account for the temporal loss of ecological function.
- Emergency permitting actions are often held to different ecological function standards. No requirement was found requiring compensatory mitigation for ecological function loss, including temporal loss, should it have occurred as a result of the emergency action(s).

DETAILED LEGISLATION SUMMARIES

SHORELINE MANAGEMENT ACT (CHAPTER 90.58 RCW)

BRIEF DESCRIPTION

Washington State adopted the Shoreline Management Act (SMA) to prevent the inherent harm that results from uncoordinated development of the state's shorelines. SMA's broad policies are translated into regulatory standards for shoreline use by local governments in their Shoreline Master Programs (SMP). The development of SMPs is governed under WAC 173-26, which was the first rule to incorporate a NNL standard requirement within its governing regulations. Specifically, WAC 173-26-201(2)(c) states:

> "These guidelines are designed to assure, at minimum, no net loss of ecological functions necessary to sustain shoreline natural resources and to plan for restoration of ecological functions where they have been impaired."

The NNL standard is intended to halt the introduction of new impacts to shoreline ecological functions resulting from new development. Local governments are expected to achieve this standard through both the SMP planning process and by regulating individual developments. It is recognized that to achieve NNL, it is necessary that both restoration and protection occur [36].

The SMA regulatory jurisdiction lies with Ecology.

CURRENT STANDARDS GOVERNING THE DETERMINATION OF NNL (I.E., METRICS USED TO DETERMINE NNL)

For determining NNL at a project permit level, local governments use SEPA (Chapter 43.21C RCW) to review proposed projects and determine the anticipated environmental impacts. Following this review, a determination of significance is issued, which determines next steps for project implementation.

For determining if NNL is achieved through local government planning efforts, SMP plans and updates are reviewed and approved by Ecology's director, who must formally conclude that the proposed SMP will result in NNL over a 20-year planning horizon. Local governments also apply SEPA to these planning and program-level decisions.

Local governments are expected to demonstrate NNL through:

1. A comprehensive SMP update planning process, and
2. Project review and permitting processes, over time.

Local governments are also encouraged to utilize the following practices to meet the NNL standard:

- Locate, design, and mitigate development within a watershed context (utilizing watershed characterization to identify areas for development, restoration and on or compensatory investigation,
- Prohibit uses that are not preferred for shoreline uses or are not-water dependent,
- Require future shoreline development be carried out so that it limits further degradation,
- Require buffers and setbacks,
- Use watershed inventory and characterization to create environment designations,
- Establish strong policies and regulations through permit review, mitigation measures and restoration requirements,
- Recommend actions for properties that are outside shoreline jurisdiction but may impact shorelands, and
- Require mitigation sequencing for all development (avoid, minimize, rectify, reduce, compensate as well as monitor and take corrective actions) [36].

During their periodic SMP Updates, which are required every eight years, local jurisdictions produce a watershed characterization, use analysis, management recommendations, and a restoration plan. A cumulative impacts analysis and NNL summary—which are meant to provide a record of the jurisdiction's decisions on SMP policies and regulations—are also required. Chapter 17 of Ecology's SMP Handbook provides guidance on the Cumulative Impacts Analysis component of a local government's SMP update. The analysis must include (1) a current circumstances assessment, (2) consideration of foreseeable future development, and (3) consideration of beneficial effects of any existing regulatory programs beyond the SMP. The analysis is not required to analyze historic trends to assess if the current SMP is achieving NNL as intended. Chapter 4 of the SMP Handbook provides guidance to local governments on how to ensure they are meeting the NNL standard [37].

Shoreline inventories are used to set the baseline against which indicators measure change. Inventories are completed during the watershed characterization process during initial SMP planning process and/or during SMP updates.

A list of potential metrics/NNL indicators have been developed by Ecology but their use by local governments is voluntary and local governments may develop their own indicators.

SMP HABITAT PRIORITIZATION/RANKING SYSTEM FOR MITIGATION

Mitigation sequencing is defined in WAC 173-26-201(2)(e) as:

> *"To ass*ure no net loss of shoreline ecological functions, master programs shall include provisions that require proposed individual uses and developments to analyze environmental impacts of the proposal and include measures to mitigate environmental impacts not otherwise avoided or mitigated by compliance with the master program and other applicable regulations."

SMP regulations must state that mitigation measures shall follow a sequence of steps, in priority of avoiding, minimizing, rectifying, reducing, or eliminating, and finally compensating. Monitoring and taking corrective measures are also listed as requirements.

SMP restoration plans should help identify priority sites for restoration and compensatory mitigation but do not suggest priority criteria (WAC 173-26-201(2)(iii)(c)). Restoration is a noted requirement to achieve NNL. While a Restoration Plan is a required element of SMPs, the implementation of proposed restoration actions is not required nor is it always evaluated during the update process.

ENFORCEMENT OF SMA

Enforcement of the NNL standard can occur during the approval process of SMPs by Ecology or through permit compliance either by the local government or through Ecology. The Shorelines Hearings Board also has an enforcement role at the SMP planning level.

Ecology may not approve a local government's SMP if the proposed SMP does not provide an adequate level of protection for shoreline ecological functions, including proving NNL of those functions through the planning process or permitting review. WAC 173-26-070(b) states:

> *"Pursua*nt to RCW 90.58.090(4), when the department determines that those parts of a master program relating to shorelines of state-wide significance do not provide for optimum implementation of the policy of chapter 90.58 RCW to satisfy the statewide interest, the department may develop and adopt by rule an alternative to the local government's master program proposal."

Ecology has adopted an alternative Master Program should Ecology not approve the local government's proposed SMP until the local government can propose a SMP that does.

The Shorelines Hearings Board hears and decides appeals challenging local governments' comprehensive plans and critical areas ordinances by those that feel that protections and standards required by the SMA, including the NNL standard, are not being upheld or if the shoreline is inadequately protected.

Local governments are expected to identify a process for periodically evaluating the cumulative effects of authorized development on shoreline conditions Chapter 4 of the SMP Handbook suggests, but does not require, that local governments use a suite of indicators to evaluate effects of development. Local governments are only required to show how a development project will achieve NNL. Chapter 4 briefly mentions that local governments are expected to implement a compliance strategy that should include a mechanism to document project review actions and a method to periodically evaluate cumulative effects of authorized shoreline development. The compliance strategy should include development project reviews and identification of enforcement priorities. This development of enforcement and resulting mitigation or restoration of impacts is the local government's responsibility [37].

ON-SITE VERSUS COMPENSATORY MITIGATION APPROACHES

The SMA does differentiate between on-site and compensatory mitigation, stating that on-site mitigation is preferred to compensatory mitigation in WAC 173-26-201(2)(e)(ii)(B):

> *"When compensatory measures are appropriate pursuant to the mitigation priority sequence above,* ***preferential consideration shall be given to measures that replace the impacted functions directly and in the immediate vicinity*** *of the impact. However, alternative compensatory mitigation within the watershed that addresses limiting factors or identified critical needs for shoreline resource conservation based on watershed or comprehensive resource management plans applicable to the area of impact may be authorized. Authorization of compensatory mitigation measures may require appropriate safeguards, terms or conditions as necessary to ensure no net loss of ecological functions" (emphasis added).*

GROWTH MANAGEMENT ACT (CHAPTER 36.70A RCW)

BRIEF DESCRIPTION

The purpose of the Growth Management Act (GMA) (chapter 36.70A RCW) is to provide for growth while protecting natural resource lands and critical areas.

Chapter 36.70A.170 WAC directs counties and cities to designate agricultural lands, forest lands, mineral resource lands and critical areas where appropriate. It also directs counties and cities to consider the guidelines adopted by the Department of Commerce (Commerce) when developing protective regulations. These guidelines are considered the minimum requirements for protecting natural resource lands and critical areas.

Commerce released an updated Critical Areas Handbook guidance in 2018 (approved in 2022) to assist local governments in reviewing and potentially revising their locally adopted programs that designate and protect critical areas [31]. Local governments have the discretion to tailor the comprehensive plans

and development regulations to their local circumstances, within the goals and requirements of the GMA.

CURRENT STANDARDS GOVERNING THE DETERMINATION OF NNL (I.E., METRICS USED TO DETERMINE NNL)

Chapter RCW 36.70A.020 (Planning Goals) does not mention "no net loss," specifically. The planning goal in RCW is stated as requiring the "conservation" of habitat, the environment, productive forest, and agricultural lands, along with conserving natural resource-based industries. Protection of water quality and availability is stated as important in supporting the state's high quality of life. There is no mention of protecting the function of habitat in the Planning Goals.

The implementing guidance for protection of critical areas does reference NNL. WAC 365-196-830(4) states that if development regulations allow harm to critical areas, compensatory mitigation is required to avoid a net loss of critical areas. The WAC states that local governments must adopt regulations to "protect" critical areas. Protection is defined in this context as preservation of the functions and values of the natural environment, or to safeguard the public from hazards to health and safety.

Local governments may develop and implement alternative means of protecting critical areas if those means provide NNL of functions and values and are developed based on best available science (WAC 365-196-830(8)).

The critical areas guidance does encourage local policymakers to take an ecosystem approach to developing regulations. The Growth Management Hearings Boards have found that "development regulations may not allow a net loss of the functions and values of the ecosystem that includes the impacted or lost critical areas" [38] [39].

WAC 365-195-925 states that, in addition to including best available science, cities and counties must also give "special consideration" for the protection and enhancement of anadromous fisheries when developing regulations and protective measures. The Supreme Court found that while "enhancement" of anadromous habitat should be given "special consideration," cities and counties are not required to adopt measures to require enhancement. The Court concluded that the "no harm" standard protected critical areas by maintaining existing conditions [40].

GMA HABITAT PRIORITIZATION/RANKING SYSTEM FOR MITIGATION

WAC 365-196-830(4) states that:

> *"Although counties and cities may protect critical areas in different ways or may allow some localized impacts to critical areas, or even the potential loss of some critical areas, development regulations must preserve the existing functions and values of critical areas. If development regulations allow harm to critical areas, they must require compensatory mitigation of the harm. Development regulations may not allow a net loss of the functions and values of the ecosystem that includes the impacted or lost critical areas."*

SEPA rules (WAC 197-11-768) and Section 404 of the federal Clean Water Act (CWA) both require that a sequence of actions be taken for proposed projects that will impact wetlands. SEPA is used to assess impacts and determine whether mitigation should be required. SEPA cannot substitute for critical area regulations because of the many exemptions in SEPA and the lack of specific standards [31].

Commerce's Critical Area Handbook discusses mitigation sequencing, stating that if a project will result in an impact to a critical area, the project proponent should, but is not necessarily required to, show how impacts were attempted to be avoided or minimized wherever practicable. The handbook further recommends directing mitigation, including compensatory mitigation towards salmon recovery priorities in the basin [31].

ENFORCEMENT OF GMA

The cumulative impact of development on habitat is assessed during the required periodic reviews outlined in comprehensive plans and critical area ordinances. These assessments focus on determining if existing regulations were achieving NNL.

Commerce can deny approval of the local government's proposed comprehensive plan if the plan would result in significant adverse impacts if losses are not mitigated.

Project action enforcement is delegated to local governments who are authorized to create their own enforcement processes to ensure the intent of the law and the requirements outlined in approved comprehensive plans followed.

The Growth Management Hearings Board hears and decides appeals challenging local governments' comprehensive plans and critical areas ordinances by those that feel that protections and standards required by the Growth Management Act, including the NNL standard, are not being upheld or habitats are inadequately protected.

ON-SITE VERSUS COMPENSATORY MITIGATION APPROACHES

The current version of the critical areas guidance [31] states that compensatory compensation or compensatory mitigation should only be utilized if avoidance and on-site mitigation are not possible. The guidance also states that if compensatory mitigation is not possible, then harm to the critical area must be avoided.

> *"Given the requirement to protect the functions and values of critical areas, compensatory mitigation should only be used after mitigation sequencing and it should be allowed with caution. Before allowing compensatory mitigation, a local government will need to determine that there is the ability to replace the functions and values through compensatory mitigation. Compensatory mitigation is specifically called out in the Minimum Guidelines as it applies to wetlands, and to geologically hazardous areas. The WAC is silent with respect to the three other types of critical areas. For some types of critical areas or for some types of impacts, compensation may not be possible. When compensatory mitigation is not possible, harm to the critical area from development activity must be avoided" [31].*

CONSTRUCTION PROJECTS IN STATE WATERS (CHAPTER 77.55 RCW)

BRIEF DESCRIPTION

Chapter 77.55 RCW is the law that defines when a hydraulic project approval (HPA) is required or exempt. HPAs are issued by WDFW and are designed to protect fish and their aquatic habitats in or near state waters. The law outlines the application contents, review and approval procedures, and violation remediation actions.

WAC 220-660-050(9)(c)(iii)(D) states:

> *"A complete applicati*on package for HPA must contain…a description of the measures that will be implemented for the protection of fish life, including any reports assessing impacts from the hydraulic project to fish life and their habitat, and plans to mitigate those impacts to ensure the project results in no net loss."

WDFW may only deny or provision an HPA on the grounds of fish life protection [32]. Forest practices that require a forest practice application and involve aquatic habitat are exempt from HPA requirements. Both the Forest Practices Act (chapter 76.09 RCW) and the hydraulic code statutes in chapter 77.55 RCW were amended in 2012 to integrate fish protection standards into forest practice rules. WDFW is required to review forest practice applications (FPA) when the FPA involves work in fish-bearing waters or shorelines of the state.

CURRENT STANDARDS GOVERNING THE DETERMINATION OF NNL (I.E., METRICS USED TO DETERMINE NNL)

As regulated in WAC 220-660-080, WDFW will determine if a proposed project will mitigate impacts to fish life and habitat based on available information. Impacts are evaluated by comparing the conditions of the habitat before project construction to the anticipated condition after project completion.

WDFW evaluates mitigation credits (i.e., positive impacts to fish life and habitat) and debits (i.e., negative impacts to fish life and habitat) based on a scientifically valid measure of habitat function, value, and quantity by habitat type. Compensatory mitigation must also compensate for temporal losses, uncertainty of performance, loss of habitat quantity by habitat type, and differences in habitat functions and value.

Mitigation plans, if required, must provide equal or better biological functions and values, compared to existing conditions, based on the following conditions:

- Relative value of the mitigation in terms of quality and quantity of biological functions and values,
- Compatibility with other existing management plans, regulations, and protection programs,
- Ability to address scarce functions and values in the watershed,
- Benefits to landscape and connectivity functions,
- Benefits of early implementation of mitigation measures, if applicable, and
- Significance of any negative impacts to non-target species.

HABITAT PRIORITIZATION/RANKING SYSTEM FOR MITIGATION

WAC 220-660-080 defines the mitigation requirements for HPAs and states that mitigation must achieve NNL. The guidance defines mitigation as "sequentially avoiding impacts, minimizing and rectifying unavoidable impacts, and compensating for remaining impacts."

If an experimental mitigation technique is proposed, WDFW may require advanced mitigation whereby the mitigation actions are fully functional prior to the project impacts.

ENFORCEMENT OF CONSTRUCTION PROJECTS IN STATE WATER

WDFW enforces compliance with Chapter 77.55 RCW. Compliance biologists visit sites during and after construction to assess compliance with HPA requirements. Correction requests are issued if WDFW determined that there is opportunity for landowners or contractors to correct the violating action(s). If voluntary compliance doesn't occur, WDFW may take further action, including notices to comply, stop work orders, notice of penalty, and referment to WDFW's Enforcement Program for criminal prosecution. Civil or criminal enforcement actions may include fines up to $10,000 per violation and/or 364 days in jail, as well as denial of future HPAs. There is also a system in place to report potential violation to WDFW.

ON-SITE VERSUS COMPENSATORY MITIGATION APPROACHES

RCW 77.55.241 gives WDFW permission to permit compensatory mitigation for hydraulic projects that require mitigation for the protection of fish life, where the mitigation may be most cost-effective and provide the most benefit to the fish resource if located compensatory.

WAC 220-660-080(4)(b) states that when compensatory mitigation is necessary to offset impacts, on-site mitigation, or mitigation immediately adjacent to the impact site is preferred. If on-site or adjacent mitigation is not possible, then WDFW prefers actions benefiting the same fish populations, habitat types and functions as those impacted by the project.

Under WAC 220-660-080, opponents of a project are permitted to request that a compensatory mitigation plan is adopted within a watershed that, pursuant to RCW 90.74.020, is not necessarily limited to the areas of on or near the project site.

MODEL TOXICS CONTROL ACT (CHAPTER 70A-305 RCW)

BRIEF DESCRIPTION

The Model Toxics Control Act (chapter 70A-305 RCW) directs the investigation, cleanup, and prevention of future contamination of sites that are contaminated by hazardous substances. The law directs Ecology to investigate any releases or threatened releases of hazardous substances, including but not limited to inspecting, sampling, or testing to determine the nature or extent of any release or threatened release of a hazardous materials. This law directs Ecology to act once a discharge of hazardous materials has happened or is threatened to happen if a reasonable basis to believe the report has been established. The MTCA is made up of three chapters that fall under Ecology's jurisdiction:

- The MTCA Cleanup Regulations (chapter 173-340 WAC) apply to all cleanup, including upland and groundwater.

- The Sediment Management Standards (chapter 173-204 WAC) apply only to cleanups in freshwater and marine environments.
- The Remedial Action Grants and Loans (RAG) (Chapter 173-322A WAC) establishes the requirements for grants and loans to local governments for remedial hazardous and toxic cleanup actions.

The regulations mentioned above use the standard of "no adverse effects" which is defined as "no acute or chronic adverse effects to biological resources as measured by a statistically and biologically significant response relative to reference or control."

CURRENT STANDARDS GOVERNING THE DETERMINATION OF NNL (I.E., METRICS USED TO DETERMINE NNL)

WAC 173-340-7490(3) sets procedures for conducting terrestrial ecological evaluations. The goal of this process is:

> *"The protection of terrestrial ecological receptors from exposure to contaminated soil with the potential to cause significant adverse effects. For species protected under the Endangered Species Act or other applicable laws that extend protection to individuals of a species, a significant adverse effect means an impact that would significantly disrupt normal behavior patterns that include, but are not limited to, breeding, feeding, or sheltering. For all other species, significant adverse effects are effects that impair reproduction, growth or survival."*

The MTCA Cleanup Regulations (WAC 173-204-320) set sediment quality standards for marine waters. Standards are measured against chemical composition and biological effects criteria. Biological effects criteria are based on growth, abundance, and mortality tolerance levels for different categories of biota (i.e., amphipods, benthic biota, microtox, larval and juvenile polycheate). Marine finfish rearing facilities are exempt from these sediment standards, as per WAC 173-204-412, and instead are addressed through the National Pollutant Discharge Elimination System or other permits issued by Ecology for facility operations.

The Cleanup Regulations and Sediment Management Standards (WAC 173-204) states that Ecology will determine the criteria, methods, and procedures necessary to meet the sediment standards rules on a case-by-case basis for low-salinity and freshwater standards, respectively.

The Sediment Management Standards (WAC 173-204) states that Ecology shall consider the following factors to determine if the potential discharge will violate marine, low salinity, and freshwater sediment standards:

- Discharge particle characteristics
- Discharge contaminant concentrations, flow and loading rate
- Sediment chemical concentration and biological effects levels
- Receiving water characteristics
- Geomorphology of sediments

- Cost mitigating factors
- Other factors deemed necessary by Ecology

The Sediment Management Standards do not, under any circumstances, relax the discharge permit requirements of other authorities, including the Water Pollution Control Act (chapter 90.48 RCW), the Water Resources Act (chapter 90.54 RCW) and the Federal Water Pollution Control Act.

MTCA HABITAT PRIORITIZATION/RANKING SYSTEM FOR MITIGATION

No ranking system identified within the MTCA or associated regulations.

ENFORCEMENT OF MTCA

WAC 173-340-310 details the investigation procedures once Ecology receives information that a release of a hazardous substance has occurred. WAC 173-204-400(8), in turn, allows Ecology to alter permit requirements in the event of a violation.

WAC 173-204-600 regulates sampling and plan standards and applies monitoring and clean up action plans authorized under the Sediment Management Standards regulations to sampling for sediment impact zones.

ON-SITE VERSUS COMPENSATORY MITIGATION APPROACHES

There were no details regarding on-site and compensatory mitigation approaches within the MTCA or associated regulations.

STATE ENVIRONMENTAL POLICY ACT (CHAPTER 43.21C RCW)

BRIEF DESCRIPTION

Washington established the State Environmental Policy Act (SEPA) under the premise that "each person has a fundamental and inalienable right to a healthful environment and that each person has a responsibility to contribute to the preservation and enhancement of the environment." SEPA is intended to ensure that state and local agencies consider environmental values during decision making SEPA rules are contained in WAC Chapter 197-11. SEPA is enforced by the lead agency which is determined for each project or non-project action based on criteria listed in WAC 197-11-938.

CURRENT STANDARDS GOVERNING THE DETERMINATION OF NNL (I.E., METRICS USED TO DETERMINE NNL)

The standard used by SEPA is "adverse environmental impacts." A checklist is used to gather information on proposed planning documents (non-project) or project actions. The information gathered is examined as a whole and a threshold determination is made, which then triggers further actions based on the level of impact expected, including the need for mitigation and/or advanced review with an Environmental Impact Statement.

The threshold determination is subjective and based, in part, on the physical setting, including, but not limited to, the sensitivity and value of the location as well as the magnitude and duration of the impact.

The determination also considers proposed mitigation activities and input from stakeholders and other permit requirements.

SEPA HABITAT PRIORITIZATION/RANKING SYSTEM FOR MITIGATION

Mitigation is listed in SEPA (WAC 197-11-768) as avoidance, minimization, rectification, compensation, or elimination of adverse impacts, and may also involve monitoring and a contingency plan for correcting problems if they occur. Applying SEPA standards to a proposed project may or may not require mitigation actions but it does not automatically require that the applicant apply the mitigation sequence. However, if mitigation required under existing local, state and federal rules is not sufficient to avoid, minimize, or compensate for significant impacts, additional mitigation can be applied with the use of SEPA substantive authority.

ENFORCEMENT OF SEPA

A lead agency can condition or deny proposals if they would result in significant adverse environmental impacts and reasonable mitigation measures are not sufficient to mitigate the identified impact to a non-significant level.

If an approved proposal is violated, the regulatory authority that issued the associated permit is responsible for enforcement.

ON-SITE VERSUS COMPENSATORY MITIGATION APPROACHES

SEPA does not distinguish between on-site and compensatory mitigation.

FOREST PRACTICES ACT (CHAPTER 76.09 RCW)

BRIEF DESCRIPTION

The Forest Practices Act (FPA) regulates forest practices on 12 million acres of state-owned and public forest lands. The Forest Practice Board (title 222 WAC) developed forest practice rules based on the negotiated and science-backed forest management strategies that would ensure the protection of "covered aquatic species to the maximum extent practicable consistent with maintaining commercial forest management as an economically viable use of forestlands" [35].

The Forest Practice Habitat Conservation Plan (FPHCP) states how protection for Endangered Species Act (ESA) listed fish and riparian-dependent species will be achieved on the land regulated under the FPA. "Incidental Take Permits" were issued by the National Marine Fisheries Service (NMFS) and the United States Fish and Wildlife Service (USFWS), which are responsible for the protection of the target species listed under the ESA, assuring the state that full implementation of the FPA would satisfy requirements of the ESA and protect those operating under the FPA from penalties as a result of "take of covered species" under the ESA.

Forest practice rules incorporate current fish protection standards in the rules adopted under chapter 77.55 RCW. Forest practice actions involving aquatic habitats are exempt from hydraulic permit requirements under the chapter 77.55 RCW.

CURRENT STANDARDS GOVERNING THE DETERMINATION OF NNL (I.E., METRICS USED TO DETERMINE NNL)

The standard of NNL is not mentioned in the FPA. The FPA was designed minimize the amount of take of covered species. The FPHCP requires the level of incidental take be estimated periodically. The FPHCP states:

> *"Estimating take for purposes of the FPHCP focuses on the number of habitat acres affected by the plan. The approach involves developing a hypothetical management strategy that it is assumed would have little if any measurable effects on species covered by the plan. This "minimal effects" strategy serves as a baseline for evaluating and comparing management under the FPHCP."*

Cumulative impacts of forest practices on the environment are reduced through a detailed adaptive management program, by utilizing SEPA reviews for forest practices which have a potential for a substantial impact on the environment, establishing minimum protection standards for all types of forest practice permits and alternative forest practice plans.

FPA HABITAT PRIORITIZATION/RANKING SYSTEM FOR MITIGATION

The FPA's focus on habitat protection for fish and riparian-dependent species, as well as water quality standards, results in a riparian and instream habitats being prioritized. Streams with fish habitat are provided more protections than non-habitat streams.

ENFORCEMENT OF FPA

WADNR enforces the forest practice rules under chapter 222-46 WAC. Compliance is the first tier of enforcement with stop work orders, notices to comply, and education. Enforcement actions escalate depending on success of compliance attempts up to and including a gross demeaner conviction, a fine between $100 and $1,000 or imprisonment for up to a year. Each violation and each day of the violation occurrence is constituted as a separate violation.

ON-SITE VERSUS COMPENSATORY MITIGATION APPROACHES

SEPA checklists and determinations are issued for forest practices that involve several specific conditions including unstable slopes, endangered species, forest practices meant for conversion rather than reforestation, and any watershed analysis. Chapter 222-10 WAC contains the determination standards for each category of forest practice subject to SEPA. Should proposed mitigation not adequately reduce the risk of significant adverse impacts identified in the final or supplemental environmental impact statement, then WADNR as the lead agency will disapprove the application or notification.

On-site or compensatory mitigation is not addressed within the FPA but may be inferred by reference to SEPA when certain application practices are proposed.

Table 1: Summary of NNL Legislation

Rule/Law						Enforcement/Monitoring/Metrics			Mitigation sequencing	
Law	**RCW/ WAC**	**Description**	**Jurisdiction**	**NNL Defined?**	**Standard**	**Methods**	**Metrics**	**Enforcement**	**Mitigation**	**Habitat prioritization/ ranking**
SMA	**90.58**	Prevents the inherent harm in an uncoordinated and piecemeal development of the state's shorelines	ECY	No	"Contemplates protecting adverse effects…while protecting rights of navigation and corollary rights incidental."	Planning at program level and permitting at project level.	Subjective assessment by Ecology of proposed planning regulations and processes protection of existing conditions during local government planning actions. Subjective assessment by local governments of project-level proposals based on assumptions presented by reports supplied by project proponent.	In rules only, not law.	In rules only, not law.	None mentioned.
SMP	**173-26**	Translates the broad policies of the SMA into standards for regulating shoreline uses	ECY	Yes	"Assure, at minimum, no net loss of ecological functions."	Mitigation sequencing for all development Buffers/ setbacks Restoration Plan.	Must consider, at a minimum, habitat, water quality, and water quantity. Additional indicators of changes in function are suggested but not required.	Local governments are expected to have a compliance strategy and to periodically evaluate cumulative impacts of NNL, but no particular structure nor process is required. Restoration Plan implementation is not required.	Follows SEPA requirements: *Avoid* *Minimize* *Rectify* *Reduce or eliminate* *Compensate* *Monitor*	Suggested objective of Restoration Plan includes priority restoration sites for restoration or compensatory mitigation.
SEPA	**43.21**	Ensures that environmental values are considered during decision making by state and local agencies	Lead Agency	No	43.21C.010(2): "to promote efforts which will prevent or eliminate damage to the environment and biosphere…"	Require assessment of "significant impact" and a threshold determination for gov't decisions	43.21C.240 Determined by local government. …"considers the specific probable adverse environmental impacts of the proposed actions and determines that these specific impacts are adequately addressed by the development regulations or other applicable requirements of [comprehensive plans and other regulations]"	Agency can deny government planning action if the action or proposal would result in significant adverse impacts and cannot be mitigated. Project action enforcement is delegated to local governments. Local governments have ability to create their own enforcement processes to ensure intent of the law	See Rule below.	None mentioned.
SEPA Rules	**197-11**	SEPA implementation rules	Lead Agency	No	"Adverse environmental impacts."	See law above.	See law above.	See law above.	197-11-768: *Avoid* *Minimize* *Rectify* *Reduce or eliminate* *Compensate* *Monitor*	None mentioned.
GMA	**36.70A**	Provides for growth while protecting natural resource lands and critical areas	Commerce	No	"Conservation" of habitat, the environment, productive forest, and agricultural lands, along with conserving natural resource-based industries.	Planning at program level and permitting at project level.	Undefined.	Growth Management Hearings Board.	See Rule below.	None mentioned.

Rule/Law						Enforcement/Monitoring/Metrics			Mitigation sequencing	
Law	**RCW/ WAC**	**Description**	**Jurisdiction**	**NNL Defined?**	**Standard**	**Methods**	**Metrics**	**Enforcement**	**Mitigation**	**Habitat prioritization/ ranking**
Comprehensive Plans and Development Regulations	**365-196**	GMA implementation rules	Commerce	Yes	WAC 365-196-830(4): "Development regulations may not allow a net loss of the functions and values of the ecosystem that includes the impacted or lost critical areas." WAC 365-196-830(8)(a): "When developing alternative means of protection, counties and cities must assure no net loss of functions and values and must include the best available science."	Planning at program level and permitting at project level.	Undefined.	Agency can deny government planning action if the action or proposal would result in significant adverse impacts and cannot be mitigated. Project action enforcement is delegated to local governments. Local governments have ability to create their own enforcement processes to ensure intent of the law.	Follows SEPA requirements: *Avoid* *Minimize* *Rectify* *Reduce or eliminate* *Compensate* *Monitor*	"Special Consideration" for protection and enhancement of anadromous fish habitat when developing regulations, protective measures, or requiring compensatory mitigation.
Construction Projects in State Waters **Hydraulic Code Rules**	**77.55** **220-660**	Hydraulic Code and Hydraulic Permit Applications	WDFW	No Yes	Protection of fish life. No net loss to fish life and their habitat.	Project level permitting, enforcement.	Conditions of habitat before project construction to anticipated condition after project completion. If found to result in temporal loss, uncertainty of performance, loss of habitat quantity, or difference in habitat function/value found, then mitigation required via sequence.	Well defined sequence from education to criminal violation; enforced by WDFW.	WAC 220-660-080: defines mitigation as “sequentially avoiding impacts, minimizing and rectifying unavoidable impacts, and compensating for remaining impacts"	None mentioned.
Model Toxics Control Act	**70A-305**	Directs the investigation, cleanup, and prevention of sites that are contaminated by hazardous substances	Ecology	No	"No adverse effects" to biological resources.				None mentioned.	None mentioned.
MTCA Cleanup Regulations	**173-340**	Guides upland and groundwater cleanup	Ecology	No	Protection from "significant adverse effects" that impair reproduction, growth, and survival of species.	Compliance monitoring.	173-340-410: Chemical constituents, biological testing, physical parameters.	Ecology enforces based when monitoring plan standards being exceeded. Cleanup plans are initiated, and permit requirements are adjusted.	Mitigation sequencing not mentioned. Cleanup plans are initiated to restore conditions.	None mentioned.
Sediment Management Standards	**173-204**	Guides fresh and marine water cleanup	Ecology	No	Not to exceed chemical composition and biological effects criteria	Compliance monitoring.	173-204-400: Water discharge characteristics compared to receiving water composition.	Ecology enforces based when monitoring plan standards being exceeded. Cleanup plans are initiated, and permit requirements are adjusted.	Mitigation sequencing not mentioned. Cleanup plans are initiated to restore conditions.	None mentioned.

APPENDIX C. INTERVIEW GUIDE

Interviewee Name (Affiliation):	
Interviewer Name:	
Date:	

INTRODUCTION

Thank you for meeting with us today. As you may know, the Washington Department of Fish and Wildlife has been tasked by the Legislature with assessing how to incorporate a Net Ecological Gain standard into state land use, development, and environmental laws and rules to achieve a goal of better statewide performance on endangered species recovery and ecological health.

As part of this process, we are here as part of a consulting team soliciting input from local governments, tribes, ports, and other subject matter experts throughout the report development process, and WDFW has identified you as a key partner in this conversation.

The 1-1 interviews are the first step in the stakeholder engagement process which will also include two roundtable discussions later this fall. Today's interview will be approximately 30 minutes and we have 8 questions to ask you during this time.

We will be taking detailed written notes to ensure we capture what you say and may occasionally pause to write things down or ask you to repeat something. I also want to note that your answers will be kept anonymous.

Thank you again for your willingness to share your perspective on the Net Ecological Gain standard.

Before we begin, are there any questions you want to ask related to the interview process or goal?

INTERVIEW QUESTIONS

NO NET LOSS – OUR EXISTING STANDARD

Before we dive into Net Ecological Gain, we'd like to discuss No Net Loss (NNL) which is the existing standard that is embedded in WA land use, development, and environmental laws and rules.

1. What is working with NNL? What isn't working with NNL?

ESTABLISHING A BASELINE UNDERSTANDING OF NEG

Now we are shifting to the topic of Net Ecological Gain. We've got two sets of questions related to NEG. The first set of questions focus on your overall understanding of NEG either as a policy framework or a concept. The second set of questions focus on implementation of NEG.

2. What is your current understanding of Net Ecological Gain? *This can be within the policy framework context or the concept behind Net Ecological Gain.*

IMPLEMENTATION OF NEG POLICY

Seeking to achieve Net Ecological Gain presents opportunities and challenges in terms of its implementation. The next few questions will focus on gaining your perspective on implementation of Net Ecological Gain policies related to land use, development, or environmental rules and laws.

3. What are the biggest near-term opportunities to implement a NEG policy?

4. What are the biggest barriers to implement a NEG policy?

5. Do you see a role in integrating salmon recovery and land use planning to achieve net ecological gain?

6. What are some components of the policy that you would need to see to support a policy on Net Ecological Gain?

7. Do you think there should be different standards in implementing NEG policies for private and public lands/projects? If so, what?

CLOSING

Thank you so much for your time and insights into the concept of Net Ecological Gain. Before we end,

8. Is there something you'd like to add that we haven't asked yet?

Please do not hesitate to reach out with follow-up questions or comments you have about any of the topics we covered today.

APPENDIX D. WSAS 2022 REPORT ON NET ECOLOGICAL GAIN

WASHINGTON STATE
Academy of Sciences
Science in the Service of Washington State

Report on Net Ecological Gain

Prepared for the Washington State Department of Fish and Wildlife

July 2022

WSAS Committee on Net Ecological Gain

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Seattle, WA

About the Washington State Academy of Sciences

The Washington State Academy of Sciences (WSAS) was requested by Governor Christine Gregoire and authorized by the Washington State Legislature in 2005. WSAS is a not-for-profit organization of Washington State's leading scientists and engineers dedicated to serving the state. Members are elected by their peers for outstanding contributions to research. Dr. Roger Myers is the President.

Formed as a working academy, not an honorary society, WSAS is modeled on the National Academies of Sciences, Engineering, and Medicine. WSAS provides independent, objective analysis and advice to the State and conducts other activities to solve complex problems and inform public policy decisions. WSAS also encourages education and research, recognizes outstanding contributions to knowledge, and increases public understanding in matters of science and engineering.

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Committee on Net Ecological Gain:

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Heather Burpee, University of Washington
Ken Currens, Northwest Indian Fisheries Commission
Heida Diefenderfer, Pacific Northwest National Laboratory and University of Washington
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This document contains two reports in their entirety, which should be cited separately.

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INTRODUCTION

The Washington Department of Fish and Wildlife (WDFW) requested that the Washington State Academy of Sciences (WSAS) inform its work on the development of a net ecological gain (NEG) standard for public projects as part of the response to a proviso contained within Engrossed Substitute Senate Bill 5092 (2021).

WSAS convened a committee of scientific and technical experts to conduct this work. The scope of work for the committee was to develop a definition, goals, objectives, and performance metrics for the net ecological gain standard, assess how sufficient existing standards have been in achieving endangered species recovery, and make recommendations about monitoring and indicators for no net loss and net ecological gain. The scope of work was divided into two report chapters.

The committee completed two separate report chapters and transmitted them to WDFW. This document contains the two reports in their entirety; the content of the chapters should still be cited separately.

The first report chapter synthesizes the committee's perspectives on a proposed definition for net ecological gain, considerations for defining net ecological gain, and goals and objectives for achieving net ecological gain. The committee interpreted the charge as producing a definition of net ecological gain that would be relevant to Washington State, as well as providing examples of specific goals and objectives for how the definition should be applied to ecosystems or projects.

The second report chapter focuses on (1) assessing whether and why existing standards of ecological protectiveness, such as no net loss (NNL) standards, have been sufficient or insufficient to protect ecological health and achieve endangered species recovery and (2) providing recommendations for developing: performance metrics for the NEG standard, indicators to assess NNL and NEG, establishment of a monitoring system, and incorporation of climate science predictions into NNL and NEG standards. The committee also presents suggestions for subsequent activities that may facilitate next steps toward successful implementation of NEG in Washington State.

The committee hopes that this report serves as a useful reference for Washington State agencies, tribes, and legislators.

WSAS COMMITTEE ON NET ECOLOGICAL GAIN

Ronald Thom (*Chair*)

Dr. Ron Thom is Staff Scientist Emeritus in the Coastal Sciences Division of the Pacific Northwest National Laboratory, where he led the Coastal Ecosystem technical group at the Marine Sciences Laboratory until retirement. His research is focused on ecosystem restoration and adaptive management in coastal and estuarine ecosystems. Dr. Thom has directed approximately 200 multidisciplinary ecological studies and authored five book chapters, around 100 peer reviewed papers, and hundreds of reports. He also served on numerous professional committees and panels; including chairing the Technical Advisory Committee of the EPA's Puget Sound Estuary Program, serving on the Expert Regional Technical Group to restore ecosystem health and salmon in the Columbia River Estuary Ecosystem Restoration Program, being a member of an EPA Science Advisory Board panel to review the Great Lakes Restoration Program, and serving on a National Academy of Science, Engineering, and Medicine panel on recovery of the Gulf of Mexico coastal ecosystem following the 2010 Deepwater Horizon oil spill. Dr. Thom was appointed by the Washington Governor to the Northwest Straits Commission and serves as a Senior Science Advisor to the Puget Sound Partnership. Dr. Thom is an elected Fellow in the American Association for the Advancement of Science. He was elected to the Washington State Academy of Sciences and was on the Board of Directors for several years before serving as president of the Academy from 2018-2020. Dr. Thom has a PhD from the University of Washington School of Aquatic and Fishery Sciences.

Heather Burpee

Heather Burpee is a Research Associate Professor and the Director of Education and Outreach at the University of Washington's Integrated Design Lab. She is an expert in high-performance buildings that reduce energy and promote healthy indoor environments. Her research includes tracking health impacts and synergies between environmental quality, natural systems, sensory environments and energy efficiency. Some of her efforts in this area include creating roadmaps and protocols for performance-based design, tracking, and auditing for hospitals, higher education, and commercial buildings. Ms. Burpee consults regularly with design teams to implement high-performance buildings and she also develops curriculum and other educational opportunities for various groups on this topic. Ms. Burpee has a Master of Architecture degree from the University of Washington College of Built Environments.

Ken Currens

Dr. Ken Currens is the manager of the Conservation Planning Program for the Northwest Indian Fisheries Commission. He has expertise in population genetics, ecology, phylogeography, conservation strategy and planning, risk assessment, and endangered species. In his current role, Dr. Currens coordinates and develops annual and long-term research and conservation plans for Western Washington Indian Tribes

and serves as the technical liaison for the tribes with the federal government, state agencies, and non-governmental organizations on conservation issues. He also contributes to endangered species and ecosystem recovery planning and manages a research program to provide support for recovery planning of fish species listed under the Endangered Species Act. Dr. Currens previously served as the Science Director for the Puget Sound Partnership. He has a PhD in population genetics, fishery science, and statistics from Oregon State University.

Heida Diefenderfer

Dr. Heida Diefenderfer is an Earth Scientist with the Energy and Environment Directorate of the Pacific Northwest National Laboratory, at PNNL's Marine and Coastal Research Lab in Sequim, WA. A restoration ecologist, Dr. Diefenderfer conducts long-term and large-scale ecological and geomorphological research across a variety of terrestrial and aquatic ecosystems with a focus on wetlands, forests, marshes, and submerged vegetation. This work spans several areas of applied research, including spatial planning, resilience, climate adaptation, endangered species recovery, and blue-carbon experimentation and field data development for Earth systems modeling. Dr. Diefenderfer's ongoing work includes research and adaptive management for the recovery of Endangered Species Act-listed fish as mitigation for energy infrastructure, and evidence-based assessment of large-scale ecosystem restoration. She also serves as chair of the Washington Natural Heritage Advisory Council. Dr. Diefenderfer received her PhD in Forest Resources and Ecosystem Analysis from the University of Washington and is a Faculty Fellow at the UW College of the Environment.

Tim Essington

Dr. Tim Essington is a Professor at the School of Aquatic and Fishery Sciences and former Director of the Center for Quantitative Sciences and the Interdisciplinary Quantitative Ecology & Resource Management Graduate Program at the University of Washington. His research uses quantitative approaches to understanding predator-prey and food web interactions among fish and other organisms in marine, estuarine, and freshwater habitats. He also investigates the conservation benefits of fisheries policy tools and how to apply risk-based approaches to decision making. Dr. Essington has served as an Editor for several scientific journals and as a member of multiple scientific advisory boards and panels, including for the Marine Stewardship Council, Puget Sound Partnership, Washington Marine Spatial Planning, the Ecosystem Science and Management Working Group with NOAA, and the National Center for Ecological Analysis. He was a Pew Marine Conservation Fellow in 2011, was awarded the Oscar Sette Award by the American Fisheries Society in 2017 for Outstanding Marine Fishery Biologist, and was appointed as an American Fisheries Society Fellow in 2021. He was awarded the UW College of the Environment Outstanding Research and Outstanding Teaching awards in 2018 and 2021, respectively. He held the Wakefield Endowed Professorship in Ocean and Fishery Sciences between 2008-2013 and again from 2021-2026. Dr. Essington has a PhD in Zoology from the University of Wisconsin-Madison.

Anand Jayakaran

Dr. Anand Jayakaran is a Professor with Washington State University based at the Puyallup Research and Extension Center. His role is to meet education and research needs in a region experiencing the impacts of rapid urbanization, a changing climate, and increasingly diverse communities. He develops strategies to manage water resources using Green Stormwater Infrastructure and ecological engineering principles. Ani's program aims to positively influence stormwater management decisions that impact traditionally underserved Black, and Indigenous communities, people of color, and lower-income groups. He holds bachelor's and master's degrees in Civil Engineering, a doctoral degree in Agricultural & Biological Engineering, and is a professionally licensed civil engineer in Washington.

Mary Ruckelshaus

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WASHINGTON STATE
Academy of Sciences
Science in the Service of Washington State

Net Ecological Gain Definition, Goals, and Objectives

Prepared for the Washington State Department of Fish and Wildlife

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Net Ecological Gain Definition, Goals, and Objectives

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I. INTERPRETATION OF CHARGE

The Washington Department of Fish and Wildlife (WDFW) requested that the Washington State Academy of Sciences (WSAS) inform its work on the development of a net ecological gain (NEG) standard for public projects as part of the response to a proviso contained within Engrossed Substitute Senate Bill 5092 (2021). WSAS convened a committee of scientific and technical experts (referred to in this document as "the committee") to conduct this scope of work. The full scope of work for the committee was to develop a definition, goals, objectives, and performance metrics for the net ecological gain standard, assess how sufficient existing standards have been in achieving endangered species recovery, and make recommendations about monitoring and indicators for no net loss and net ecological gain.

The committee interpreted the charge as producing a definition of net ecological gain relevant to Washington State, as well as providing examples of specific goals and objectives for how the definition would be applied to ecosystems or projects. The committee was informed that watersheds are of particular interest to WDFW, which has a goal of achieving resilient, self-perpetuating, viable ecosystems and biodiversity across the state. Similarly, the committee interpreted the charge as identifying performance metrics that are relevant across the state, although it is expected that these may vary according to ecological community types. The committee aimed to maintain the level of detail and rigor allowed by the science while meeting the task set out by WDFW by developing a report comprising two chapters.

This first report chapter synthesizes the committee's preliminary perspectives—developed since its first meeting on November 15, 2021—on a proposed definition for net ecological gain, considerations for defining net ecological gain, and goals and objectives for achieving net ecological gain. The subsequent chapter focuses on recommendations for metrics, monitoring, and indicators for net ecological gain standards and provides an assessment of no net loss.

II. DEFINITION OF NET ECOLOGICAL GAIN

Preamble

Earth's natural systems have been profoundly affected by human activities, particularly over the past century when human population growth and industrialization (Figure 1) have transformed terrestrial and aquatic ecosystems. These transformations have often led to habitat loss and degradation for species that have cultural or economic roles recognized by humans. The balance between population and economic growth and management of ecosystem health is complex and dynamic. Specifically, as a key part of coupled human-natural systems, people are agents of change who affect the biophysical condition of ecosystems but also simultaneously (1) require functional ecosystems to provide life-supporting services that affect our well-being and (2) alter our behavior in response to ecosystem dynamics.

Net ecological gain (NEG) must be viewed in this larger context. In many cases, applications of NEG may occur in ecosystems that are already highly impacted and degraded by prior human activity. Thus, it may not always be feasible to return these ecosystems to states that resemble those of a century ago. Additionally, the effects of atmospheric greenhouse gases on climate, hydrologic patterns, and ocean chemistry will continue to grow, even under the most optimistic scenarios (Pörtner et al., 2022), meaning that ecosystems require the capacity to absorb or adapt to those effects without undergoing irreversible or deleterious transformation.

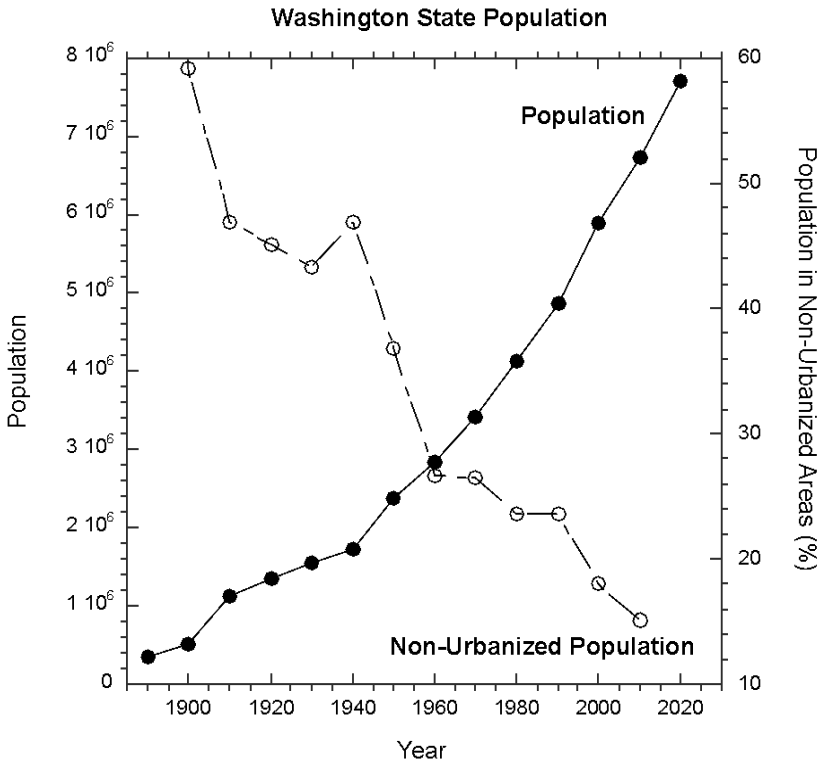


Figure 1. *Between 1890 and 2020, the population of Washington State grew from approximately 360,000 to 7.7 million people, of whom more than 84% (about 6.6 million) now live in urban areas (Iowa Community Indicators Program, 2022; U.S. Census Bureau, 2010). The population is expected to continue growing over the next decade. With continued urbanization, suburbanization, and sprawl come associated loss and degradation of natural habitats in those areas and the ecosystem services they provide. Net ecological gain is intended to buffer these changes.*

Conceptually, one can view NEG in the context illustrated in Figure 2. Although the health of many ecosystems is degraded compared to historic baselines, thoughtful infrastructure design and other development in terrestrial and aquatic systems can still lead to improvements in ecosystem status. Moreover, we judge these improvements based on a comparison to a theoretical future in which such developments and designs are not implemented.

While conceptually simple, deriving practical and specific guidelines for implementing net ecological gain is difficult in practice. This is because social-ecological systems are inherently complex and affected

by a variety of human activities and sociopolitical drivers. These complexities have led to frequent reformulations within the scientific community regarding how terms like ecosystem health and ecosystem integrity are defined.

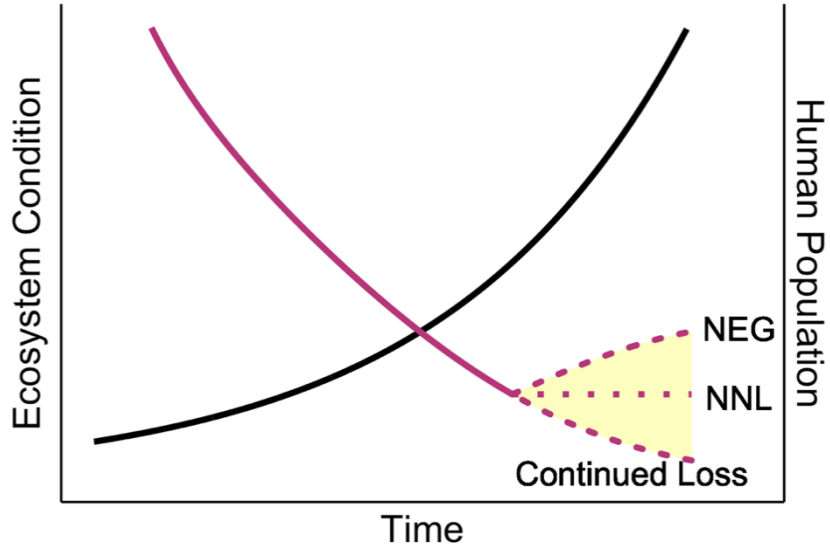


Figure 2. *Conceptual relationship between changes in population and ecosystem condition and the corresponding effects of implementing NEG or no net loss (NNL) vs. continued degradation of the ecosystem condition under current scenarios. Human population is depicted in black; ecosystem condition is in purple. This conceptual figure is based on population and ecosystem trends identified by the Washington Biodiversity Council (2007). Note that the human population is no longer increasing exponentially in the U.S. but shifting consumption choices may have similarly negative ecosystem impacts.*

Three key characteristics or elements of ecosystems must be recognized to frame definitions of net ecological gain:

- **Ecosystem**: The collection of fauna and flora and the key physical, biological, and chemical drivers that influence them in a specific location
- **Ecosystem Structure**: The biological, physical, and chemical constituents, how these constituents are organized and linked to one another, and the size of the ecosystem
- **Ecosystem Processes**: Feedbacks among ecosystem structure and composition occur through a series of processes, such as nutrient or water cycling, many of which benefit people through the production of goods and services.

The combined dynamic interaction of ecosystem components, structure, and processes creates the emergent properties of ecosystems that are relevant for ecosystem protection and restoration and that can maintain benefits to people. Some common emergent properties include:

- Biodiversity, defined as "the variability among living organisms from all sources including terrestrial, marine and other aquatic ecosystems and the ecological complexes of which they are part" (National Infrastructure Commission, 2021; Wilson, 1988)
- Resilience and adaptive capacity—the ability to cope with and adapt to changing conditions (e.g., climate change, sea level rise, wildfire, flooding, water quality)
- Productive habitat for culturally or economically valuable species
- Ecological regulation of air, soil, and water quality

Due to the variety of situations under which NEG could be considered or implemented in the future, any definition of net ecological gain that attempts to be applicable in all situations would risk being cumbersome, overly general, and not necessarily appropriate to guide decision-making. For that reason, the committee chose to define net ecological gain in terms that are specifically applicable to Washington State.

Definition

WSAS convened a committee of scientific experts to review the existing science and develop a definition of net ecological gain. The committee constructed this definition primarily from two existing definitions of NEG (Apex Goal Task Force, 2020; National Infrastructure Commission, 2021), also articulating additional components and considerations.

The proposed definition for NEG in the state of Washington is as follows:

> **Net ecological gain means that after development, there is an increase in biodiversity or resilience that improves the delivery of valued ecosystem functions in the affected ecosystem.**

Applying this definition of NEG will be contextual in nature and depend on the characteristics of the given social-ecological system. External considerations, such as the type of ecosystem (e.g., marine, nearshore, freshwater, prairie, shrub steppe—see Rocchio & Crawford, 2011), biogeographic region, and legacy conditions from human development and natural catastrophes shape both the biophysical and human conditions of the ecosystem. For any given intervention, the priority ecosystem objectives, attributes, and current and likely future stressors (e.g., climate impacts) will also vary. For example, ecosystem composition, structure, processes, and functions will vary depending on the type of ecosystem. These elements will, in turn, produce different kinds of goods and services that affect human well-being. There is also a wide variety of attributes that may be enhanced as part of NEG. Table 1 lists examples of such attributes, categorized by ecosystem element or property. Depending on values and the institutions where development is proposed, different individual and collective choices need to be considered for NEG to succeed. Likewise, explicit consideration of the spatial and temporal extent of post-construction restoration, maintenance, and monitoring will be necessary.

Several assumptions are also implicit within this proposed definition of NEG. First, some level of ecosystem degradation is coincident with meeting the demands created by humanity, such as the needs

for sustenance and materials (Locke et al., 2021). However, ecosystem degradation ultimately results in reduced ecosystem services, thereby harming the people who rely on them. Ecosystem stewardship that aims to minimize degradation and increase key ecosystem attributes through recovery planning, conservation efforts, and restoration activities will facilitate the realization of NEG as defined in this report.

Table 1. *Examples of some key components or attributes of socio-ecological systems within Washington State that may be enhanced under NEG*

Ecosystem element or property	**Attributes that may be enhanced**
Ecosystem structure	● area/spatial extent ● spatial structure (e.g., continuity, connectivity) ● temporal structure ● habitat heterogeneity and complexity ● composition (e.g., native species abundance and distribution)
Biodiversity	● the number and relative abundance of viable species ● population status and trends for native flora, fauna, and fungi relative to historical conditions ● genetic diversity (including varieties) ● diversity of communities and ecosystems ● conservation and/or prevention of local extinction of native species
Ecosystem processes	● hydrology and water cycles ● nutrient cycling ● fluxes of mineral and organic materials ● primary and secondary productivity ● decomposition ● habitat formation ● species interactions ● species movements ● disturbance regimes
Ecosystem functions and services	● recreation ● flood and erosion regulation ● water provision and regulation ● distributed stormwater and runoff management, especially via green stormwater infrastructure ● elimination, reduction, or mitigation of environmental stressors, such as toxins, pollutants, or non-native species, including pollution filtration processes that reduce pollutants to downstream water bodies ● food and fiber production and sovereignty ● pollination ● soil health ● regulation of infectious agents and pests ● climate regulation through carbon storage and sequestration ● cultural and spiritual interactions and benefits ● treaty rights ● added green space or urban greening that provides physical and mental health benefits, especially for under-resourced communities and other vulnerable groups

	● promotion of equity and protection of human well-being through livelihoods, economic returns, community diversity, and sense of place ● other ecosystem processes that provide goods and services that contribute to economies, satisfaction of human needs, and health, either directly or indirectly
Ecosystem resilience	● ability of the ecosystem, including urban ecosystems, to absorb disturbances and reorganize to maintain critical functions ● ability of the ecosystem, including urban ecosystems, to withstand shocks and stresses and recover from them so that the system does not surpass irreversible thresholds

Net Ecological Gain and the Mitigation Hierarchy

The goal of net ecological gain falls within a hierarchy of action steps—known internationally as the mitigation hierarchy—that is intended to limit the impacts of development on biodiversity and ecosystem functions relative to a predetermined reference condition (Business and Biodiversity Offsets Programme, 2018; Maron et al., 2018). Understanding the theoretical and practical challenges learned from use of the mitigation hierarchy over the last 15 years is critical for developing a net ecological gain standard for Washington State.

Sequentially, the action steps of the mitigation hierarchy are applied to evaluate a proposed activity or intervention and relocate or redesign the intervention so that it can: 1) avoid, 2) minimize, 3) remediate, and/or 4) offset negative impacts on ecosystems and the net benefits they provide (Figure 3; Arlidge et al., 2018; Wende et al., 2018). Although there is often more interest from developers in focusing on the latter steps, the conservation benefits from the first steps are expected to be greater than those associated with the subsequent steps because uncertainty of success increases as the steps progress (Arlidge et al., 2018).

The first of the four steps of the mitigation hierarchy—avoid—focuses on assessing impacts prior to project design and development and selecting an alternative site for the development with fewer potential impacts (Phalan et al., 2018). Impacts to biological, ecological, or social elements that are deemed irreplaceable or that will require long restoration times (e.g., to endangered endemic species, iconic wilderness, unique archaeological sites, fragile coral systems) by definition cannot be offset to provide net gain because gains somewhere else are not comparable in type or amount (Arlidge et al., 2018; however, see discussion on comparability in Pope et al., 2021). The second step—minimize—involves using the most environmentally friendly design or construction practices available. The third step—remediate—emphasizes replacing or remedying the loss of biodiversity and ecosystem functions at the same location of the development or project. Finally, the fourth step—offset—involves improvement in biodiversity and ecosystem functions in another location that creates positive impacts that are equal to or greater than the residual impacts not addressed by the first three steps. Without offsets, net gain is generally impossible because not all impacts can be addressed by the first three steps. Offsets are accomplished either by protecting against an anticipated loss at another location through the removal of threats or by enhancing and restoring an already degraded location (Maron et al., 2012). Offsets are the most uncertain and controversial step because they require the assumption that impacts at a site can be accurately measured and appropriately balanced by actions elsewhere (Maron et al., 2016).

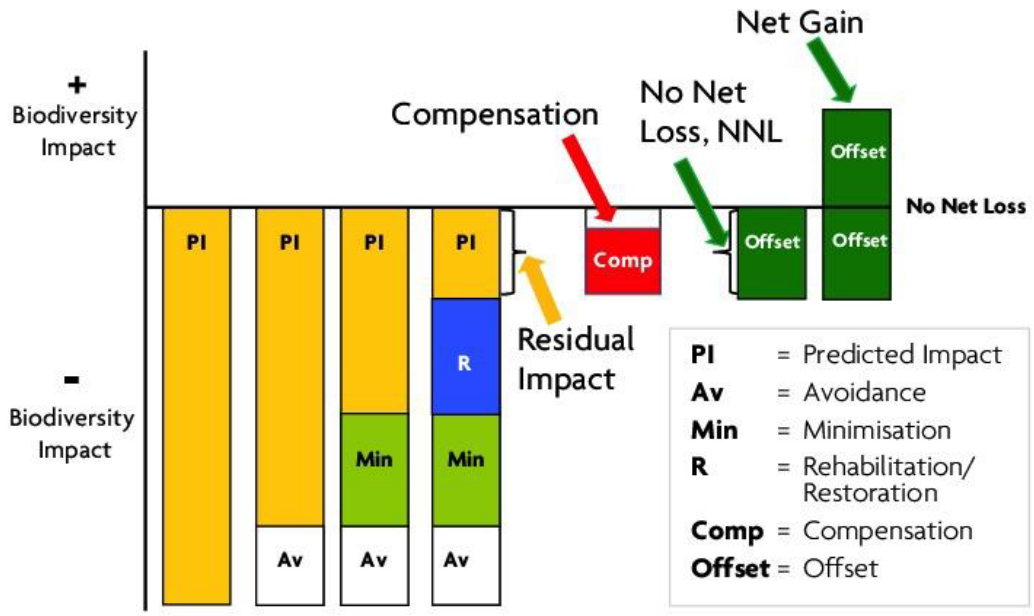


Figure 3. *Steps of the mitigation hierarchy for biodiversity impacts leading to net gain (Business and Biodiversity Offsets Programme, 2018, adapted from Rio Tinto and Govt. of Australia)*

The theoretical and practical challenges to successfully implementing the mitigation hierarchy have been well described elsewhere (e.g., Arlidge et al., 2018; Bull et al., 2014; Moilanen & Kotiaho, 2018; Tallis et al., 2015). Many of these challenges are associated with failure to resolve conceptual issues, inappropriate implementation of the hierarchy, inadequate monitoring, inequitable distribution of impact and offset, and lack of compliance. Two key issues deserve emphasis in a discussion of the mitigation hierarchy and its relevance to net ecological gain. One is the choice of reference scenarios for evaluating success because the concept of net gain is meaningless unless it is specified relative to alternative possible scenarios. Developing and agreeing on these scenarios is challenging, however, due to uncertainties associated with making projections and opportunities for gaming outcomes (Ruhl & Salzman, 2011). The other key issue is the importance of setting targets and monitoring outcomes. In this case, choosing appropriate metrics to ensure net gain is achieved is a critical and context-specific step. Metrics need to be 1) sensitive and predictably responsive to anticipated development impacts, 2) informative at different spatial scales, 3) feasible to monitor, and 4) cost effective. These topics will be addressed in more detail in the subsequent chapter by the committee.

III. CONSIDERATIONS FOR IMPLEMENTING NET ECOLOGICAL GAIN

The implementation of the proposed NEG definition requires an expanded operational definition to specify the attributes of the system that will be improved. The committee recommends considering the following factors to promote clarity and successful implementation of NEG.

Level of Specificity

The definition must be specific enough to readily address unique individual ecosystems, yet broad enough to be operationalizable for a wide range of diverse ecosystems and contexts across the state. Implementation of the definition must also encompass the built environment and address various aspects of human health and well-being, including economic and cultural consequences, physical and mental health, environmental justice, and intergenerational equity (Díaz et al., 2020).

Geographical Scale

The committee recommends a focus on NEG at the project level but urges that potential changes in the ecosystem attributes and services outlined in Table 1 also be considered within the context of the broader system (e.g., the watershed within which a site occurs and the body of water into which it discharges), which is likely subject to larger-scale processes affecting long-term NEG outcomes (Griffiths et al., 2019). Impacts to a particular site can affect other locations. Thus, implementation of a net ecological gain standard must include an integrated assessment of how individual sites fit into overarching ecosystems and landscapes, including how impacts of different projects could potentially interact with one another (Diefenderfer et al., 2021; National Academies of Science, Engineering, and Medicine, 2022).

Time Scale and Baseline Measurements

Effects of development or other interventions on a site may occur immediately or manifest well after the conclusion of a project. For this reason, monitoring by taking consistent measurements over time, including beyond the timespan of the project, is necessary to ensure that long-term gains result from implementation of the NEG standard. Implementing the NEG framework therefore requires identification of and accounting for potential prolonged human intervention and external resources to ensure key ecosystem processes are maintained. Further, the consideration of cumulative effects across time, including anticipated future effects–whether beneficial or detrimental–is crucial for ensuring successful NEG (Diefenderfer et al., 2021).

Based on findings from past practice (National Research Council, 2001) and the understanding of ecosystem response times (Carpenter & Turner, 2001), mitigation timeframes that are restricted to the duration of the activity will typically fail to advance ecosystem resilience. Rather, NEG requires that indicators be measured regularly against a baseline measurement from a specific point in time (Maron et al., 2021), ideally against the aforementioned reference condition. However, ecosystems are dynamic, so even some baseline measurements will have already been influenced by the widespread and historical impacts of human activity.

Notably, based on extensive documentation of impacts to date, researchers anticipate that climate change and the projected growth and consumption patterns of the human population will continue to accelerate impacts to ecosystems. These factors must be accounted for, and goals must be adjusted accordingly in instances where the aim is to restore a system (Centers for Disease Control and Prevention, 2021; Locke et al., 2021).

IV. GOALS AND OBJECTIVES FOR NET ECOLOGICAL GAIN

The committee articulated the following general goals for net ecological gain, each with corresponding objective(s) for desired outcomes. These intended outcomes would achieve improvements to the natural environment and fortify ecosystem resilience.

Sustain and Recover Biodiversity

Biodiversity is a key measure of an ecosystem's overall condition. To promote net ecological gain for biodiversity through the lens of enhancing ecosystem integrity, (1) the species diversity and genetic diversity of the biological community must be preserved or enhanced, (2) vulnerable species must be protected, and (3) viable populations must be maintained (Díaz et al., 2020; Stange et al., 2021). Washington contains an extensive array of ecosystems (Washington State Department of Natural Resources, 2022). Previous work has established methods to measure the ecological integrity of these ecosystems (Rocchio & Crawford, 2011; Rocchio et al., 2020a, 2020b). Some of these methods can also be applied to measure the progress of NEG during and after projects to ensure the protection and/or recovery of native species associated with impacted ecosystems.

Objective: Protect, conserve, restore, and enhance ecosystems to sustain biodiversity. Safeguarding biodiversity requires acknowledgement of the strong interconnections of life at all hierarchical levels of an ecosystem. It also calls for the articulation of required net outcomes and related methods of measurement pertaining to species populations, habitat ranges, and functions that are key to adaptation and persistence (Maron et al., 2021).

Protect and Enhance Natural Capital, Ecosystem Services, and Human Well-Being

Society relies on the natural environment for a variety of benefits essential to human survival, such as the provision of food, breathable air, and clean water. Species, habitats, and other ecosystem attributes constitute natural capital assets (Díaz et al., 2020). The flow of benefits from ecosystem structures and processes can be quantified by accounting for beneficiaries; some examples of this process may include identifying the number and demographic characteristics of people affected or calculating monetary values (e.g., avoided damages, livelihood support, food prices). Collectively, these ecosystem assets and flows are referred to as ecosystem services (National Infrastructure Commission, 2021).

Given the multifaceted relationship between humans and their natural surroundings, the well-being of humanity is intimately tied to ecosystem health. Thus, the concept of NEG extends beyond purely ecological implications to also include socioeconomic and human health considerations (Breslow et al., 2017; Griffiths et al., 2019). Economies from the global to local scale depend upon a wide variety of renewable and non-renewable resources that stem from natural capital (Locke et al., 2021). Additionally, two critical aspects of human well-being relate directly to ecological management: the ability to benefit from natural resources through both use and non-use values and the capability to thrive in one's surroundings (Breslow et al., 2017). For example, human physical health is affected by provision of air and water quality amid development projects, and mental health is affected by the amount of green space experienced. Both physical and mental health are key components of one's capacity to thrive in one's surroundings (Centers for Disease Control and Prevention, 2021).

Griffiths et al. (2019) proposed a "no worse-off principle" regarding the human health aspect of no net loss. According to this principle, the well-being of those affected by development projects must be prioritized as a component of NEG, with the outcome being equal to or better than their level of well-being prior to the project (Griffiths et al., 2019). Typically, underserved or impoverished groups are most affected by ecological loss, with wealthier members of the same community disproportionately benefiting through mitigation actions. It is important that those impacted by a project perceive that their well-being matches or exceeds what it was prior to the project. Further, special attention must be given to ensuring that vulnerable communities who may be disproportionately impacted are treated equitably and that effects on future generations are considered to promote intergenerational equity (Griffiths et al., 2019).

Objective: Maintain natural capital assets, which include components of the ecosystem composition such as habitat and species, so that they retain their ability to provide current or improved levels of ecosystem services and the resulting flows of benefits to people into the future.

Objective: Apply the mitigation hierarchy (which could include social compensation, for example) to ensure that affected communities emerge from the project "no worse-off" than they were before. Environmental justice and intergenerational equity are key considerations in determining fairness in social impacts (Griffiths et al., 2019).

Strengthen Ecosystem Resilience

By definition, a landscape may be composed of more than one ecosystem type. Activities at the project or site level that are incongruent with the overarching landscape can destabilize natural landscape-scale processes; therefore, it is critical to strengthen the resilience of ecosystem composition, structure, and processes at the ecosystem level. For example, increased resilience to natural disasters and human impacts can occur through ecosystem-based management and integrated landscape-scale planning.

Anthropogenic greenhouse gas emissions are another factor affecting resilience, with notable outcomes including dramatic increases in air and water temperatures, increased frequency of wildfires and floods, acidification of state waters, and loss of glacier and snowpack water reserves (Shukla et al., 2022). Revegetation and restricted degradation of ecosystems aid in reducing carbon emissions and thus support the mitigation of climate change impacts (Locke et al., 2021). Intact and restored ecosystems also can confer significant climate adaptation benefits through provision of ecosystem services, as described above. Because it affects all aspects of ecological integrity, from performance measurements to ecosystem and landscape resilience, climate change is an essential consideration in implementing the NEG standard. Urban ecosystems also have related resilience components within their own contexts (e.g., McPhearson et al., 2015).

Objective: Contextualize NEG efforts to the project site and larger scales to consider effects and the actions that are needed to confer resilience through larger-scale processes.

Objective: Foster greater ecosystem resilience by anticipating uncertainty around climate change impacts and incorporating expected impacts on the ecosystem into the design of mitigation and adaptation actions, including protection and restoration.

Objective: Protect against negative ecological impacts that result from safeguards against natural processes that are considered hazardous, such as flooding, wildfires, and landslides. Rather than attempts to prevent these natural processes, these occurrences must be accommodated and managed.

Objective: Protect and restore ecosystem-forming and maintaining processes (e.g., hydrology, sediment dynamics) that are impaired as a result of development projects.

Monitor and Record Best Practices

To continually improve the implementation of NEG, lessons learned must be captured and publicly disseminated according to best practices, such as the FAIR principles: Findability, Accessibility, Interoperability, and Reuse of digital assets (Wilkinson et al., 2016). This aspect of ecological management will significantly advance the ability of scientists and communities to contribute to increasing the success of future actions related to NEG. Such documentation requires a strong public commitment to structured approaches to compile and track project outcomes and findings, as well as a commitment to ongoing process improvement through continual implementation of best practices (Biber, 2011; Conservation Measures Partnership, 2020).

Objective: Compile and track the baseline measurements, subsequent periodic measurements, and observations or implications for future actions that emerge from these measurements.

Summary of Goals and Objectives

Table 2. *Summary of goals and corresponding objectives for net ecological gain*

Goal	Objectives
Sustain and Recover Biodiversity	● Protect, recover, and sustain native species biodiversity to enhance ecological integrity
Protect and Enhance Natural Capital, Ecosystem Services, and Human Well-Being	● Maintain and improve natural capital assets (e.g., habitats, species) so that they retain their ability to provide current or improved levels of ecosystem services and the resulting flows of benefits to people into the future ● Apply the mitigation hierarchy to ensure that affected communities emerge from the project “no worse-off” than they were before
Strengthen Ecosystem Resilience	● Contextualize NEG efforts to the project site and larger scales to consider effects and the actions that are needed to confer resilience through larger-scale processes ● Foster greater ecosystem resilience by anticipating uncertainty around climate change impacts and incorporating expected impacts on the ecosystem into the design of mitigation and adaptation actions ● Protect against negative ecological impacts that result from safeguards against natural processes that are considered hazardous, such as flooding, wildfires, and landslides ● Protect and restore ecosystem-forming and maintaining processes that are impaired due to development projects

Monitor and Record Best Practices for NEG	● Compile and track the baseline measurements, subsequent periodic measurements, and observations or implications for future actions that emerge from these measurements in a manner that is publicly accessible and usable for the long term

V. CONCLUSION

Net ecological gain is an approach aimed at reversing the human-associated degradation and loss of natural ecosystems and the species and services of those ecosystems. It recognizes that substantial human disturbance of ecosystems has occurred and will continue, while providing an approach that takes advantage of redesign and redevelopment to improve ecological functions, services, biodiversity, and resilience. Along with improving environmental conditions, realized NEG can improve human health and well-being. NEG is a simple concept but presents scientific, engineering, and human-based challenges. Having clear goals and objectives will guide implementation of an NEG standard. There are project examples of NEG in Washington State and internationally that demonstrate what can be achieved by creating strong operational definitions and following clearly outlined goals. The following chapter from the committee will focus on recommendations for metrics, monitoring, and indicators for a net ecological gain standard and provide an assessment of no net loss.

VI. REFERENCES

Apex Goal Task Force. (2020). *Apex Goal Task force on Target 1 "no net loss/net gain" meaning and principles*. A Global Goal for Nature. https://www.naturepositive.org/en/resources

Arlidge, W. N., Bull, J. W., Addison, P. F., Burgass, M. J., Gianunca, D., Gorham, T. M., Jacob, C., Shumway, N., Sinclair, S. P., & Watson, J. E. (2018). A global mitigation hierarchy for nature conservation. *BioScience, 68*, 336–347.

Biber, E. (2011). The problem of environmental monitoring. *University of Colorado Law Review, 83,* 1.

Breslow, S. J., Allen, M., Holstein, D., Sojka, B., Barnea, R., Basurto, X., Carothers, C., Charnley, S., Coulthard, S., Dolšak, N., Donatuto, J., García-Quijano, C., Hicks, C. C., Levine, A., Mascia, M. B., Norman, K., Poe, M., Satterfield, T., St. Martin, K., & Levin, P. S. (2017). Evaluating indicators of human well-being for ecosystem-based management. *Ecosystem Health and Sustainability, 3*(12), 1–18.

Bull, J. W., Gordon, A., Law, E. A., Suttle, K. B., & Milner-Gulland, E. J. (2014). Importance of baseline specification in evaluating conservation interventions and achieving no net loss of biodiversity. *Conservation Biology, 28*(3)*,* 799–809.

Business and Biodiversity Offsets Programme. (2018). *Working for biodiversity net gain: An overview of the Business and Biodiversity Offsets Programme (BBOP) 2004–2018*. https://www.forest-trends.org/bbop_pubs/overview2018

Carpenter, S. R., & Turner, M. G. (2001). Hares and tortoises: Interactions of fast and slow variables in ecosystems. *Ecosystems*, 495–497.

Centers for Disease Control and Prevention. (2021). *Climate and health: Regional health effects*. https://www.cdc.gov/climateandhealth/effects/default.htm

Conservation Measures Partnership. (2020). *Open standards for the practice of conservation (Version 4).* http://conservationstandards.org/wp-content/uploads/sites/3/2020/12/CMP-Open-Standards-for-the-Practice-of-Conservation-v4.0-English.pdf

Díaz, S., Zafra-Calvo, N., Purvis, A., Verburg, P. H., Obura, D., Leadley, P., Chaplin-Kramer, R., De Meester, L., Dulloo, E., Martín-López, B., Shaw, M. R., Visconti, P., Broadgate, W., Bruford, M. W., Burgess, N. D., Bares, J. C., DeClerck, F., Fernández-Palacios, J. M., Garibaldi, L. A., … Zanne, A. E. (2020). Set ambitious goals for biodiversity and sustainability. *Science, 370*(6515), 411–413.

Diefenderfer, H. L., Steyer, G. D., Harwell, M. C., LoSchiavo, A. J., Neckles, H. A., Burdick, D. M., Johnson, G. E., Buenau, K. E., Trujillo, E., Callaway, J. C., Thom, R. M., Ganju, N. K., & Twilley, R. R. (2021). Applying cumulative effects to strategically advance large-scale ecosystem restoration. *Frontiers in Ecology and the Environment, 19*(2), 108–117.

Griffiths, V. F., Bull, J. W., Baker, J., & Milner-Gulland, E. J. (2019). No net loss for people and biodiversity. *Conservation Biology, 33*(1), 76–87.

Iowa Community Indicators Program. (2022). *Urban percentage of the population for states, historical*. Iowa State University. https://www.icip.iastate.edu/tables/population/urban-pct-states

Locke, H., Rockström, J., Bakker, P., Bapna, M., Gough, M., Hilty, J., Lambertini, M., Morris, J., Polman, P., Rodriguez, C. M., Samper, C., Sanjayan, M., Zabey, E., & Zurita, P. (2021). *A nature-positive world: The global goal for nature*. https://www.naturepositive.org/en/resources

Maron, M., Brownlie, S., Bull, J. W., Evans, M. C., von Hase, A., Quétier, F., Watson, J. E., & Gordon, A. (2018). The many meanings of no net loss in environmental policy. *Nature Sustainability, 1*(1), 19–27.

Maron, M., Hobbs, R. J., Moilanen, A., Matthews, J. W., Christie, K., Gardner, T. A., Keith, D. A., Lindenmayer, D. B., & McAlpine, C. A. (2012). Faustian bargains? Restoration realities in the context of biodiversity offset policies. *Biological Conservation, 155,* 141–148.

Maron, M., Ives, C. D., Kujala, H., Bull, J. W., Maseyk, F. J., Bekessy, S., Gordon, A., Watson, J. E., Lentini, P. E., & Gibbons, P. (2016). Taming a wicked problem: Resolving controversies in biodiversity offsetting. *BioScience, 66*(6), 489–498.

Maron, M., Juffe-Bignoli, D., Krueger, L., Kiesecker, J., Kümpel, N. F., Kate, K. T., Milner-Gulland, E. J., Arlidge, W. N. S., Booth, H., Bull, J. W., Starkey, M., Ekstrom, J. M., Strassburg, B., Verburg, P. H., & Watson, J. E. M. (2021). Setting robust biodiversity goals. *Conservation Letters*, 14.

McPhearson, T., Andersson, E., Elmqvist, T., & Frantzeskaki, N. (2015). Resilience of and through urban ecosystem services. *Ecosystem Services, 12*, 152–156.

Moilanen, A., & Kotiaho, J. S. (2018). Fifteen operationally important decisions in the planning of biodiversity offsets. *Biological Conservation, 227,* 112–120.

National Academies of Sciences, Engineering, and Medicine. (2022). *An approach for assessing U.S. Gulf Coast ecosystem restoration: A Gulf Research Program environmental monitoring report*. National Academies Press. https://doi.org/10.17226/26335

National Infrastructure Commission. (2021). *Natural capital and environmental net gain.* https://nic.org.uk/studies-reports/natural-capital-environmental-net-gain/

National Research Council. (2001). *Compensating for wetland losses under the Clean Water Act*. National Academies Press.

Phalan, B., Hayes, G., Brooks, S., Marsh, D., Howard, P., Costelloe, B., Vira, B., Kowalska, A., & Whitaker, S. (2018). Avoiding impacts on biodiversity through strengthening the first stage of the mitigation hierarchy. *Oryx, 52*(2), 316–324.

Pope, J., Morrison-Saunders, A., Bond, A., & Retief, F. (2021). When is an offset not an offset? A framework of necessary conditions for biodiversity offsets. *Environmental Management, 67*(2), 424–435.

Pörtner, H. O., Roberts, D. C., Adams, H., Adler, C., Aldunce, P., Ali, E., Begum, R. A., Betts, R., Kerr, R. B., & Biesbroek, R. (2022). *Climate change 2022: Impacts, adaptation, and vulnerability. Contribution of Working Group II to the sixth assessment report of the Intergovernmental Panel on Climate Change*. Cambridge University Press.

Rocchio, F. J., & Crawford, R. C. (2011). *Applying NatureServe's ecological integrity assessment methodology to Washington's ecological systems*. Washington Natural Heritage Program, Washington State Department of Natural Resources.

Rocchio, F. J., Crawford, R. C., & Ramm-Granberg, T. (2020a). *Field manual for applying rapid ecological integrity assessments in wetlands and riparian areas in Washington State (Version 1.2)*. Washington State Department of Natural Resources. https://doi.org/ 10.13140/RG.2.2.30936.52486

Rocchio, F. J., Ramm-Granberg, T., & Crawford, R. C. (2020b). *Field manual for applying rapid ecological integrity assessments in upland plant communities of Washington State (Version 1.3)*. Washington State Department of Natural Resources. https://doi.org/ 10.13140/RG.2.2.36389.12004

Ruhl, J. B., & Salzman, J. (2011). Gaming the past: The theory and practice of historic baselines in the administrative state. *Vand. L. Rev., 64*, 1.

Shukla, P. R., Skea, J., Slade, R., Al Khourdajie, A., van Diemen, R., McCollum, D., Pathak, M., Some, S., Vyas, P., Fradera, R., Belkacemi, M., Hasija, A., Lisboa, G., Luz, S., & Malley, J. (Eds.). (2022). *Climate change 2022: Mitigation of climate Change. Contribution of Working Group III to the sixth assessment report of the*

Intergovernmental Panel on Climate Change. Cambridge University Press. https://doi.org/10.1017/9781009157926

Stange, M., Barrett, R. D., & Hendry, A. P. (2021). The importance of genomic variation for biodiversity, ecosystems and people. *Nature Reviews Genetics, 22*(2), 89–105.

Tallis, H., Kennedy, C. M., Ruckelshaus, M., Goldstein, J., & Kiesecker, J. M. (2015). Mitigation for one & all: An integrated framework for mitigation of development impacts on biodiversity and ecosystem services. *Environmental Impact Assessment Review, 55*, 21–34.

U.S. Census Bureau. (2010). *Dicennial census of population and housing data*. https://www.census.gov/programs-surveys/decennial-census/data.html.

Washington Biodiversity Council. (2007). *Washington's biodiversity: Status and threats*. Washington State Recreation and Conservation Office.

Washington State Department of Natural Resources. (2022). *Natural Heritage Program*. https://www.dnr.wa.gov/natural-heritage-program.

Wende, W., Tucker, G., Quétier, F., Rayment, M., & Darbi, M. (2018). *Biodiversity offsets—the European perspective on no net loss of biodiversity and ecosystem services*. Springer.

Wilkinson, M. D., Dumontier, M., Aalbersberg, I. J., Appleton, G., Axton, M., Baak, A., Blomberg, N., Boiten, J.W., Santos, da Silva Santos, L.B., Bourne, P. E., & Bouwman, J. (2016) The FAIR Guiding Principles for scientific data management and stewardship. *Scientific data, 3*(1), 1-9.

Wilson, E. O. (1988). The current state of biological diversity. *Biodiversity, 521*(1), 3-18.

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Academy of Sciences
Science in the Service of Washington State

Assessment of No Net Loss and Recommendations for Net Ecological Gain Metrics, Indicators, and Monitoring

Prepared for the Washington State Department of Fish and Wildlife

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I. INTERPRETATION OF CHARGE

The Washington Department of Fish and Wildlife (WDFW) requested that the Washington State Academy of Sciences (WSAS) inform its work on the development of a net ecological gain (NEG) standard for public projects as part of the response to a proviso contained within Engrossed Substitute Senate Bill 5092 (2021). WSAS convened a committee of scientific and technical experts (referred to in this document as "the committee") to conduct this scope of work. The full scope of work for the committee was to develop a definition, goals, objectives, and performance metrics for the net ecological gain standard; assess the sufficiency of existing standards in achieving endangered species recovery; and make recommendations about monitoring and indicators for no net loss and net ecological gain.

The committee's first chapter on the NEG definition, goals, and objectives was previously shared with WDFW (Washington State Academy of Sciences, 2022). The committee interpreted their charge for this subsequent chapter, as outlined in the scope of work with WDFW, as (1) assessing whether and why existing standards of ecological protectiveness, such as no net loss (NNL) standards, have been sufficient or insufficient to protect ecological health and achieve endangered species recovery and (2) providing recommendations for:

- Performance metrics for the NEG standard
- Indicators to assess NNL and NEG
- Establishment of a monitoring system
- Incorporation of climate science predictions into NNL and NEG standards

This report chapter synthesizes the committee's perspectives on the effectiveness of existing ecological protection standards and focuses on recommendations regarding NEG metrics, monitoring, and indicators. The primary intended audiences for this document are Washington State agencies, tribes, and legislators.

To operationalize the concepts reviewed in this chapter, several additional steps are necessary, including educating agency staff and the public on NEG, developing inter-agency partnerships, building a workforce trained in interdisciplinary and transdisciplinary approaches to addressing socio-ecological challenges relevant to NEG, and helping to provide the scientific basis for any necessary legislation. In the concluding section of this chapter, the committee presents suggestions for some follow-on activities that may facilitate these next steps toward successful implementation of NEG in Washington State.

II. ASSESSMENT OF NO NET LOSS

The concept of no net loss (NNL) seeks to minimize impacts of human infrastructure on the environment, typically by applying some form of the mitigation hierarchy to sequentially avoid, minimize, remediate, and offset biodiversity impacts from new development (Bennett et al., 2017; also see the committee's first chapter on the NEG definition, goals, and objectives, Washington State

Academy of Sciences, 2022). NNL was first introduced through the 1970 National Environmental Policy Act. Upon issuance of the Clean Water Act in 1972, the Army Corps of Engineers applied NNL to manage dredge materials and mitigate the disposal of contaminants into water. The George H. W. Bush Administration further promulgated the concept, implementing a no net loss standard for wetlands in the early 1990s.

Yet, many natural ecosystems continue to be converted to residential and commercial development under existing standards. When considering whether existing ecological standards, including NNL, have been sufficient in safeguarding ecological health and achieving endangered species recovery, **the committee's consensus view is that NNL has not been an effective approach for ecosystem or habitat management and protection nor for the maintenance of ecosystem services**. Within the larger scientific community, shortcomings of the NNL approach were articulated as long as 30 years ago. For example, two National Academies reports (National Research Council, 1992, 2001) on compensatory mitigation for wetland loss through development were highly critical of NNL. Other global studies have found little to no documented evidence of NNL success and high regional variability in such success (e.g., Bull & Strange, 2018; zu Ermgassen et al., 2019).

The failure of NNL is directly relevant to Washington State ecosystems and the health and well-being of its residents. In Washington, there are 33 known extirpated plants and 6 known extirpated animals—one freshwater bivalve, two species of butterfly, one beetle, and two bird species (Washington Department of Natural Resources, 2022). An entire extirpated ecosystem has been identified by the Washington Natural Heritage Program to date: the noble fir-redwood sorrel forest of the Willapa Hills. There are another 179 endangered ecosystems in the state, including forest types associated with Oregon white oak woodlands, red alder-bigleaf maple-Douglas fir rainforests, Douglas fir-Western hemlock rainforests, silver fir-Western hemlock rainforests, Western hemlock-Sitka spruce rainforests, Douglas fir-madrone woodland, paper birch and quaking aspen swamp forests, 20 riparian forest types, and four maritime swamp forest types. The Western juniper ecosystem is also endangered, as are numerous grassland, shrubland, bog, fen, marsh, vernal pool, and wet meadow ecosystem types.

Additionally, an assessment process for the intensive climate change vulnerability index (Dawson et al., 2011; Young et al., 2012), which is currently being implemented in Washington, has already identified many plant species that are highly or extremely vulnerable (Fertig, 2020, 2022). There are widespread threats to game species habitats as well. Some of these are a result of negative impacts of wind and solar energy development on mule deer in Eastern Washington. Band-tailed pigeon harvest opportunities have also been reduced despite a hunting closure that was implemented from 1991 to 2001 (Washington Department of Fish and Wildlife, 2021).

Clearly, there have been net losses of species and habitats in Washington. The committee is reasonably confident that without policy changes, these types of losses will continue and will contribute to the disappearance of distinct habitats and ecosystem types from Washington's terrestrial and aquatic landscapes.

Application of NNL has been unsuccessful in most instances for a variety of reasons. First, there are challenges associated with establishing appropriate baseline conditions. For sites that have experienced

significant loss of habitat, biodiversity, or ecological functions, using the current condition as a baseline falls short of promoting adequate management and protection. For such sites, NEG is often a better approach because it necessitates an improvement in ecosystem biodiversity or resilience without requiring that the site revert to pristine conditions.

A second challenge of NNL lies in uneven distribution of impact and mitigation. Often, compensatory mitigation occurs offsite and fails to provide in-kind compensation for the loss. For example, a forest may be established offsite to compensate for wetland habitat loss, which does not truly offset the impacts of this loss. Poor implementation of NNL has been another common obstacle. For example, many wetland restorations have been inadequate. Limited funding and insufficient institutional structure for implementation often result in inadequate monitoring and enforcement before, during, and after a project. In addition, accurate assessment of the success of a standard's implementation can be difficult because this process requires the identification of appropriate targets, indicators, and metrics, as well as the determination of the appropriate spatial and temporal scales for monitoring. Finally, community buy-in for NNL has grown more difficult due to disproportionate impacts to low-income communities, as well as a pattern of compensatory actions under NNL failing to benefit the people most heavily impacted by a project.

Examining the reasons NNL has failed is imperative to designing and implementing a successful NEG standard. Many of the same challenges will persist under NEG without intentional action to improve the current approach to implementing ecological protection standards and overcome challenges related to funding and infrastructure limitations, incorporation of climate change science, monitoring, assessment, and community buy-in.

Beyond No Net Loss to Net Ecological Gain

In the committee's first chapter to WDFW (Washington State Academy of Sciences, 2022), the committee provided a definition, goals, and objectives for NEG in Washington State. The committee's proposed definition for NEG is:

> **Net ecological gain means that after development, there is an increase in biodiversity or resilience that improves the delivery of valued ecosystem functions in the affected ecosystem.**

NEG aims to achieve improvements to ecosystem health in comparison to a theoretical future in which the developments or projects did not occur, rather than using current conditions as a baseline. This approach seeks to go beyond simply offsetting loss to stopping and even reversing it.

The state of Washington has been considering NEG as an approach to preserve and restore ecological systems. The case studies provided in this chapter aim to demonstrate how the committee's broad definition, goals, objectives, and performance metrics for net ecological gain can be applied to various public projects in Washington State. The committee acknowledges that the case studies do not encompass all possible ecosystems and development situations in Washington State; they instead serve as examples to put these abstract concepts into perspective.

Future successful implementation of NEG in Washington will necessarily include the processes of defining targets, indicators, and metrics; building community support for the approach; establishing monitoring, assessment, and accountability systems; factoring in impacts of climate change; and assessing outcomes. These processes can be informed by existing ecologically relevant conceptual frameworks across various fields of study, as discussed throughout this chapter.

III. IMPLEMENTING AND ASSESSING A NET ECOLOGICAL GAIN STANDARD

Structured Decision Making and Ecosystem Planning

To progress toward the NEG goals and objectives outlined in committee's first chapter on the NEG definition, goals, and objectives, the committee recommends employing a conceptual framework that can effectively measure ecological function, structure, and processes. The field of ecological assessment includes several accepted frameworks for determining an ecosystem's condition by comparing its composition, structure, and function to baseline measurements. For instance, steps for measuring ecological integrity include identifying ecological attributes; determining metrics to measure degradation against baseline levels; assessing the attributes using remote sensing, rapid ground-based, and intensive ground-based metrics; and presenting the resulting measurements in a matrix that illustrates the interconnectedness of the attributes, metrics, and findings (Karr et al., 2021; Rocchio & Crawford, 2011; Rohwer & Marris, 2021; Wurtzebach & Schultz, 2016).

A well-accepted framework that is applicable to implementation of NEG is 'Structured Decision Making & Ecosystem Planning' (Gregory et al., 2012; Levin et al., 2018), which has been successfully applied to questions of fish and avian ecosystem management and restoration (Buenau et al., 2014; Neckles et al., 2015). This generic planning framework can be repurposed and adapted to a variety of scenarios.

Box 1. Fundamental Recommendations to Enhance the Probability of Successful NEG include:

- Understand controlling factors and linkages in the ecosystem
- Understand the role and mode of the actions of stressors and disturbances
- Apply science-based understanding to project design and development
- Apply simple yet effective technological solutions where appropriate
- Apply appropriate restoration and monitoring strategies
- Admit uncertainties and overcompensate in the design of projects for unavoidable damages

(modified from Thom et al., 2005b)

In the context of NEG and how it fits into a broader ecosystem planning process, this framework includes activities that aim to accomplish the following:

1. Describe the current state of the ecosystem (e.g., through state indicators and by creating an inventory of threats) and use conceptual models (e.g., Bayesian belief networks, qualitative models, Driver-Pressure-State-Impact-Response framework) to represent the way the ecosystem elements are thought to interact with each other, how they will respond to threats, and the potential pathways of human benefits
2. Articulate a set of desired futures, potentially including but not limited to a vision, strategic objectives, risk analysis, prioritization, and operational objectives
3. Create a plan to address top-priority threats and operational objectives, including:
    - Setting performance measures (which may or may not be the same as the previously described state indicators or threat indicators)
    - Identifying potential management strategies
    - Evaluating the range of outcomes for each objective
4. Implement the plan (in the context of NEG, this involves creating a built environment that seeks to achieve NEG) and establish time-bound measures of success and resources to monitor outcomes

Indicators developed using a structured decision making framework serve a variety of purposes and are selected based specifically on these purposes. Performance indicators need to be SMART: Specific, Measurable, Attainable, Relevant, and Time-bound.

Structured decision making is meant to provide a logic model that captures the pieces that need to be considered when evaluating NEG. **Structured decision making is a systematic and transparent process to evaluate a potential project and its impacts.** The process can be applied at different scales with varying intensity, but importantly, it must be as objective and transparent as possible, with conclusions drawn from available scientific evidence.

From a process standpoint, structured decision making also includes facilitating stakeholder identification of and consensus on the main threats and prioritizing multiple objectives. Involvement of diverse stakeholders and the affected community as early as practically possible helps generate buy-in and establish a forum for identifying goals, objectives, approaches, and solutions.

Ideally, the structured decision making process should be stakeholder-based and incorporate multiple objectives and values to determine how to best achieve NEG. Generally, the sooner stakeholders are brought into the process, the more successful the outcome will be (Gregory et al., 2012). There are various ways to do this, such as using a structured decision-making model that focuses on the science and engages stakeholders separately or by building stakeholder engagement into the process throughout (e.g., Environmental Protection Agency, 2022). Different approaches may also be required for different groups of stakeholders. Although such a process can be time-intensive, this engagement is critical for achieving long-term NEG (see the section on Human Well-Being, Stakeholder Engagement, and Community Buy-In below).

Overall, applying recognized and widely used frameworks such as structured decision making will help to maximize the efficiency, transparency, and replicability of NEG implementation.

Box 2. Case Study: Clinton Ferry Terminal Rebuild

The Clinton Ferry Terminal was redeveloped to address traffic concerns and needed repairs. The initial proposal was projected to remove approximately 3,000 square meters of eelgrass and create wide, shaded areas near the shore that would inhibit juvenile salmon migration. Terminal design engineers and scientists worked together to redesign the dock. The redesign included a narrower but longer dock, fewer pilings, reorientation of ferry slips to minimize bottom disturbances and turbidity, and addition of glass blocks in the walkway to allow light to pass. The net effect of this redesign was a reduction in projected loss of eelgrass to about 300 square meters.

Prior to the outset of the project, eelgrass shoots from the site were harvested and grown in culture, where they multiplied. Prior to completing the terminal rebuild, the cultured eelgrass was transplanted into previously disturbed areas, which resulted in an approximate 4:1 increase in eelgrass near the terminal over baseline conditions. While the eelgrass beneath the dock did not appear to respond to the additional light enabled by the glass blocks, it did show resilience and overall expansion over a 10-year period. The placement of the glass blocks also appeared to aid with the movement of salmon around the dock. Salmon primarily passed under the dock when there was minimal shadow. Overall, due to the redesign, the project resulted in a net gain in eelgrass and generally improved conditions for young salmon (Thom et al., 2005a, 2005b, 2012). Natural resource agencies met annually for 10 years with scientists and Washington State Ferry staff to review the monitoring results.

This project was rooted in a conceptual framework for measuring the goals and outcomes, which was in place prior to project initiation, thereby allowing review and mitigation of projected impacts in advance of the project's start. The Federal Highway Administration recognized this project with the 1997 National Environmental Excellence Award.

Tenets of the NEG definition articulated in the committee's first chapter on the NEG definition, goals, and objectives can be seen within this case study. For example, measurable net improvement to the ecosystem's structure and resilience can be seen in the expansion and resilience of eelgrass. Parallels can also be drawn between the goals and metrics presented in this chapter and the implementation of the Clinton Ferry Terminal rebuild (see below). Some of the project metrics that reflect the concepts presented in this document and the committee's first chapter (Washington State Academy of Sciences, 2022) include measurements of strengthened ecosystem resilience through the persistence of ecosystem structure and measurements of sustained biodiversity through improvements in populations of native species.

IV. ADDITIONAL CONSIDERATIONS FOR NEG IMPLEMENTATION

There are considerations specific to implementing NEG that have the potential to extend beyond a generic decision-making framework. Some of these considerations include the following.

- **Scale**. Potential impacts of any development project should be considered with careful attention to spatial, functional, and temporal scales because these considerations have the capacity to tip net outcomes from gain to loss.
    - Spatial scale may comprise an area as small as a building or property or may be most appropriately considered at the site, ecosystem or habitat, or landscape scale at which processes occur.
    - Functional scale pertains to the reach of impacts, including the location and demographics of the people affected.
    - Temporal scale refers to time-related considerations, such as the duration and anticipated peak of project outcomes. Evaluating temporal scale can be challenging because measurements typically occur after the conclusion of the project.

- **Distribution of impact**. It is important to consider the scale at which measurements are made versus the scale at which impacts accumulate. For example, a case study by the National Academies of Science, Engineering and Medicine (2022) details the relatively minor improvements in farmland management in the Mississippi River Basin relative to the size of the recurring hypoxic zone in the Gulf of Mexico. Conducting projections of what future conditions would be without the project is one method of adjusting project outcome measurements to potential changes in background environmental conditions that could occur for other reasons.

- **Distributional effects of restoration actions.** In addition to considering the distribution of impact, it is also critical to assess outcomes within the context of how a specific site contributes to critical ecosystem processes of the overall region in which it is situated. Individual sites vary in terms of their functional importance, their components or attributes, and the extent to which they contribute to human well-being (see Table 1 in the committee's first chapter on the NEG definition, goals, and objectives, Washington State Academy of Sciences, 2022). The determination of whether to move forward with a project, as well as the NEG considerations for that site, should take into account whether a site has high functional importance relative to the surrounding landscape.

- **Multiple objectives**. Often, impact assessments only examine a single objective, while NEG is a whole-system approach that takes place within the broad context of the complex, dynamic relationships between population and economic growth and the management of ecosystem health. Consideration of multiple objectives is important for situating NEG efforts within the larger context. As an example, the Puget Sound Partnership uses a structured decision analytic model developed by EPA (Yeardley et al., 2011) that enables the inclusion of multiple objectives and evolving scenarios. The flexibility of this model supports specific inquiry regarding outcomes. NEG efforts for impacts to the Columbia estuary followed a similar approach

(Diefenderfer et al., 2016), which is currently being adapted to the Whidbey Basin of Puget Sound (Whidbey Cumulative Effects Group, 2022).

- **Evaluation of uncertainties.** It is crucial to assess which pathways to NEG will be robust and able to accommodate uncertainties in the long-term. There are often critical uncertainties associated with development and ecological restoration projects relative to achieving the stated goals for the project outcomes. In addition, climate change poses a significant level of uncertainty for all ecosystems. Designing and employing an adaptive management process (e.g., Levin et al., 2018) is therefore important for NEG projects.

The committee's proposed definition of NEG emphasizes that the preferred approach is to first avoid or limit ecological losses that occur through development, thereby curtailing degradation that would require restoration efforts with less certain outcomes. Consistent with the hierarchy of mitigation, it is also assumed that development resulting in adverse effects is not allowable for ecosystems that are especially fragile or that play a central role in biodiversity or in the functioning of ecosystems and landscapes and the benefits they provide to humans (Díaz et al., 2020; Locke et al., 2021; Maron et al., 2021). **For critical ecosystems such as these, there are limits that will preclude achieving NEG from development**. Some of the critical ecosystems in Washington include those which have been systematically identified and classified statewide by the Washington Natural Heritage Program through implementation of the Natural Area Preserves Act (RCW 79.70.070) (Washington Natural Heritage Program, 2022). When projects move forward regardless of the environmental impacts to critical ecosystems, determining how to attain NEG can pose significant or even insurmountable challenges.

The concept of NEG is meaningless unless the proposed outcome is specified relative to alternative possible scenarios. Considering alternative scenarios is important for describing the anticipated outcomes if a particular project or action is not carried out. For example, impact-specific policies for no net loss and net ecological gain generally use counterfactual scenarios that describe what would be expected to happen in the absence of development and present associated mitigation actions as the basis for scenarios (Bull et al., 2014; Maron et al., 2018). Developing and agreeing on appropriate counterfactual scenarios can be challenging due to prediction-making uncertainties that are further exacerbated by climate change effects and potential opportunities for gaming outcomes (Salzman & Ruhl, 2010). Moreover, where a project impacts different biota and ecological processes, expected rates of change may vary spatially and temporally. The process of developing these counterfactual scenarios is important for the understanding of relevant ecological processes and the application of the chosen reference scenario for setting targets for NEG (i.e., desired outcomes of NEG-based activities).

To effectively promote net gain by addressing all variable factors, impact-specific scenarios should also be developed that go beyond counterfactual scenarios. Impact-specific scenarios consider the additional and cumulative impacts of ecosystem pressures attributable to threats that are unrelated to proposed development.

Broad, overarching policies for no net loss or net gain of biodiversity across a jurisdiction (e.g., state-wide goals by 2040 to achieve no net loss of biodiversity or a net increase in riparian habitat) often imply alternative reference scenarios in which all potential sources of loss need to be considered. However,

although counterfactual scenarios can describe an assessment of potential impacts that can be translated into a no net loss threshold, they do not identify targets for net gain. Quantitative targets and metrics must be defined and monitored to demonstrate success in offsetting negative impacts (Arlidge et al., 2018; Wende et al., 2018). This process of setting targets is similar to the objective-setting process defined in EPA's Decision Analysis for a Sustainable Environment, Economy & Society (DASEES; Yeardley et al., 2011).

For context, Washington State is an area identified by the Intergovernmental Panel on Climate Change (IPCC) as having high conservation importance based on the high number of freshwater and terrestrial species and high projected habitat losses, with a 20% loss of marine fish and benthic animal biomass expected even under the lower-risk scenario (IPCC, 2022). The IPCC's Working Group II had high confidence that the migration, distribution, and abundance of key fish resources have been impacted in the Northeast Pacific (Pörtner et al., in press). Climate change will further impact these ecosystem attributes in a variety of ways. Some of the implications of climate change include larger, longer-burning, more frequent, and more severe fires; increased stream temperatures; and glacial recession and reduced snowpack impacting summer streamflow (Frans et al., 2018; Halofsky et al., 2020; Koontz et al., 2018). Even without further land conversion to accommodate the expansion of residential populations and commercial enterprises, widespread climate change effects detrimental to Pacific Northwest ecosystems are expected to continue.

Targets and eventual outcomes must meet three conditions (Gardner et al., 2013). First, losses and gains of biodiversity and ecosystem functions must be *comparable* in type and magnitude. This condition is often challenged by policy makers who want more flexibility and by some conservation biologists who advocate for "trading up" by exchanging offset areas with like-for-like potential for other areas that they view as having higher conservation value (Moilanen & Kotiaho, 2018).

Second, the desired gains through offsets must be *in addition* to those that would have occurred if the development did not take place. Projections of gains should extend beyond the site scale and explicitly take into consideration the cumulative effects of impacts at the landscape scale (Figure 1; Diefenderfer et al., 2021; Hood et al., 2022; National Academies of Science, Engineering and Medicine, 2022). For example, different sites within a watershed may have varying innate functions, meaning that the expectations for each site should also vary. Sites must be accounted for within the context of what that site provides to the function of the overall landscape. A challenge for both NNL and NEG is deciding what constitutes sufficient gain. Multiplier and mitigation ratios based on expected loss are one approach for simplifying the process of setting targets; these ratios should be informed by available science.

Third, desired gains must be *lasting*, exceeding or at least equaling the duration of the residual impacts of the development in the face of climate change. When identifying quantitative outcomes for offset gains, the timing of when outcomes are achieved must also be considered. Unless offset targets are achieved before development, delays usually at least temporarily cause losses of biodiversity or ecosystem functions (Gann et al., 2018); further, targets not achieved before the project onset may fail to address ecological losses that occur at offset locations during the delay. The impacts of such time lags

are often addressed through multiplier or mitigation ratios that expand the offset target in proportion to expected delays, although this approach does not guarantee a net gain (Pope et al., 2021).

Choosing metrics to ensure net gain is achieved is a critical and context-specific step. Metrics need to be 1) sensitive and predictably responsive to anticipated development impacts, 2) informative at different spatial scales, and 3) feasible to monitor at the appropriate timescales to assess short- and long-term project outcomes.

Prioritization of NEG also requires that there be an "exit ramp" in the project development process, with one option being that the proposed project does not move forward as planned. Ideally, an initial step in project planning should entail an assessment of whether a location can reasonably withstand the proposed project. If implementation of NEG is infeasible because of too much risk or uncertainty, the project should be reconsidered for an alternative site or canceled.

Cumulative Effects and a Need for Large-Scale Planning to Achieve NEG

In addition to the localized impacts of an individual project, the cumulative impacts to surrounding ecosystems must be considered in planning for NEG. Successful implementation of NEG requires a transdisciplinary approach that addresses diverse socio-ecological needs across multiple spatial scales. This process may require assessing project impacts within the context of other ongoing or future projects and the current condition of the surrounding landscape (Fig. 1).

To assess and predict the cumulative ecosystem impacts of development, overarching goals should be set at the landscape scale in partnership with interdisciplinary experts, including scientists at state agencies, communities, and interested stakeholders. Examples of landscape-scale prioritization approaches include the WDFW strategies for nearshore protection and restoration in Puget Sound (Cereghino et al., 2012), the proposed use of landscape ecology principles in habitat restoration across the Columbia River Estuary (Hood et al., 2022), and prioritization of shoreline habitats for restoration under the Shoreline Master Program in Jefferson County (Diefenderfer et al., 2009).

In some cases, scientifically established and vetted goals set by state agencies can serve as these overarching goals; however, **Washington State currently lacks a systematic, state-wide landscape approach for evaluating the ecological processes that connect and sustain each of its ecosystem types and their natural factors of scale**, such as watershed or estuary size, gradients, and hydrology (see the section on Establishing a Monitoring System for NEG below).

In addition to setting overarching goals, **approaches that prioritize NEG should consider the cumulative impacts of individual projects toward larger landscape-scale targets**. A major drawback of many mitigation frameworks is that they focus on a single component of an ecosystem, such as floodplains or salmon. Combining these frameworks into an integrated approach would aid in addressing cumulative effects. For example, an overarching framework that integrates salmon recovery strategies with watershed goals would enable the assessment of how individual activities fit into broad, science-based goals that were set at the landscape level. For urban watersheds, this framework might integrate needs related to runoff, salmon habitat, and the impact of flows along marine shorelines.

In some cases, NEG may succeed at the project scale but fall short of the broader targets. It is nevertheless important to continually consider NEG within the larger context of cumulative impacts and to refine and adapt the associated approaches to work toward NEG at the landscape scale.

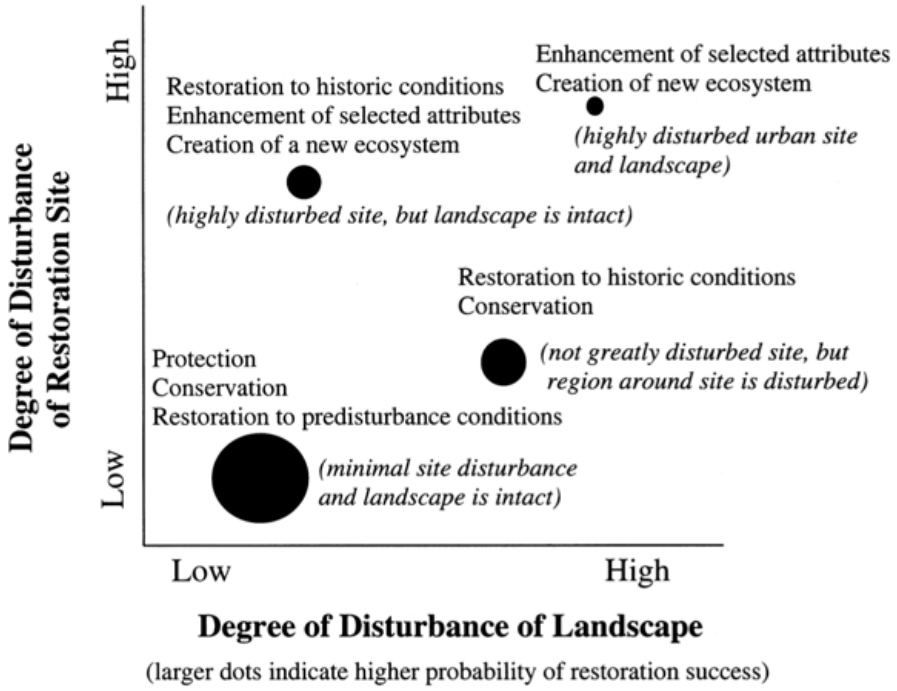


Figure 1*. This graphic illustrates the generalized relationship between the level of disturbance or degradation of the site and the landscape within which the site is located. The most appropriate restoration strategies, including ecological protection and the enhancement of selected attributes, are listed for four theoretical conditions. The larger the dot, the greater the chance that the site could be restored (Thom et al., 2005b).*

Human Well-Being, Stakeholder Engagement, and Community Buy-In

As noted in the committee's first chapter on the NEG definition, goals, and objectives (Washington State Academy of Sciences, 2022), there is an interdependent relationship between human well-being and ecosystem health. Communities depend on ecosystem goods and services, such as clean water and air, to sustain human well-being, and thus are profoundly affected by impacts to the ecosystems around them (Environmental Protection Agency, 2022).

Inclusively engaging communities in decision making is integral to ensuring policies, programs, and decisions themselves reflect the diverse interests, values, beliefs, and perspectives regarding a given area or issue. The value of engaging communities early and at all stages of decision making is well documented (e.g., IPBES, 2015). Early, continued engagement can help ensure decisions are more transparent, democratic, and equitable both in process and outcome.

Research increasingly demonstrates the importance of incorporating local community and Indigenous knowledge within environmental decision making and planning. By intentionally and inclusively

engaging communities, decision makers can become better informed or more able to fully understand the complexity of a given issue, its underlying causes or factors, and its potential impacts. This process helps to ensure longer-term stewardship and trust in governance around these issues. Activities associated with the new Healthy Environment for All (HEAL) Act (Washington State Legislature, 2021), which requires that agencies gather community input as part of environmental justice assessments, could help inform NEG efforts across Washington State.

The approach for obtaining community input varies depending upon the project scale and the composition and needs of the stakeholder group. However, a foundation of trust and community buy-in is critical to garner effective stakeholder engagement. Structured decision making is one way to involve stakeholders. A conceptual framework developed by the Intergovernmental Platform on Biodiversity and Ecosystem Services (IPBES) presents another approach for leveraging community input to co-create an integrative knowledge base. This framework relies on a multidisciplinary, participatory approach to synthesize diverse stakeholder knowledge and create greater comparability across assessments (Díaz et al., 2015). Other forms of participatory research that are becoming increasingly popular, such as the use of crowdsourced environmental data sensing and/or volunteer community scientists, also offer promising ways to engage communities and generate buy-in.

Box 3. Case Study: Floodplains by Design

Floodplains by Design (https://www.floodplainsbydesign.org/) is a public-private partnership led by the Department of Ecology, The Nature Conservancy, the Bonneville Environmental Foundation, and Puget Sound Partnership which aims to reduce flood risks and restore habitat along Washington's major river corridors by restoring former agricultural lands located in habitats supporting salmon and other biodiversity. For example, to develop a solution that was satisfactory for all stakeholders, the project team gathered input on a land management solution from local landowners, neighboring property owners, land use commissioners, scientists, and watershed managers in Skagit County. The collaborative solution resulted in natural capital (restored land and salmon habitat), economic capital, and social capital (good will established between governing bodies and local landowners and a sense of stewardship over the land). The Floodplains by Design approach has been applied to projects across Washington State since 2013. This approach offers an excellent example of the value of stakeholder involvement in NEG initiatives. **Stakeholder involvement can support positive outcomes for all involved parties and build community trust and buy-in.**

V. PERFORMANCE METRICS AND INDICATORS

To measure and document the effects of restorative and protective actions, it is critical to use appropriate and well-developed measures of change. The committee defines a metric as anything one measures, while an indicator is specific to a particular decision and is assessed as part of an evaluation cycle that measures progress toward a specified objective. Indicators are more general than metrics. In other words, all indicators are metrics, but not all metrics are indicators. For example, when assessing

water quality, measurement of dissolved oxygen may be a metric, with an indicator for this assessment being the areal extent of water with quality that exceeds a predetermined oxygen level. Moreover, an indicator may comprise many metrics. Within the context of these definitions, many components of an ecosystem can be measured (metrics), but only a subset of those components are indicative of a particular ecosystem characteristic and directly useful for setting policy and making decisions (indicators). Some examples of recently published indicators include the use of growing-season sum exceedance value of hourly surface-water depth as a wetland inundation indicator within a proposed predictive framework for studies on estuarine–tidal river systems (Borde et al., 2020), as well as 7-day average daily maximum water depth as an indicator of marsh sediment accretion in a study on floodplain wetland morphology (Diefenderfer et al., 2021).

Process and Criteria for Setting NEG Indicators

This section describes approaches for developing criteria and indicators for net ecological gain. Rather than suggest specific indicators for net ecological gain across all habitat types and ecosystems represented in Washington, the committee aims to provide guidance on how to navigate the process of selecting indicators and tracking progress toward net ecological gain. The general process, criteria, and development of indicators discussed in this chapter build on the extensive work of the Business and Biodiversity Offset Programme (BBOP) and its technical documents (BBOP, 2012a, 2012b). Given that professionals throughout Washington are already working on ecological indicators for various plant and animal communities and ecosystems across the state, the committee also encourages inter-agency communication to develop appropriate indicators for Washington ecosystems based on existing data and information.

During the process of establishing indicators, it is important to consider (as described previously):

- Sites within their larger contexts, including their functions within the overall landscape and their contributions to cumulative impacts
- Geographical and temporal scale, because the scale at which a measurement is taken may differ from the scale at which the impacts accumulate
- An accepted and relevant conceptual framework
- Measurements that align with existing restoration strategies for the given region

To aid in identifying appropriate indicators, a baseline should be established prior to the beginning of a project. Creating a baseline can be challenging. Data from existing monitoring programs and ecosystem models can be helpful resources for compiling potential baseline or simulated data sets.

Indicators should be identified for both implementation and ecological outcomes. *Implementation indicators* measure the outputs of the planning and implementation processes for achieving net ecological gain. Implementation indicators are usually similar from case to case; a few examples of implementation indicators are summarized in Box 4 (also, see more in-depth examples in Appendix 1). In contrast, *ecological indicators*, which assess ecological outcomes, depend on the location (e.g., ecoregion and type of habitat), ecological and geographical scale (e.g., project size, dominant ecological

processes, and landscape context), and anticipated direct and indirect impacts of the project. Ecological indicators often differ across projects and systems.

Box 4. Example of principles (P), criteria (C), and implementation indicators (I) as part of the orientation and planning steps of a net ecological gain process

These examples are excerpted and adapted from the Business and Biodiversity Offsets Programme (BBOP 2012a, BBOP 2012b) to illustrate concepts. The full process includes tribal and stakeholder participation components, which, for brevity, are not outlined here.

P: Adherence to the mitigation hierarchy: A biodiversity offset is a commitment to compensate for significant residual adverse impacts on biodiversity identified after appropriate avoidance, minimization, and onsite rehabilitation measures have been taken according to the mitigation hierarchy.

> C: The developer identifies, implements, and documents appropriate measures to avoid and minimize the direct, indirect, and cumulative negative impacts of the development project and to undertake onsite rehabilitation/restoration.
>
> I: An assessment of the development project's impacts on biodiversity (including direct, indirect, and cumulative impacts, as appropriate) is conducted with stakeholder participation

P: Net Ecological Gain: A biodiversity offset should be designed and implemented to achieve in situ, measurable conservation outcomes that can reasonably be expected to result in net gain of biodiversity and resilience.

> C: The net gain goal for the development project is explicitly stated, and the offset design and conservation outcomes required to achieve this goal are clearly described.
>
> I: All residual biodiversity losses due to the project are quantified relative to the 'pre-project' condition of affected biodiversity, which is identified, characterized, and documented.
>
> C: An explicit calculation of loss and gain is undertaken as the basis for the offset design and demonstrates the manner in which a net gain of biodiversity can be achieved by the offset.
>
> I: A set of key biodiversity components at the species, habitat, and ecosystem levels, including landscape features and components related to use and cultural values, is identified. The rationale for selecting these key biodiversity components to represent all biodiversity affected by the project is explained and documented.

P: Limits to what can be offset: There are situations in which residual impacts cannot be fully compensated for by a biodiversity offset because of the irreplaceability or vulnerability of the biodiversity affected.

> C: The degree of risk that the project's residual impacts on biodiversity may not be capable of being offset ('non-offsetable') is assessed and measures are taken to minimize this risk.
>
> I: An assessment is undertaken to predict the level of risk that the project's residual impacts on biodiversity will or will not be capable of being offset, with special attention afforded to any highly irreplaceable and vulnerable biodiversity components.

Example: Indicators of Salmon Ecosystems

The following example describes the Puget Sound Recovery Implementation Technical Team's (PS RITT) application of the Open Standards for the Practice of Conservation framework to identify ecological indicators (PS RITT, 2015). The committee chose to highlight PS RITT's work because it is the result of a multi-decade process and is considered the "gold standard" for developing and selecting criteria for biophysical indicators. Notably, the salmon ecosystem for which these indicators were developed is one of the best studied ecosystems in Washington State. Not all successful projects that achieve NEG will necessarily have the capacity to follow such a comprehensive process.

The basic approach used by PS RITT to develop their extensive list of indicators was to first identify linkages among the major components of the salmon ecosystem and then characterize the key ecological attributes (KEAs), pressures, and indicators. Ecosystem components are the attributes we care about conserving and include biodiversity, species, habitat types, ecological processes, and particular ecosystems that encompass the full breadth of conservation objectives for a specific project. KEAs are the characteristics of an ecosystem component that, if present, would support a viable component but, if missing or altered, would lead to loss or degradation of the component over time. Pressures are the proximate human activities or processes that have caused, are causing, or may cause the destruction, degradation, or impairment of KEAs and ecosystem components.

Within this example, PS RITT sorted 14 major ecosystem components of Chinook salmon ecosystems into three different categories: freshwater habitats, estuarine and marine habitats, and biological communities (i.e., species and food webs). These categories and the corresponding ecosystem components are shown in Table 1.

Table 1. *Ecological components by category in PS RITT's identification of indicators, adapted from Puget Sound Recovery Implementation Technical Team (PS RITT, 2015)*

Category	**Components**
Freshwater habitats	• Uplands • channels >50 m bankfull width • Channels <50 m bankfull width • Side channels • Non-channel lakes and wetlands
Estuarine and marine habitats	• Large estuaries • Coastal landforms • Bluff-backed beaches • Pocket estuaries and embayments • Rocky pocket estuaries • Rocky beaches • Offshore marine systems
Biological communities	• Species and food webs

Key ecological processes associated with each of these components were then used to identify KEAs. For freshwater salmon habitats, for example, seven key ecological processes highlighted 15 KEAs (PS RITT, 2015; Table 2).

Table 2. *Key ecological attributes identified by ecological process in PS RITT's identification of indicators, adapted from Puget Sound Recovery Implementation Technical Team (from Table 8, PS RITT, 2015)*

Ecological Process	**KEAs**
Sediment processes	• Sediment delivery • Sediment transport and storage
Hydrological processes	• High flow hydrological regime • Low flow hydrological regime
Organic matter processes	• Organic matter inputs • Organic matter retention and processing
Riparian processes	• Spatial extent and continuity • Riparian community structure • Riparian function
Nutrient supply	• Nutrient concentration • Water quality • Nutrient flux and cycling
Floodplain-channel interactions	• Floodplain connectivity • Floodplain structure and function
Habitat connectivity	• Habitat connectivity

Each KEA was mapped to an associated ecosystem component. Next, KEA indicators and pressure indicators (Table 3) were identified based on review of the scientific literature for each KEA. This demonstrates how different types of indicators can be developed for a key ecosystem process. The same approach was used for marine/estuarine and species and food web components (PS RITT, 2015).

These tables provide a relevant example developed by PS RITT (2015) for salmon ecosystems. The process they used to identify and develop indicators could be applied to other types of habitats and biological communities, as well, such as shrubsteppe, prairie, or grassland ecosystems.

Table 3. *KEA and pressure indicators for hydrology across relevant spatial scales, as an example of how different types of indicators can be developed for a key ecosystem process. (adapted from Table 10, PS RITT, 2015).*

Scale	KEA	KEA Indicators	Pressure Indicators
Watershed	• High-flow hydrology regime • Low-flow hydrology regime	• Area/basin discharge, threshold discharge, point discharge, groundwater recharge/discharge • Land cover, including percentages of impervious surface area and vegetative cover • Hydrographic patterns unique to each watershed will determine specific measures and the seasonal patterns most affecting Chinook (e.g., 7-day low-flow and peak-flow frequency, magnitude, and duration) • Groundwater elevation/flows	• Regulated instream flow hydrograph • Volume of in-basin storage • Withdrawals and consumption • Volume of out-of-basin transfer • Volume and location of stormwater discharge and related alteration of natural hydrologic processes (e.g., infiltration, surface water and groundwater flow patterns)
Reach	• High-flow hydrology regime • Low-flow hydrology regime	Seasonal hydrological patterns: • Water depth and velocity • Area and type of habitat units, including seasonal variation • Residual pool depth • Stage/discharge/habitat relationships (e.g., low flow resulting in isolated habitats, high velocities resulting in redd scouring)	• Scour depth in incubation habitats • Area of redd stranding due to natural or regulated flows • Area and connectivity of floodplain channels leading to stranding of juveniles during low-flow time periods • Rapid decreases in flow stage (e.g., ramping of regulated flows) that isolate pools in floodplain channels and wetlands

Choosing Indicators

Effective indicators are those that not only reflect that state of socio-ecological systems, but also are meaningful to people and inform decision making and planning cycles. James et al. (2012) provided an example of useful selection criteria and a possible method for ranking indicators. In this example, the authors divided criteria for choosing indicators into three categories: scientific credibility and relevance, data issues, and communication and sustainability (Table 4). Criteria were weighted by importance based on the project's goals and a review of the scientific literature. Each criterion for every possible

indicator was then scored. Next, each indicator's score was calculated by totaling the products of each criterion evaluation by individual criterion weights.

To highlight ecological indicators for resilience, for example, ecological indicators such as those used by PS RITT (2015) can be weighted based on the review of resilience indicators in scientific literature (e.g., Grantham et al., 2019; Timpane-Padgham et al., 2017) and by how well they act as surrogates for resilience.

Table 4. *Criteria for choosing and ranking indicators, adapted from James et al. (2012).*

Category	Criteria
Scientific Credibility	• Theoretically sound, based on peer-reviewed findings, and capable of acting as a surrogate for a key ecosystem attribute • Relevant to management concerns, goals, and strategies • Responds predictably and is sufficiently sensitive to changes in a specific key ecosystem attribute • Responds predictably and sufficiently sensitive to a specific management action or pressure • Capable of being linked to defined reference points and/or progress targets to judge progress
Data Issues	• Directly measurable • Supported by historical data or information • Operationally simple so that sampling, measuring, processing, and analyzing the indicator is technically feasible • Quantitative measurements if possible • Spatial coverage available in all areas of interest • Time series available • Spatial and temporal variation understood • High signal-to-noise ratio to ensure that natural variability in indicator values does not prevent detection of significant changes
Communication & Sustainability	• Simple to interpret, easy to communicate, and supportive of public understanding that is consistent with technical definitions • Perceived as reliable and meaningful by a history of reporting • Cost-effective • Able to signal changes in key ecosystem attributes before they occur and, ideally, with sufficient lead time to allow for a management response • Comparable to those used in other geographic locations to contextualize ecosystem state and changes relative to other locations

VI. ESTABLISHING A MONITORING SYSTEM FOR NEG

NEG is most likely to succeed when accompanied by appropriate monitoring, assessment, and accountability systems. Individual projects that aim to achieve NEG require both targeted and long-term monitoring of relevant ecological processes at the regional or landscape scale. Monitoring at multiple scales is necessary because landscape-scale ecological conditions and dynamics are important benchmark metrics against which to measure the cumulative effects of individual projects. However, an

important tenet of adaptive management is to use existing streams of monitoring data whenever possible, only adding further monitoring as needed to address critical uncertainties that pose risks to the achievement of project outcomes or to stakeholder interests (Ebberts et al., 2018). Although maintaining or establishing new monitoring programs can be challenging due to infrastructure and funding needs (Biber, 2011; Lindenmayer, 2020; Lovett et al., 2007), **monitoring is a critical component of NEG implementation that must be budgeted for and incorporated into planning at the regional and project scales.**

Knowledge of the relevant ecological system and its stressors, as well as awareness of the broader context, are foundational for developing comprehensive monitoring systems. As mentioned above in the section on Additional Considerations, a key component of implementing NEG is being able to understand and account for multiple interacting pressures on a system. Monitoring for multiple goals, including overarching landscape-scale goals, is therefore very important. Moreover, detecting and identifying pressures on a system requires long-term data collection, especially for detecting responses by the biological community. In some cases it may be possible to focus on a system's specific stressors and whether those stressors have been alleviated; however, this approach requires substantial prior knowledge of the system, its stressors, and what the effects of the development will be, and this level of knowledge is rarely available.

Other key considerations include timescale and geographic scale. Ideally, monitoring should entail comparison of metrics over time and should be calibrated to the timescale of affected processes, especially those that may extend past the project timeline. For example, monitoring of sediment accumulations in a breached levy would require time for the sediment to amass before measurements can be taken for comparison. In this example, targets at the project scale might pertain to limiting runoff, while targets at the landscape scale might pertain to achieving a cleaner overall outflow despite cumulative effects. In addition to accommodating temporal and geographic considerations, priorities and indicators for monitoring should be aligned across agencies.

Considerations for Urbanized Systems

Urban systems confer similar considerations as larger natural ecological systems. Establishing baseline measures or benchmarking existing conditions helps teams to understand the context of the project, set actionable goals, and establish how projects fit into a larger context of improving current or past states. Quantitative metrics to measure progress toward goals aid in decision making throughout the design process and after implementation. Projects often cross jurisdictional and disciplinary boundaries, sometimes requiring challenging collaborations among separate yet interrelated agencies and disciplines. Through integrated design and decision making, stakeholders can help define project goals and decision-making frameworks and contribute to establishing measurement and monitoring approaches. This integrated approach enables better documentation and understanding of successes or shortcomings within the projects and the impacts to the site, larger neighborhood, and beyond.

As with best practices in adaptive monitoring, there is value in using existing monitoring and metrics systems in urban systems (e.g., building-level municipal systems for monitoring water and energy). Use of public data sources enables assessment of how much water or energy is being used, where it is used,

and whether that usage matches the design intent. Although this type of data collection and monitoring is often already in place to quantify usage within a site context, such data could be used more extensively across larger spatial scales for project-based evaluations.

Similar to the other fundamental considerations for monitoring outlined above, urban systems require effective interagency collaboration to reach better benchmarking goals and carry out sufficient monitoring. Prioritizing the monitoring of cumulative effects across multiple objectives is also critical as development projects are planned and executed. In addition, there is a need for clear communication with design teams about current or past states so that these teams can set appropriate goals relevant to design, operation, and use and better understand how their work contributes to larger NEG goals. For example, in the Aurora Swales project, described in Box 5, communicating the composition of stormwater runoff prior to and after project implementation aids the project team in assessing the impact of the work, helps the agencies with jurisdiction confirm the effectiveness of the project, and supports decision making for implementing similar solutions in other scenarios.

Box 5. Case Study: Aurora Bridge Swales

Background: Urban populations are growing and so are the number of cars on roadways and the amount of toxins entering the environment. Within the past 6 years, researchers in the Pacific Northwest have identified thousands of chemicals present in urban stormwater runoff, including toxins specifically responsible for the drastic decline of salmon populations in Puget Sound.

As an indicator species, salmon serve as a signal to the overall health of the marine environment. A dramatic decline in Pacific Northwest salmon populations spurred researchers to study the effects of stormwater runoff on the health of aquatic environments. The findings conclusively linked roadway runoff with salmon deaths (Chow et al., 2019), but surprisingly, the expected culprits—heavy metals and petroleum—were not responsible for salmon declines. While the specific source of the issue was unclear at the time, research findings did reveal that soil could be used to effectively filter the toxins (Spromberg et al., 2016), thereby reducing the negative effects of runoff on the salmon.

At the same time as the preliminary research was published, the project team of a new commercial office development project in the Fremont neighborhood of Seattle, WA, was assembling. Inspired by the recent research about stormwater effects on salmon mortality, the group wanted to see how they could apply the findings to their new building. The proposed building site was directly adjacent to and below the Aurora Bridge, a historic structure in Seattle under which all five of the region's salmon species swim to reach the network of rivers and streams for spawning.

Solution: The initial idea was simple: leverage the project's adjacency to the bridge to divert a downspout from the bridge and clean the water using a vegetated area before the water reached the salmon.

The solution was to locate a swale on a steep roadway instead of creating the settling pools used in more conventional green infrastructure. Embracing the steep grade of the roadway, the swales step and overflow through Corten steel weirs with every 2 feet of grade change. The use of steel is echoed in all phases, with custom details expressing the water story throughout. Native plants provide a robust forest

floor below the canopy simulated by the bridge structure and columns. Flowering plants were also chosen to attract and support multiple species of local pollinators.

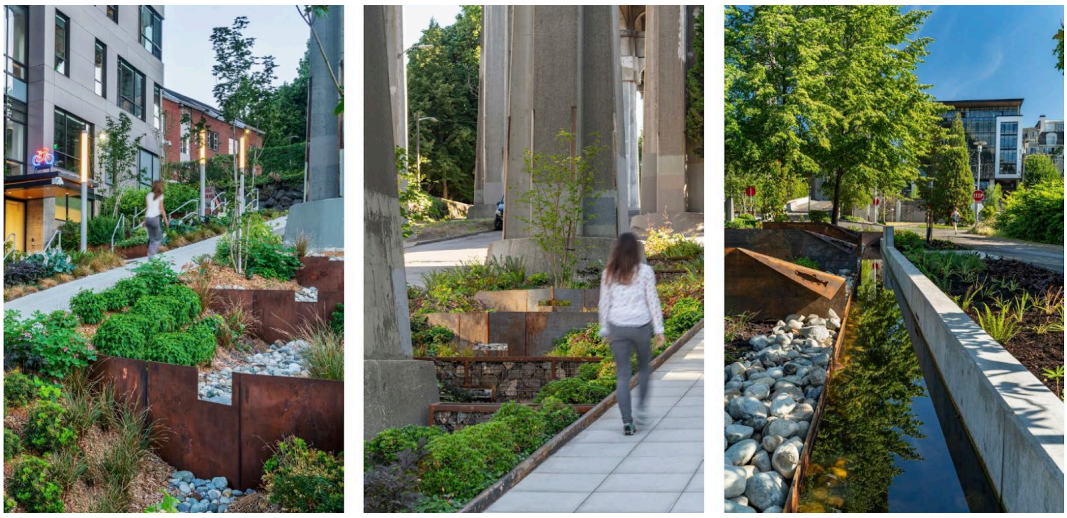


Figure 2. *The Aurora Bridge Swales phases I, II, and III is a first-of-its kind project that incorporates terraces of native plants and soils on three sites along the public right-of-way (Weber Thompson, 2022). These features function as a natural filter, and the project serves as a powerful example of the ability of private development to deploy a large-scale environmental response that can approach 100% effectiveness in reversing pollution's impacts through a replicable model.* ***This multi-faceted solution achieves NEG by beautifying the urban environment, improving biodiversity, mitigating heat-island impacts, and improving water quality while raising public awareness through community outreach and interactive educational elements.*** *Image credit: Meghan Montgomery, Built Work Photography.*

Challenges: Several barriers complicated the implementation of this vision. Among the most significant were the involvement of multiple municipal agencies and the lack of precedence for a private development to propose improvements that reach beyond the property boundary of the site. Specifically, the stormwater that falls on the Aurora Bridge changes jurisdiction many times before its outfall into Lake Union. Initially, rain falls onto the Washington State-owned bridge, where it flows into downspouts that are owned by the state but maintained by the Seattle Department of Transportation (SDOT). The downspouts end about 1 foot above the street below, where jurisdiction shifts solely to SDOT. From there, the stormwater enters a catch basin leading to a storm drain managed by Seattle Public Utilities, a subdivision of SDOT. When the storm drain crosses into a shoreline buffer within 200 feet of the water's edge of Lake Union, a set of Department of Ecology requirements and permits take effect, which include a below-grade outfall at the edge of the lake.

The simplicity of temporarily diverting stormwater was a critical factor in gaining support from the many review agencies. The approach avoided disputes over water rights or issues that might disenfranchise downstream users considering the water quality improvement.

Implementation: The second phase of the swales' construction occurred when the same design and development team proposed another office building on the opposite side of the bridge. With a clearer path for permitting and an established precedent, the project elected to divert two downspouts and take on the larger project goal of eliminating the use of potable water for non-potable uses within the building. The project installed a 20,000-gallon cistern to collect roof runoff and used the swale to slow and filter cistern overflow, which occurs for approximately 4 months out of the year.

A nearby property was also identified where five additional downspouts could be diverted into a grassy area. The third phase increased the volume of filtered bridge water to 2 million gallons, effectively treating the north half of the bridge deck above. **The goodwill and relationships built during the first and second phases helped to secure donations from other Fremont businesses for the third phase, as well as a matching grant from the state government.** As the third phase neared completion, researchers also successfully identified the chemical responsible for salmon deaths as 6PPD-quinone, a derivative of a preservative found in car tires (McIntyre et al., 2021; Tian et al., 2021).

Outcome: Tests of the water entering and leaving the swales confirmed measurable filtration of a large range of contaminants. The Aurora Bridge Swales project has won multiple awards for its successful design—most recently, the Honor Award in the General Design, Private Ownership category at the 2022 Washington Chapter American Society of Landscape Architects Awards (Weber Thompson, 2022).

Replicability: This project has high potential for replicability. Most urban bridges align with a roadway below; in these cases, green infrastructure is especially effective when the overflow at the end of the swale connects back to the existing storm pipe infrastructure that previously carried the unfiltered water to the lake or waterbody. **Reliance on green infrastructure can save municipalities from spending money to mechanically filter water at expensive treatment facilities.** Seattle Public Utilities has begun programs to incentivize similar improvements for private developments. A case study of the swales has also been included in a United Nations Guide for Sustainable Practices as a model to encourage professional designers to include green infrastructure as standard practice (Mossin et al., 2020).

Public communication and engagement: Public awareness of the transdisciplinary and innovative approach to this project is reinforced through many forms of public signage. Brass numbers embedded in the sidewalk illuminate the amount of water each swale cell mitigates. In addition, interactive brass plaques illustrate the many benefits of the strategies employed. Laser cutouts of the silhouettes of the five salmon species alert pedestrians to the greater story of how, **through smart development and design, we can help restore the aquatic environment.**



Figure 3. *The swales are built adjacent to the Aurora Bridge, a historic structure in Seattle where all five of the region's salmon species swim to reach the network of rivers and streams for spawning each year. Image credit: Weber Thompson.*

Box 6. Case Study: Seattle Waterfront

The current design of the Seattle waterfront is an excellent example of **how engineers and scientists used an interdisciplinary approach** to enhance the corridor that young salmon utilize along the waterfront as they out-migrate from the Duwamish River (Accola et al., 2022). This design was accomplished during the redevelopment of the Seattle waterfront for commercial and transportation operations.

The seawall and other structures of the highly developed Seattle waterfront suffered damage during an earthquake in 2001. A comprehensive effort to rebuild the waterfront included innovative measures to improve conditions for juvenile salmon migrating seaward from the adjacent Duwamish River. Scientists from the University of Washington and state agencies developed a plan to improve the migratory corridor used by salmon. This approach included texturizing the seawall, as well as enhancing light by incorporating glass blocks in the pedestrian walkway that borders the shoreline. The glass blocks allowed light to reach areas along the new seawall that supported algae growth. Algae form habitat for prey utilized by juvenile salmon. The light also enhanced the young salmon's ability to maintain their out-migration pattern. Research has demonstrated that the juveniles have benefited from these science-backed innovations (Accola et al., 2022). The combination of seawall enhancements and light transmittance through the walkway is considered a clear example of net ecological gain within the context of a highly active and developed shoreline redevelopment project.

Although the Seattle waterfront project includes elements from the Clinton Ferry Terminal Rebuild example, the Seattle project took advantage of a natural disaster to enhance a selected attribute (e.g., salmon feeding, rearing, and migration) in support of net ecological gain. The city of Seattle took the opportunity to highlight the positive benefits of the project and educate residents about salmon and how the community can use science to improve the environment.

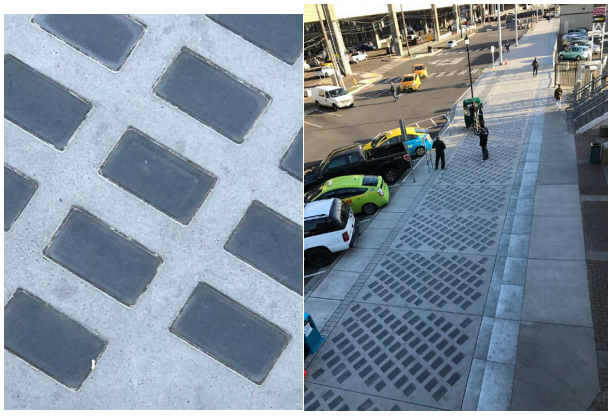


Figure 4. *View of glass blocks in Seattle waterfront walkway. These blocks allow light to stimulate growth of benthic algae that harbor prey for juvenile salmon. The blocks also provide a lighted corridor for migration of the juveniles as they exit Elliott Bay.*

VII. MONITORING IN WASHINGTON STATE

Several successful monitoring programs are found throughout the state. There are also newly developed tools and approaches for facilitating efficient monitoring across larger geographic areas (NASEM, 2022). However, not all of these resources are designed to assess indicators at the fine spatial or temporal scales that may be required at the project scale. Thus, **for individual projects, when there are critical uncertainties that would affect a system or community, there should be resources allocated for assessing variables and monitoring outcomes that go beyond data collection from previously existing regional monitoring programs**. There should also be contingency plans to repair and restore critical ecosystem elements if unexpected issues arise. This process is especially important for built infrastructure, which poses unique challenges to monitoring because development projects cannot typically be redone once they are completed.

At the landscape scale, there may also be potential for existing monitoring programs in the state to be strengthened and integrated with one another. Increased interagency collaboration and improved coordination of monitoring efforts across public and private entities could help expand spatial and temporal coverage and provide more comprehensive data on ecological trends across the state. This coordination and adequate funds to enable it are increasingly important as ecosystems and the species within them respond to climate change and land use change simultaneously.

Ecosystem types are classified by the Washington Natural Heritage Program (Washington State Department of Natural Resources, 2022), with data maintained through the international NatureServe network (http://www.natureserve.com) and summarized on an approximately 5-year cycle in State Natural Heritage Plans. Department of Natural Resources scientists have prioritized these ecosystems by conservation status ranks across each ecosystem's state (S) range and entire or global (G) range (Washington Natural Heritage Program, 2022).

A helpful step toward ecosystem process-based understanding would be the creation of a resource available to practitioners and stakeholders that is structured by the state's ecosystem types and includes the various monitoring programs that are or were implemented within each ecosystem's boundaries. The monitoring programs listed would include, for example, those for water quality and quantity, sediment transport, land cover type, geological evolution, and biota, with links to monitoring data and published reports, journal articles, and student theses and dissertations.

One demonstrated way of approaching the challenge of monitoring is to define Essential (or Potential) Conservation Areas. Several other states, including Colorado and Virginia, designate such areas as part of their natural heritage methodology. These areas are established by defining ecological boundaries around the occurrence of certain ecological elements that require long-term protection. Box 7 presents an example of how Colorado approaches this challenge.

Box 7. Potential Conservation Area (PCA):

"PCAs represent Colorado Natural Heritage's Program's best estimates of the primary areas supporting the long-term survival of targeted element occurrences and typically include adjacent suitable habitat and buffers from disturbance. PCA refers to the ability of a conservation area to maintain healthy, viable targets over the long term (100+ years), including the ability to respond to natural or human-caused environmental change. PCAs do not necessarily preclude human activities, but their ability to function naturally may be greatly influenced by them. PCAs at all scales may require ecological management or restoration to maintain their functionality. PCAs are assigned biodiversity significance ranks ranging from 1 (Outstanding Significance) to 5 (General Interest). Ranks are based on the rarity and quality of the element occurrences in the site.

Additionally, PCAs:

- Are often based on desk-top scientific references and need ground-truthing
- Focus on biological and physical factors and do not account for land ownership and political concerns
- Support land-use planning and conservation strategies but do not have legal meaning or in any way represent an attempt to regulate or limit the use of private property
- Do not automatically exclude specific activities, rather it is hypothesized that some activities will cause degradation to the elements or the processes on which they depend, while others will not."

(Colorado Natural Heritage Program, https://cnhp.colostate.edu/ourdata/help/)

VIII. NEXT STEPS FOR ADVANCING NEG IN WASHINGTON STATE

Within this report, the committee aimed to provide guidance on implementing NEG but recognizes that other critical steps must be taken prior to operationalizing this concept. Enabling NEG is a complicated process and a fairly new concept for which implementation practices will likely be learned and refined over time. Moreover, the successful implementation of NEG will vary by project scope and scale, with no single correct approach or solution.

The committee recommends the following initial steps to lay the groundwork for implementing and attaining NEG.

- Engage with the public throughout the project to increase trust, buy-in, and input around the NEG concept.
- Ensure adequate monitoring of ecosystems and habitats throughout the state to provide baselines and identify key indicators for NEG in future projects.
- Enable and incentivize cross-agency and cross-disciplinary communication and collaboration on NEG-related issues throughout the state.
- Create resources that provide information on all current monitoring systems to facilitate collaboration and access to relevant information.

- Invest in research, monitoring, and planning regarding climate change resilience to ensure ecosystem resilience and infrastructure sufficiency for addressing the impacts of future climate stressors.
- Provide funding and educational opportunities to develop a workforce trained in collaborative, interdisciplinary approaches to solving socio-ecological challenges in Washington State.

Overall, NEG provides an opportunity to take a transdisciplinary approach to promoting the health and well-being of Washington residents and the ecosystems they rely on. The precise approaches to NEG will vary by project and will depend upon available scientific evidence, engineering capabilities, and community needs. To help determine the appropriate approach for each situation, **the committee recommends the creation of a joint, interagency NEG council or committee comprising contributors from each state agency.** The Natural Areas Preserve Act of 1972—and the subsequently formed Natural Heritage Advisory Council and Natural Resources Conservation Areas—provide a possible template for cross-agency efforts to identify areas in need of protection and approaches for promoting NEG when such areas may be impacted. The committee urges that regional experts; natural, physical, and social scientists; engineers; and community leaders and partners be involved in assembling this council.

IX. CONCLUSION

In this chapter, the Committee addressed the present understanding of no net loss relative to net ecological gain and provided background information and recommendations on the process of developing metrics and indicators for net ecological gain.

Local, national, and global studies have shown that the NNL approach has been widely used but has been generally unsuccessful for several reasons. Reasons include the continued loss of habitat quality and area, inadequate implementation, offsite (as opposed to onsite) actions, and lack of enforcement. In contrast, NEG aims to achieve documented improvement in ecosystem health from the baseline ecosystem condition following redevelopment.

Successful implementation of NEG requires systematic assessment of (1) baseline conditions at a location and how the site contributes to ecological processes regionally and (2) what approaches can best be applied to maximize the probability of quantifiable gain following a redevelopment of the site. The first step should rely on available science, while the second requires input from natural and social scientists, engineers, and stakeholders to define the desired state, appropriate indicators, and steps that can be taken to achieve the desired state. The committee recognizes the complexity of these tasks and recommends employing the systematic process of structured decision making. The committee also advises applying a transdisciplinary approach that addresses social-ecological needs across multiple spatial scales.

Because of the wide array of physical and ecological conditions, as well as the diversity of potential development projects, the application of NEG is contextual. This diversity emphasizes the need to establish a process that is applicable across a range of conditions and situations. Project impacts must

also be assessed within the context of ongoing or future projects, the current condition of the surrounding landscape, and the human well-being aspects of the location, as well as projected climate change impacts.

Throughout the process of planning and quantifying NEG, there is a need for objective, science-based metrics and indicators. Within this chapter, the committee has provided a set of standard methods and guidance to develop metrics, set indicators, and establish a performance monitoring system. The committee has also included examples of recognized NEG projects in Washington State. Finally, the committee has recommended steps, including strong public involvement, to move forward in enabling and implementing NEG.

X. REFERENCES

Accola, K., Horne, J., Cordell, J., & Toft, J. (2022). Acoustic characterization of juvenile Pacific salmon distributions along an eco-engineered seawall. *Marine Ecology Progress Series*, *682*, 207–220. https://doi.org/10.3354/meps13917

Arlidge, W. N., Bull, J. W., Addison, P. F., Burgass, M. J., Gianuca, D., Gorham, T. M., Jacob, C., Shumway, N., Sinclair, S. P., & Watson, J. E. (2018). A global mitigation hierarchy for nature conservation. *BioScience*, *68*(5), 336–347.

Bennett, G., Gallant, M., & Ten Kate, K. (2017). State of biodiversity mitigation 2017: Markets and compensation for global infrastructure development. *Forest Trends' Ecosystem Marketplace, Washington, DC*.

Biber, E. (2011). The problem of environmental monitoring. *University of Colorado Law Review*, *83*(1).

Borde, A. B., Diefenderfer, H. L., Cullinan, V. I., Zimmerman, S. A., & Thom, R. M. (2020). Ecohydrology of wetland plant communities along an estuarine to tidal river gradient. *Ecosphere*, *11*(9), e03185.

Buenau, K. E., Hiller, T. L., & Tyre, A. J. (2014). Modelling the effects of river flow on population dynamics of piping plovers (Charadrius melodus) and least terns (Sternula antillarum) nesting on the Missouri River. *River Research and Applications*, *30*(8), 964–975.

Bull, J. W., Gordon, A., Law, E. A., Suttle, K. B., & Milner-Gulland, E. J. (2014). Importance of baseline specification in evaluating conservation interventions and achieving no net loss of biodiversity. *Conservation Biology*, *28*(3), 799–809.

Bull, J. W., & Strange, N. (2018). The global extent of biodiversity offset implementation under no net loss policies. *Nature Sustainability*, *1*(12), 790–798.

Business and Biodiversity Offsets Programme (BBOP). (2012a). *Guidance notes to the Standard on Biodiversity Offsets*. BBOP.

Business and Biodiversity Offsets Programme (BBOP). (2012b). *Standard on Biodiversity Offsets*. BBOP.

Cereghino, P., Toft, J. D., Simenstad, C. A., Iverson, E., & Burke, J. (2012). *Strategies for nearshore protection and restoration in Puget Sound*. U.S. Army Corps of Engineers, Seattle District.

Chow, M. I., Lundin, J. I., Mitchell, C. J., Davis, J. W., Young, G., Scholz, N. L., & McIntyre, J. K. (2019). An urban stormwater runoff mortality syndrome in juvenile Coho salmon. *Aquatic Toxicology*, *214*, 105231.

Colorado Natural Heritage Program (CNHP), Colorado State University. (2022). *Colorado Natural Heritage Program*. https://cnhp.colostate.edu/ourdata/help/

Dawson, T. P., Jackson, S. T., House, J. I., Prentice, I. C., & Mace, G. M. (2011). Beyond predictions: Biodiversity conservation in a changing climate. *Science*, *332*(6025), 53–58.

Díaz, S., Demissew, S., Carabias, J., Joly, C., Lonsdale, M., Ash, N., Larigauderie, A., Adhikari, J. R., Arico, S., & Báldi, A. (2015). The IPBES Conceptual Framework—Connecting nature and people. *Current Opinion in Environmental Sustainability*, *14*, 1–16.

Díaz, S., Zafra-Calvo, N., Purvis, A., Verburg, P. H., Obura, D., Leadley, P., Chaplin-Kramer, R., De Meester, L., Dulloo, E., Martín-López, B., Shaw, M. R., Visconti, P., Broadgate, W., Bruford, M. W., Burgess, N. D., Cavender-Bares, J., DeClerck, F., Fernández-Palacios, J. M., Garibaldi, L. A., … Zanne, A. E. (2020). Set ambitious goals for biodiversity and sustainability. *Science*, *370*(6515), 411–413. https://doi.org/10.1126/science.abe1530

Diefenderfer, H. L., Borde, A. B., & Cullinan, V. I. (2021). Floodplain wetland channel planform, cross-sectional morphology, and sediment characteristics along an estuarine to tidal river gradient. *Journal of Geophysical Research: Earth Surface*, *126*(5), e2019JF005391.

Diefenderfer, H. L., Johnson, G. E., Thom, R. M., Buenau, K. E., Weitkamp, L. A., Woodley, C. M., Borde, A. B., & Kropp, R. K. (2016). Evidence-based evaluation of the cumulative effects of ecosystem restoration. *Ecosphere*, *7*(3), e012421. https://doi.org/10.1002/ecs2.1242

Diefenderfer, H. L., Sobocinski, K. L., Thom, R. M., May, C. W., Borde, A. B., Southard, S. L., Vavrinec, J., & Sather, N. K. (2009). Multiscale analysis of restoration priorities for marine shoreline planning. *Environmental Management*, *44*(4), 712–731. https://doi.org/10.1007/s00267-009-9298-4

Diefenderfer, H. L., Steyer, G. D., Harwell, M. C., LoSchiavo, A. J., Neckles, H. A., Burdick, D. M., Johnson, G. E., Buenau, K. E., Trujillo, E., Callaway, J. C., Thom, R. M., Ganju, N. K., & Twilley, R. R. (2020). Applying cumulative effects to strategically advance large-scale ecosystem restoration. *Frontiers in Ecology and the Environment*, *19*(2), 108–117. https://doi.org/10.1002/fee.2274

Ebberts, B. D., Zelinsky, B. D., Karnezis, J. P., Studebaker, C. A., Lopez-Johnston, S., Creason, A. M., Krasnow, L., Johnson, G. E., & Thom, R. M. (2018). Estuary ecosystem restoration: Implementing and institutionalizing adaptive management: Institutionalizing adaptive management. *Restoration Ecology*, *26*(2), 360–369. https://doi.org/10.1111/rec.12562

Fertig, W. (n.d.-a). *Climate Change Vulnerability Index reports for selected Washington State rare plant species. Natural heritage report 2020-04* (No. 2020–04). U.S. Forest Service.

Fertig, W. (n.d.-b). *Climate Change Vulnerability Index reports for selected Washington State rare plant species: Phase II. Natural heritage report 2022-01* (No. 2022–01). U.S. Forest Service.

Frans, C., Istanbulluoglu, E., Lettenmaier, D. P., Fountain, A. G., & Riedel, J. (2018). Glacier recession and the response of summer streamflow in the Pacific Northwest United States, 1960–2099. *Water Resources Research*, *54*(9), 6202–6225.

Gann, G. D., McDonald, T., Walder, B., Aronson, J., Nelson, C. R., Jonson, J., Hallett, J. G., Eisenberg, C., Guariguata, M. R., & Liu, J. (2019). International principles and standards for the practice of ecological restoration. *Restoration Ecology. 27 (S1): S1-S46.*, *27*(S1), S1–S46.

Gardner, T. A., Von Hase, A., Brownlie, S., Ekstrom, J. M. M., Pilgrim, J. D., Savy, C. E., Stephens, R. T. T., Treweek, J., Ussher, G. T., Ward, G., & Ten Kate, K. (2013). Biodiversity offsets and the challenge of achieving no net loss: Biodiversity offsets and no net loss. *Conservation Biology*, *27*(6), 1254–1264. https://doi.org/10.1111/cobi.12118

Grantham, T. E., Matthews, J. H., & Bledsoe, B. P. (2019). Shifting currents: Managing freshwater systems for ecological resilience in a changing climate. *Water Security*, *8*, 100049.

Gregory, R., Failing, L., Harstone, M., Long, G., McDaniels, T., & Ohlson, D. (2012). *Structured decision making: A practical guide to environmental management choices*. John Wiley & Sons.

Halofsky, J. E., Peterson, D. L., & Harvey, B. J. (2020). Changing wildfire, changing forests: The effects of climate change on fire regimes and vegetation in the Pacific Northwest, USA. *Fire Ecology*, *16*(1), 1–26.

Hood, W. G., Blauvelt, K., Bottom, D. L., Castro, J. M., Johnson, G. E., Jones, K. K., Krueger, K. L., Thom, R. M., & Wilson, A. (2022). Using landscape ecology principles to prioritize habitat restoration projects across the Columbia River Estuary. *Restoration Ecology*, *30*(3), e13519.

Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES). (2015). *IPBES/3/18—Report of the Plenary of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services on the work of its third session, Decision IPBES-3/4: Communications, stakeholder engagement and strategic partnership*.

James, C. A., Kershner, J., Samhouri, J., O'Neill, S., & Levin, P. S. (2012). A methodology for evaluating and ranking water quantity indicators in support of ecosystem-based management. *Environmental Management*, *49*(3), 703–719.

Karr, J. R., Larson, E. R., & Chu, E. W. (2021). Ecological integrity is both real and valuable. *Conservation Science and Practice*. https://doi.org/10.1111/csp2.583

Koontz, E. D., Steel, E. A., & Olden, J. D. (2018). Stream thermal responses to wildfire in the Pacific Northwest. *Freshwater Science*, *37*(4), 731–746.

Levin, P. S., Essington, T. E., Marshall, K. N., Koehn, L. E., Anderson, L. G., Bundy, A., Carothers, C., Coleman, F., Gerber, L. R., & Grabowski, J. H. (2018). Building effective fishery ecosystem plans. *Marine Policy*, *92*, 48–57.

Lindenmayer, D. (2020). Improving restoration programs through greater connection with ecological theory and better monitoring. *Frontiers in Ecology and Evolution*, *8*, 50. https://doi.org/10.3389/fevo.2020.00050

Locke, H., Rockström, J., Bakker, P., Bapna, M., Gough, M., Lambertini, M., Morris, J., Polman, P., Samper, C., Sanjayan, M., Zabey, E., & Zurita, P. (2021). *A nature-positive world: The global goal for nature*.

Lovett, G. M., Burns, D. A., Driscoll, C. T., Jenkins, J. C., Mitchell, M. J., Rustad, L., Shanley, J. B., Likens, G. E., & Haeuber, R. (2007). Who needs environmental monitoring? *Frontiers in Ecology and the Environment*, *5*(5), 253–260. https://doi.org/10.1890/1540-9295(2007)5[253:WNEM]2.0.CO;2

Maron, M., Brownlie, S., Bull, J. W., Evans, M. C., von Hase, A., Quétier, F., Watson, J. E., & Gordon, A. (2018). The many meanings of no net loss in environmental policy. *Nature Sustainability*, *1*, 19–27.

Maron, M., Juffe-Bignoli, D., Krueger, L., Kiesecker, J., Kümpel, N. F., ten Kate, K., Milner-Gulland, E. J., Arlidge, W. N. S., Booth, H., Bull, J. W., Starkey, M., Ekstrom, J. M., Strassburg, B., Verburg, P. H., & Watson, J. E. M. (2021). Setting robust biodiversity goals. *Conservation Letters*, *14*(5). https://doi.org/10.1111/conl.12816

McIntyre, J. K., Prat, J., Cameron, J., Wetzel, J., Mudrock, E., Peter, K. T., Tian, Z., Mackenzie, C., Lundin, J., Stark, J. D., King, K., Davis, J. W., Kolodziej, E. P., & Scholz, N. L. (2021). Treading water: Tire wear particle leachate recreates an urban runoff mortality syndrome in Coho but not chum salmon. *Environmental Science & Technology*, *55*(17), 11767–11774. https://doi.org/10.1021/acs.est.1c03569

Moilanen, A., & Kotiaho, J. S. (2018). Fifteen operationally important decisions in the planning of biodiversity offsets. *Biological Conservation*, *227*, 112–120.

Mossin, N., Stilling, S., Bøjstrup, T. C., & Hau, I. (2020). *An architecture guide to the UN 17 sustainable development goals: Volume 2*.

National Academies of Sciences, Engineering, and Medicine. (2022). *An approach for assessing U.S. Gulf Coast ecosystem restoration: A Gulf Research Program environmental monitoring report*. The National Academies Press. https://doi.org/10.17226/26335

National Research Council. (1992). *Restoration of aquatic ecosystems: Science, technology, and public policy*. National Academies Press.

National Research Council. (2001). *Compensating for wetland losses under the Clean Water Act*. National Academies Press.

Neckles, H. A., Lyons, J. E., Guntenspergen, G. R., Shriver, W. G., & Adamowicz, S. C. (2015). Use of structured decision making to identify monitoring variables and management priorities for salt marsh ecosystems. *Estuaries and Coasts*, *38*(4), 1215–1232. https://doi.org/10.1007/s12237-014-9822-5

Pope, J., Morrison-Saunders, A., Bond, A., & Retief, F. (2021). When is an offset not an offset? A framework of necessary conditions for biodiversity offsets. *Environmental Management*, *67*(2), 424–435.

Pörtner, H. O., Alegría, A., Möller, V., Poloczanska, E. S., Mintenbeck, K., & Götze, S. (In press). IPCC, 2022: Annex I: Global to regional atlas. In H. O. Pörtner, D. C. Roberts, M. Tignor, E. S. Poloczanska, K. Mintenbeck, A. Alegría, M. Craig, S. Langsdorf, S. Löschke, V. Möller, A. Okem, & B. Rama (Eds.), *Climate change 2022: Impacts, adaptation, and vulnerability. Contribution of Working Group II to the sixth assessment report of the Intergovernmental Panel on Climate Change*. Cambridge University Press.

Puget Sound Recovery Implementation Technical Team. (2015). *Puget Sound Chinook salmon recovery: A framework for the development of monitoring and adaptive management plans*. National Oceanic and Atmospheric Administration.

Rocchio, F. J., & Crawford, R. C. (2011). *Applying NatureServe's ecological integrity assessment methodology to Washington's ecological systems*. Washington Natural Heritage Program, Washington Department of Natural Resources. http://www1. dnr. wa. gov/nhp/refdesk/communities/pdf/eia/applying_eia. pdf

Rohwer, Y., & Marris, E. (2021). Ecosystem integrity is neither real nor valuable. *Conservation Science and Practice*, *3*(4). https://doi.org/10.1111/csp2.411

Ruhl, J. B., & Salzman, J. (2011). Gaming the past: The theory and practice of historic baselines in the administrative state. *Vand. L. Rev.*, *64*, 1.

Spromberg, J. A., Baldwin, D. H., Damm, S. E., McIntyre, J. K., Huff, M., Sloan, C. A., Anulacion, B. F., Davis, J. W., & Scholz, N. L. (2016). Coho salmon spawner mortality in western U.S. urban watersheds: Bioinfiltration prevents lethal storm water impacts. *Journal of Applied Ecology*, *53*(2), 398–407. https://doi.org/10.1111/1365-2664.12534

Thom, R. M., Diefenderfer, H. L., Vavrinec, J., & Borde, A. B. (2012). Restoring resiliency: Case studies from Pacific Northwest estuarine eelgrass (Zostera marina L.) ecosystems. *Estuaries and Coasts*, *35*(1), 78–91. https://doi.org/10.1007/s12237-011-9430-6

Thom, R. M., Williams, G., Borde, A., Southard, J., Sargeant, S., Woodruff, D., Laufle, J. C., & Glasoe, S. (2005a). Adaptively addressing uncertainty in estuarine and near coastal restoration projects. *Journal of Coastal Research*, 94–108. JSTOR.

Thom, R. M., Williams, G. W., & Diefenderfer, H. L. (2005b). Balancing the need to develop coastal areas with the desire for an ecologically functioning coastal environment: Is net ecosystem improvement possible? *Restoration Ecology*, *13*(1), 193–203. https://doi.org/10.1111/j.1526-100X.2005.00024.x

Tian, Z., Zhao, H., Peter, K. T., Gonzalez, M., Wetzel, J., Wu, C., Hu, X., Prat, J., Mudrock, E., Hettinger, R., Cortina, A. E., Biswas, R. G., Kock, F. V. C., Soong, R., Jenne, A., Du, B., Hou, F., He, H., Lundeen, R., … Kolodziej, E. P. (2021). A ubiquitous tire rubber-derived chemical induces acute mortality in Coho salmon. *Science*, *371*(6525), 185–189. https://doi.org/10.1126/science.abd6951

Timpane-Padgham, B. L., Beechie, T., & Klinger, T. (2017). A systematic review of ecological attributes that confer resilience to climate change in environmental restoration. *PLOS ONE*, *12*(3), e0173812. https://doi.org/10.1371/journal.pone.0173812

U.S. Environmental Protection Agency. (2022). *Ecosystem services*. https://www.epa.gov/eco-research/ecosystem-services

Washington Department of Fish and Wildlife. (2021). *2021 game status and trend report*. https://wdfw.wa.gov/sites/default/files/publications/02298/wdfw02298.pdf

Washington Department of Natural Resources. (2022). *State of Washington Natural Heritage Plan* (p. 92). Washington Department of Natural Resources.

Washington State Academy of Sciences. (2022). *Net ecological gain definition, goals, and objectives* (pp. 1–16). WSAS.

Washington State Department of Natural Resources. (2022). *Natural Heritage Program*. https://www.dnr.wa.gov/natural-heritage-program

Washington State Legislature. (2021). *SB 5141—2021-22: Implementing the recommendations of the environmental justice task force.* https://app.leg.wa.gov/billsummary?BillNumber=5141&Initiative=false&Year=2021

Weber Thompson. (2022). *Aurora Bridge Swales Project*.

Wende, W., Tucker, G., Quétier, F., Rayment, M., & Darbi, M. (2018). *Biodiversity offsets*. Springer.

Whidbey Cumulative Effects Group. (2022). *The cumulative effects of nearshore habitat recovery on juvenile salmonids in the Whidbey Basin: A study development report*. Puget Sound Partnership.

Wurtzebach, Z., & Schultz, C. (2016). Measuring ecological integrity: History, practical applications, and research opportunities. *BioScience*, *66*(6), 446–457. https://doi.org/10.1093/biosci/biw037

Yeardley, R. B. J., Dyson, B., & Tenbrink, M. (2011). *EPA growing DASEES (Decision Analysis for a Sustainable Environment, Economy & Society)—To aid in making decisions on complex environmental issues*. U.S. Environmental Protection Agency.

Young, B., Hall, K., Byers, E., Gravuer, K., Hammerson, G., Redder, A., & Szabo, K. (n.d.). Rapid assessment of plant and animal vulnerability to climate change. In J. F. Brodie, E. Post, & D. F. Doak (Eds.), *Wildlife conservation in a changing climate* (pp. 129–150). University of Chicago Press.

zu Ermgassen, S. O. S. E., Baker, J., Griffiths, R. A., Strange, N., Struebig, M. J., & Bull, J. W. (2019). The ecological outcomes of biodiversity offsets under “no net loss” policies: A global review. *Conservation Letters*, *12*(6). https://doi.org/10.1111/conl.12664

Appendix A.

Example of principles (P), criteria (C), and implementation indicators (I) to consider during the orientation and planning steps of a net ecological gain process. Table is divided into the four major stages of the process, and for each stage, the relevant Principles, Criteria, and Indicators are described in summary form. Although stages are organized sequentially, planning is usually iterative as some activities may call for refining earlier work. Excerpted and adapted from the Business and Biodiversity Offsets Programme (BBOP; 2012a, 2012b) to illustrate concepts.

Stage and Activity	Principles (P), Criteria (C) & Indicators
Review project scope & activities	P1: *Adherence to the mitigation hierarchy: A biodiversity offset is a commitment to compensate for significant residual adverse impacts on biodiversity identified after appropriate avoidance, minimization and on-site rehabilitation measures have been taken according to the mitigation hierarchy.*
	C: The developer shall identify, implement, and document appropriate measures to avoid and minimize the direct, indirect and cumulative negative impacts of the development project and to undertake on-site rehabilitation/restoration.
	I: An assessment of the development project's impacts on biodiversity (including direct, indirect and cumulative impacts, as appropriate) is conducted with stakeholder participation
Review the legal framework and/or policy context for a biodiversity offset	P4: *Net Ecological Gain: A biodiversity offset should be designed and implemented to achieve in situ, measurable conservation outcomes that can reasonably be expected to result in net gain of biodiversity and resilience.*
	C: The net gain goal for the development project shall be explicitly stated, and the offset design and conservation outcomes required to achieve this goal clearly described.
	I: All residual biodiversity losses due to the project are quantified relative to the 'pre-project' condition of affected biodiversity, which is identified, characterized, and documented.
	C: An explicit calculation of loss and gain shall be undertaken as the basis for the offset design and shall demonstrate the manner in which a net gain of biodiversity can be achieved by the offset.
	I: A set of key biodiversity components at species, habitats, and ecosystem levels, including landscape features and components related to use and cultural values, is identified. The rationale for selecting these key biodiversity components to represent all the biodiversity affected by the project is explained and documented.
	P2: *Limits to what can be offset: There are situations where residual impacts cannot be fully compensated for by a biodiversity offset because of the irreplaceability or vulnerability of the biodiversity affected.*
	C: The risk that the project's residual impacts on biodiversity may not be capable of being offset ('non-offsetable') shall be assessed and measures taken to minimize this risk.

	I: An assessment is undertaken to predict the level of risk that the project's residual impacts on biodiversity will be or not be capable of being offset, with special attention afforded to any highly irreplaceable and vulnerable biodiversity components.
Initiate a tribal participation process	*P6: Tribal participation: Tribes who depend on the land and its biodiversity to sustain their treaty rights will be included in the decision-making about biodiversity offsets, including their evaluation, selection, design, implementation, and monitoring.*
	C: Consultation and participation of tribes shall be integrated into the decision-making process for offset design and implementation and documented in the Biodiversity Offset Management Plan.
	I: For projects and/or offsets with adverse impacts on tribes, their free, prior and informed consent (FPIC) will be obtained and documented.
Initiate a stakeholder participation process	P6: *Stakeholder participation: In areas affected by the development project and by the biodiversity offset, the effective participation of stakeholders should be ensured in decision-making about biodiversity offsets, including their evaluation, selection, design, implementation, and monitoring.*
	C: Consultation and participation of relevant stakeholders shall be integrated into the decision-making process for offset design and implementation and documented in the Biodiversity Offset Management Plan.
	I: Documentation of consultation and participation of stakeholders.
Apply mitigation hierarchy. Review significance of impact at regional and landscape level	P1: *Adherence to the mitigation hierarchy:*
	C: The developer shall identify, implement and document appropriate measures to avoid and minimise the direct, indirect and cumulative negative impacts of the development project and to undertake on-site rehabilitation/restoration.
	I: Measures to avoid and minimise biodiversity loss and to rehabilitate/restore biodiversity affected by the project are defined and documented, and these measures implemented, monitored and managed for the duration of the project's impacts.
	C: The biodiversity offset shall only address the residual impacts of the development project, namely those impacts left after all the appropriate avoidance, minimisation and rehabilitation/restoration actions have been identified.
	I: Any residual losses of biodiversity that may exist following avoidance, minimisation and rehabilitation/restoration are identified and described in the Biodiversity Offset Management Plan.
	P2: *Limits to what can be offset*
	C: The risk that the project's residual impacts on biodiversity may not be capable of being offset ('non-offsetable') shall be assessed and measures taken to minimise this risk.

	I: The risk assessment demonstrates how the project's residual impacts can and will be offset through specific measures and commitments, taking into account the level of risk and uncertainties regarding the delivery of the offset.
Determine the need for an offset based on residual adverse effects	*P6: Tribal participation*
	C: Consultation and participation of relevant tribes shall be integrated into the decision-making process for offset design and implementation, and documented in the Biodiversity Offset Management Plan.
	I: Relevant tribes are identified and informed of the desire to design and implement a biodiversity offset for the project.
	I: Records are maintained that document the results of informed consultation and participation of relevant tribes related to the design and implementation of the biodiversity offset.
	P6: *Stakeholder participation*
	C: Consultation and participation of relevant stakeholders shall be integrated into the decision-making process for offset design and implementation, and documented in the Biodiversity Offset Management Plan.
	I: Relevant stakeholders are identified and informed of the plan to design and implement a biodiversity offset for the project.
	I: Records are maintained that document the results of informed consultation and participation of relevant stakeholders related to the design and implementation of the biodiversity offset.
	P9: Transparency: The design and implementation of a biodiversity offset, and communication of its results to the public, should be undertaken in a transparent and timely manner.
	C: The developer responsible for designing and implementing the biodiversity offset shall ensure that clear, up to date, and easily accessible information is provided to stakeholders and the public on the offset design and implementation, including outcomes to date.
	I: An independent mechanism (such as a steering committee, review panel, or system for peer review) is established to oversee the offset design and implementation process and report regularly to the public on their assessment of progress.
	I: Information on baseline findings, impact assessment as well as offset design and implementation is reported to stakeholders and the public in appropriate media during offset design and implementation

BIBLIOGRAPHY

Bibliography of Sources

[1] Washington State Academy of Science, "Report on Net Ecological Gain," Prepared for the Washington State Department of Fish and Wildlife, 2022.

[2] Department of Ecology, "SMP Handbook Chapter 4 No Net Loss of Shoreline Ecological Functions," 2009.

[3] G. Tucker, W. Wende, F. Quétier, M. Rayment and M. Darbi, "Biodiversity Offsets—The European Perspective on No Net Loss of Biodiversity and Ecosystem Services," 2018.

[4] Washington Biodiversity Council, "Washington Biodiversity Status and Threats," 2019.

[5] Washington State Academy of Sciences, "Assessment of No Net Loss and Recommendations for Net Ecological Gain Metrics, Indicators, and Monitoring," Prepared for the Washington State Department of Fish and Wildlife, 2022.

[6] S. zu Ermgassen, J. Baker, R. Griffiths, N. Strange, M. Struebig and J. Bull, "The ecological outcomes of biodiversity offsets under “no net loss” policies: A global review," *Conservation Letters,* vol. 12, no. 6, 2019.

[7] POST (Parliamentary Office of Science and Technology), "POSTbrief 34: Net Gain," UK Parliament, 2019.

[8] The Environment Bank, "Accounting for Biodiversity in Planning. A toolkit for Local Planning Authorities in England.," 2018.

[9] Tahoe Regional Planning Agency, "Threshold Standards and Regional Plan," 2012.

[10] J. Bull and S. Brownlie, "The transition from No Net Loss to a Net Gain of biodiversity is far from trivial," *Oryx,* vol. 51, no. 1, pp. 53-59, 2015.

[11] S. Trémolet, I. Dickie, J. Treweek and T. Reisch, "Biodiversity Net Gain in England: Developing Effective Market Mechanisms. A Discussion Paper," The Nature Conservancy, London, 2021.

[12] J. Baker, "Biodiversity Net Gain: Good practice principles for development," 2016.

[13] J. Baker, R. Hoskin and T. Betterworth, "Biodiversity net gain. Good practice principles for development. A practical guide.," 2019.

[14] Chartered Institution of Water and Environmental Management, "Environmental Net Gain. Measurement, Devlivery, and Application.," Findings of the CIWEM conference, London, 2018.

[15] State of Washington Office of the Attorney General Bob Ferguson, "Advisory Memorandum and Recommended Process for Evaluating Proposed Regulatory or Administrative Actions to Avoid Unconstitutional Takings of Private Property," 2018.

[16] J. P. G. Jones, J. W. Bull, D. Roe, J. Baker, V. F. Griffiths, M. Starkey, L. J. Sonter and E. Milner-Gulland, "Net Gain: Seeking Better Outcomes for Local People when Mitigating Biodiversity Loss from Development," *One Earth,* vol. 1, no. 2, pp. 195-201, 2019.

[17] Tahoe Regional Planning Council, "Threshold Standards and Regional Plan," 1987.

[18] Ministry of Housing, Communities & Local Government, "National Planning Policy Framework," London, 2021.

[19] Department for Environment Food and Rural Affairs, "Biodiversity Offsetting Pilots. Technical Paper: the metric for the biodiversity offsetting pilot in England," 2012.

[20] U.S. Environmental Protection Agency, "Ecosystems and Climate Change Research," 2022.

[21] H. &. Jackson, "Synthesis of Two Decades of US EPA's Ecosystem Services Research to Inform Environmental, Community, and Sustainability Decision Making," *Sustainability 13, no. 15: 8249.,* 2009.

[22] B. &. Banzhaf, ""Valuing the Protection of Ecological Systems and Services: A Report of the EPA Science Advisory Board," 2007.

[23] "What are ecosystem services? The need for standardized environmental accounting units," *Ecological economics, 63(2-3),* pp. pp.616-626..

[24] P. L. I. T.-O. S. e. a. Menéndez, "The Global Flood Protection Benefits of Mangroves," *Sci Rep 10, 4404 ,* 2020.

[25] U.S. Environmental Protection Agency, "Ecosystem Services Research".

[26] Washington State Academy of Sciences, "Assessment of No Net Loss and Recommendations for Net Ecological Gain Metrics, Indicators, and Monitoring," Prepared for the Washington State Department of Fish and Wildlife, 2022.

[27] Planning Advisory Service, "Biodiversity Net Gain FAQs - Frequently Asked Questions," 2022. [Online]. Available: https://www.local.gov.uk/pas/topics/environment/biodiversity-net-gain-local-authorities/biodiversity-net-gain-faqs. [Accessed 20 September 2022].

[28] Department for Environment Food & Rural Affairs, "Net Gain. Summary of responses and government response," 2019.

[29] J. Bull, J. Baker, V. Griffiths, J. Jones and E. Milner-Gulland, "Ensuring No Net Loss for people and biodiversity: good practice principles.," Oxford, 2018.

[30] Washington State Legislature, "WAC 173-26-201(2)(c)," 2004.

[31] Commerce, "Critical Areas Handbook," Washington Department of Commerce, Olympia, WA, 2018.

[32] Washington State Legislature, "WAC 220-660-050 (13)".

[33] Washington State Legislature, "WAC 173-204".

[34] Washington State Legislature, "State Environmental Policy Act (chapter 43.21C RCW)," 1983.

[35] WADNR, "Forest Practices Habitat Conservation Plan," Washington Department of Natural Resources, Olympia, WA, 2005.

[36] Washington Department of Ecology, "Shoreline Master Programs Handbook," Olympia, WA, 2017.

[37] Washington Department of Ecology, "Shoreline Master Programs Handbook," 2017.

[38] *Whidbey Environmental Action Network v. Island County,* 2015.

[39] *Ann Aagaard, Judy Fisher, Bob Fisher, Glen Conley, and Save a Valuable Environment (SAVE)v. City of Bothell,* 2015.

[40] *Swinomish Indian Tribal Community v. Western Washington Growth Management Hearings Board,* 2007.

[41] *Whidbey Environmental Action Network v. Island County,* 2015.

[42] U.S. Environmental Protection Agency, "Ecosystem Services - EnviroAtlas Overview. Accessed," 2022.

[43] U.S. Environmental Protection Agency, Office of the Administrator, Science Advisory Board , 2009.

Riparian Ecosystems, Volume 1: Science Synthesis and Management Implications



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Washington Department of FISH and WILDLIFE

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Leopard Frog Lithobates pipiens/*Scott Fitkin, WDFW*

Preface

This Priority Habitats and Species (PHS) document of the Washington Department of Fish and Wildlife (WDFW) is provided in support of the agency's mission to preserve, protect, and perpetuate the state's fish, wildlife, and ecosystems while providing sustainable fish and wildlife recreational and commercial opportunities. WDFW works cooperatively with land use decision makers and landowners to facilitate solutions that accommodate local needs and needs of fish and wildlife. One of WDFW's important roles in land use decision making is that of technical advisor: we provide information about the habitat needs of fish and wildlife and the likely implications of various land use decisions for fish and wildlife.

The nine chapters of Volume 1 are a partial update of a 1997 document entitled *Management Recommendations for Washington's Priority Habitats: Riparian.* This document, called *Riparian Ecosystems, Volume 1: Science Synthesis and Management Implications* is a partial update because it addresses only aquatic species. Riparian needs of terrestrial species will be updated in the future. Until that update is complete, readers can consult the 1997 document, available at **http://wdfw.wa.gov/publications/00029/**, for information about riparian ecosystems and terrestrial species.

Priority Habitats are places that warrant special consideration for protection when land use decisions are made. For more information, see *Washington Department of Fish and Wildlife. 2008. Priority Habitat and Species List,* available at **https://wdfw.wa.gov/species-habitats/at-risk/phs.**

The PHS program provides land use decision support to clients such as local governments, tribes, government agencies, non-governmental organizations, and landowners. PHS consists of a PHS List, PHS Maps available at **https://wdfw.wa.gov/species-habitats/at-risk/phs/maps**, PHS Management Recommendations, and technical assistance from our regional habitat biologists.

This PHS document compliments a family of PHS documents including *Landscape Planning for Washington's Wildlife: Managing for Biodiversity in Developing Areas* and *Land Use Planning for Salmon, Steelhead and Trout: A land use planner's guide to salmonid habitat protection and recovery,* available at **https://wdfw.wa.gov/species-habitats/at-risk/phs/recommendations**.

List of Acronyms

BAS	best available science
BFW	bankfull width
CMZ	channel migration zone
DBH	diameter at breast height
DNR	(Washington) Department of Natural Resources
EPA or (US)EPA	United States Environmental Protection Agency
FEMAT	Forest Ecosystem Management Assessment Team
HCP	habitat conservation plan
IMW	intensively monitored watersheds
LWD	large woody debris
NOAA	National Oceanographic and Atmospheric Administration
NRC	National Research Council
PHS	Priority Habitats and Species
PNW	Pacific Northwest
RCW	Revised Code of Washington
RMZ	riparian management zone
SMA	Shoreline Management Act
SPTH	site-potential tree height
$SPTH_{200}$	site-potential tree height at tree age equal to 200 years
TAG	Technical Advisory Group
USFS	United States Forest Service
USFWS	United States Fish and Wildlife Service
USGS	United States Geological Survey
WAC	Washington Administrative Code
WDFW	Washington Department of Fish and Wildlife
WNHP	Washington Natural Heritage Program
WSAS	Washington State Academy of Sciences



Bank of the Chehalis River/Kaysie Cox, WDFW

Chapter 1. Introduction

By: Timothy Quinn, Kirk L. Krueger, and George F. Wilhere

1.1. Document Description

Volume 1 is part one of a two-volume set. It contains reviews and syntheses of scientific literature for the purpose of informing the development of policies related to management of riparian areas and watersheds of Washington State. Volume 1 adds additional information to the science summarized in the PHS report titled *Management Recommendations for Washington's Priority Habitats: Riparian* (Knutson and Naef 1997).

Volume 1 was designed to answer the following three general questions:

- What is currently known about the key ecological functions of riparian areas?
- How do riparian areas and watersheds affect the freshwater habitats of fish and wildlife?
- How do human activities affect the capacity of riparian areas and watersheds to provide habitat for fish and wildlife in rivers and streams?

Volume 1 is intended to serve two goals. The first goal is to be a source of best available science (BAS) for understanding how riparian areas and surrounding



Chehalis River meander paths between 1938 and 2013/Ken Pierce, WDFW

watersheds affect ecological functions and aquatic habitats. The second goal is to provide a scientific foundation for management recommendations presented in Volume 2, which are consistent with Washington Department of Fish and Wildlife's (WDFW) mandate (RCW 77.04.012) to protect, preserve, and perpetuate Washington's fish and wildlife. Both goals also relate to WDFW's responsibility to support and provide technical assistance for conservation and protection measures necessary to preserve or enhance anadromous fisheries under the Growth Management Act (GMA; RCW 36.70A.172) and the Shoreline Management Act (SMA; WAC 173-26-221(5)(b)).

Volume 1 does not directly address instream flows as affected by water withdrawal for domestic and commercial uses, or instream water quality, both of which are regulated by the Washington Department of Ecology. However, because water quality is affected by land use, we discuss this issue in the context of riparian and watershed science. In addition, Volume 1 does not specifically address riverine wetlands, i.e., wetland associated with rivers and streams and commonly found in floodplains. Rather, riverine wetlands are usually considered part of riparian ecosystems, which are the focus of this document. Other specific wetland management guidance is available from Washington Department of Ecology (https://ecology.wa.gov/Water-Shorelines/Wetlands).

Volume 2 translates these science reviews and syntheses into land use guidance for local governments and other organizations to conserve watershed processes and riparian ecosystems in support of aquatic species and their habitats. The guidance presented in Volume 2 is not in and of itself "best available science." Rather, it represents the recommendations of WDFW as to how a local government could include the best available science in policies, plans, and regulations to protect riparian ecosystems and their associated aquatic habitats.

WDFW recognizes that natural resource management and land use policies must often balance competing ecological, economic, and social goals (Wilhere and Quinn 2018). In fact, one of WDFW's conservation principles is that management decisions should integrate ecological, economic, and social perspectives. This volume addresses only the ecology of riparian areas within the context of watershed conditions; it does not cover economic and social aspects. Determining an acceptable balance requires a political process involving stakeholders, local governments, tribes, and state agencies. Such a process would establish society's goals for freshwater habitats for salmon and other species of fish and wildlife, and lead to management for achieving those goals. This volume can help to inform that process.

1.1.1. Ecosystems

The ecosystem, a fundamental concept in natural resource management, can be defined as "a spatially explicit unit of the Earth that includes all of the organisms, along with all components of the abiotic environment" (Likens 1992). Throughout this document we use the term ecosystem composition to mean "the different parts (components) which something is made of" (Oxford Dictionary 2015). We define ecosystem structure as the "arrangement of and relations among the parts or elements of something complex" (Oxford Dictionary 2015). We define ecosystem function(ing) to include the first and second definitions of ecological function by Jax (2005): 1) the process, or the cause-effect-relationship underlying two or more interacting components, and 2) the sum of processes that sustain the system. Note that the definitions of functions we use here are broader and more inclusive than "functions" defined solely as ecosystem outputs that benefit humans, namely goods and services (Jax 2005; MEA 2005).

In this volume, we explicitly consider the composition, structure, and function of riparian ecosystems in the context of the surrounding watershed. This is especially important in light of the challenges of managing ecosystems sustainably and the risks associated with scientific uncertainty, i.e., the consequences of being wrong.

The composition, structure, and function of ecosystems describe the organization of biotic and abiotic elements and the processes occurring among elements. These concepts are closely related but not equally well studied nor understood. For example, describing an ecosystem's composition and structure is easier than describing its functions (Hunter et al. 1988; Noss 1992). Likewise, management objectives are often expressed in terms of composition and structure, not functions, because they are easier to characterize.

Composition and structure versus function have a chicken-and-egg relationship. That is, functions (processes) are in large part responsible for maintaining composition and structure, but some functions could not exist without an ecosystem's particular composition and structure. Myster (2001), for instance, argues that ecosystem structure can be defined as the minimal organization necessary for a function to operate. Others argue that managing for functions (Beechie and Bolton 1999) is likely to be more successful than managing for composition and structure because processes likely exert stronger influences on composition and structure than the other way around (Odum 1953), and processes are more directly affected by land use activities (Reid 1998). Furthermore, some land use laws or regulations stipulate no net loss of ecological functions, not no net loss of composition and structure (RCW 90.58, WAC 173-26-186, WAC 365-196-830), however, compliance is often determined through evaluating ecosystem composition and structure, not functions. Such conceptual ambiguity suggests that we consider the entire ecosystem, i.e., composition, structure, and functions, when studying riparian areas, and furthermore, that land managers understand how composition and structure manifest ecological functions. The following chapters synthesize our review of the relationships among composition, structure, and functions of riparian ecosystems in the Pacific Northwest.

1.1.2. Riparian Ecosystems

WDFW has adopted the following conceptual definition of riparian ecosystems:

Riparian areas are transitional between terrestrial and aquatic ecosystems and are distinguished by gradients in biophysical conditions, ecological processes, and biota. They are areas through which surface and subsurface hydrology connect waterbodies with their adjacent uplands. They include those portions of terrestrial ecosystems that significantly influence exchanges of energy and matter with aquatic ecosystems (i.e., a zone of influence).



Riparian ecosystem/Scott Fitkin, WDFW

Riparian ecosystems are sometimes referred to by different names: riparian areas, riparian zones, or riparian habitats. To compound confusion, the "riparian zone" is sometimes identified as a distinctive area within riparian ecosystems (Sedell et al. 1989; Naiman et al. 1992; Steiner et al. 1994). Some definitions include the adjacent waters whereas others do not. Unless stated otherwise, we consider riparian area, riparian habitat, riparian corridor, and riparian ecosystem to be synonyms. Furthermore, our definition of riparian ecosystem does not include adjacent waters (i.e., rivers or streams) and recognizes the riparian zone as a distinctive area within riparian ecosystems. The riparian zone contains wet or moist soils and plants adapted to growing conditions associated with periodically saturated soils.

Recent definitions reflect common conceptual understanding and identify similar composition, structure, and functions, including distinct plant communities and soil types; disturbance regimes unique to fluvial systems; gradients in soil, vegetation, and microclimate that manifest an ecotone between terrestrial and aquatic environments; and essential interactions between terrestrial and aquatic ecosystems. Riparian areas are the loci of terrestrial and aquatic interactions, however, the exact boundaries of riparian ecosystems can be difficult to delineate because: 1) ecosystems are not uniquely identified entities (Karr 1996); 2) the environmental heterogeneity of riparian areas is expressed in a variety of plant life history strategies and successional patterns; and 3) some ecosystem functions depend on environmental setting (Naiman et al. 1998).

Following Naiman et al. (1998), our definition of riparian ecosystem includes the active floodplain, including riverine wetlands, and the terraces or adjacent uplands that directly contribute organic matter or large wood to the active channel or active floodplain (Figure 1.1 and 1.2). Terraces and adjacent uplands that contribute organic matter or large wood are located in the "zone of influence." The active channel is defined by the lower limit of continuous riparian vegetation (Naiman et al. 1998), and it may be delineated by absence of both moss on rocks and rooted vegetation (USFS 2008). The upper most elevation of the active channel is sometimes equated with the ordinary high water mark. The active floodplain is located between the active channel and adjacent terrace or hillslopes (Fetherston et al. 1995; Harris 1987). Depending on the watershed, the flood return interval of the active floodplain varies between 1 and 10 years (Wolman and Leopold 1957; Ward and Stanford 1995; Lichvar et al. 2006; Williams et al. 2009; BLM 2015).

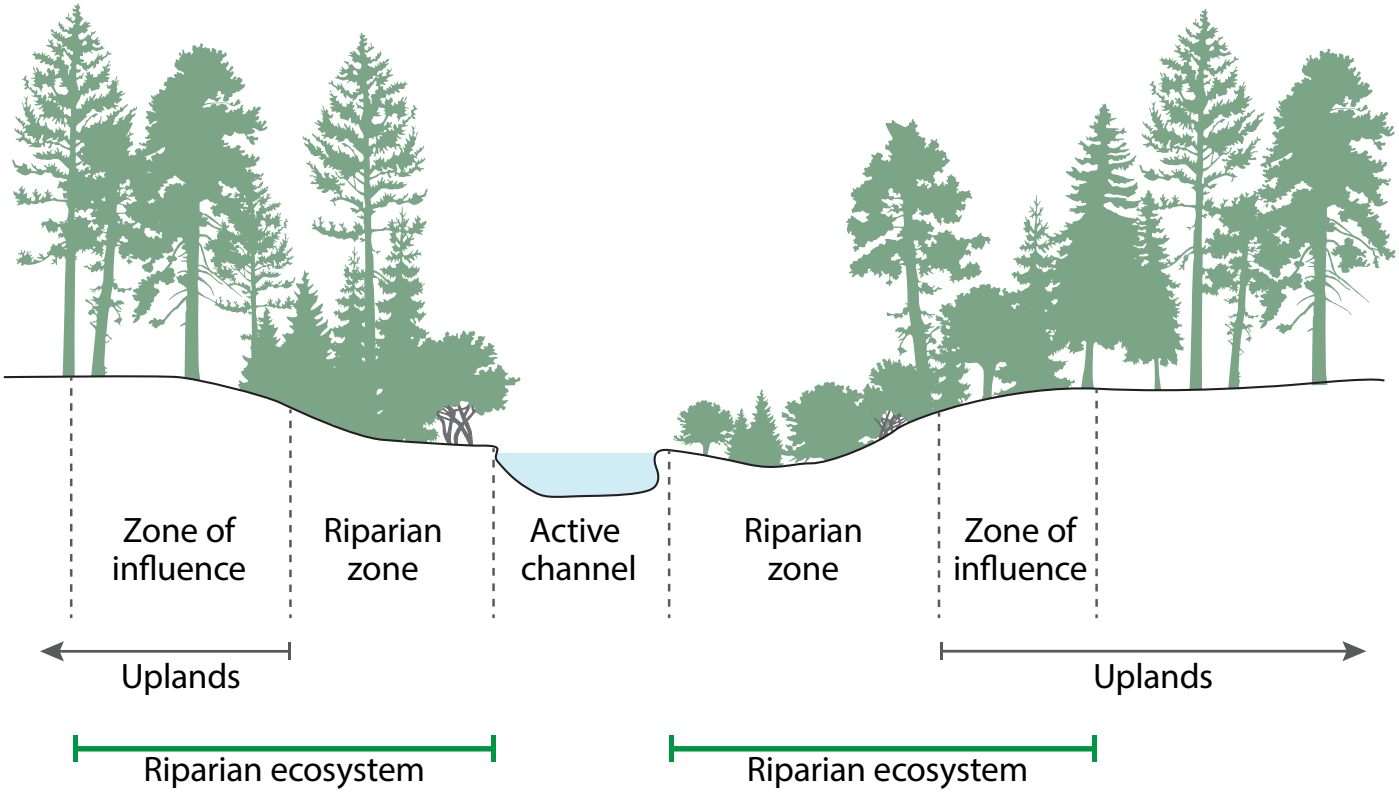
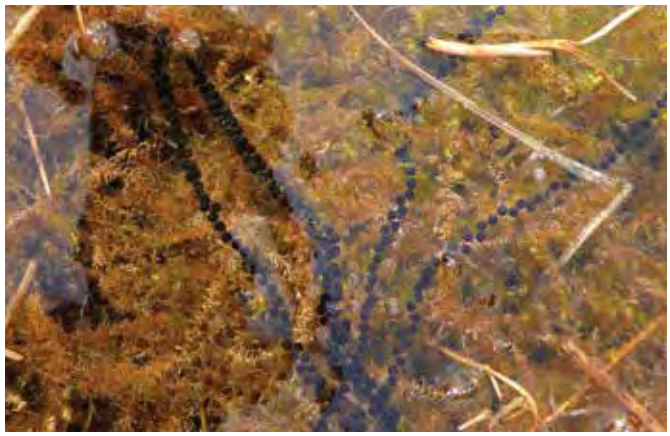


Figure 1.1. A generalized diagram of the riparian ecosystem. The NRC (2002) states that, "Riparian areas are transitional between terrestrial and aquatic ecosystems and are distinguished by gradients in biophysical conditions, ecological processes, and biota. They are areas through which surface and subsurface hydrology connect waterbodies with their adjacent uplands. They include those portions of terrestrial ecosystems that significantly influence exchanges of energy and matter with aquatic ecosystems (i.e., the zone of influence)." The portion of the ecosystem characterized by moist soils and plants adapted to periodically saturated soils is the riparian zone. The width of the riparian ecosystem is typically based on riparian functions (i.e., wood recruitment to the stream in forested regions and the pollution removal function in dryland regions).

Riparian ecosystems are priority habitats in part because wildlife occurs more often and in greater variety in riparian areas than in any other habitat type. "Natural riparian corridors are the most diverse, dynamic, and complex biophysical habitats on the terrestrial portion of the earth" (Naiman et al. 1993). Although riparian ecosystems constitute a small portion of the surface landscape, approximately 85% of Washington's wildlife species are known to use riparian areas associated with rivers and streams (Knutson and Naef 1997). Of these, 170 species including 134 mollusks, 11 amphibians, 3 reptiles, 10 birds, and 9 mammals may be riparian obligates, i.e., require riparian habitat to survive (T. Quinn, unpublished). In addition, habitat for many upland and aquatic species is directly enhanced by the presence of adjacent riparian areas. A principal reason for high fish and wildlife diversity is that riparian ecosystems are exceptionally productive. Riparian



Western Toad Anaxyrus boreas *egg strings/Scott Fitkin, WDFW*

ecosystems are characterized by the availability of water, milder microclimate, and relatively fertile soils. These factors enhance the productivity of plant communities and support a complex food web that includes a rich variety and abundance of fish, invertebrates, amphibians, plants, bacteria, fungi, reptiles, birds, and mammals (Cummins 1974; Johnson and Carothers 1982). It is not surprising then, that $1.4 billion (57%) of $2.5 billion spent to recover salmon in Pacific Northwest since 2000 has been directed at enhancing, restoring, and maintaining salmon habitat (e.g., large wood supplementation, riparian planting, fine sediment remediation, land acquisition) previously provided in large part by functioning riparian areas (NOAA 2015).

In addition to their essential role as fish and wildlife habitats, riparian areas provide other significant benefits to humans (Naiman and Bilby 1998; NRC 2002). Briefly, riparian areas help provide a variety of ecosystem goods and services: provisioning services such as food and water; regulating services such as decreasing flood flows; supporting services such as nutrient cycling, sediment and pollutant filtering, and carbon sequestration; and cultural services such as recreational, spiritual, and other nonmaterial benefits (MEA 2005). These services provide real but often unquantified economic benefits to individuals and society; benefits that largely go unnoticed until they are lacking. According to the NRC (2002), protection and restoration of riparian areas should be a national goal because they have a major influence on achieving important national standards of the Clean Water Act, the Endangered Species Act, and flood damage control programs.

This document includes consideration of river-associated wetlands but does not consider other types of wetlands, which are covered by the Washington

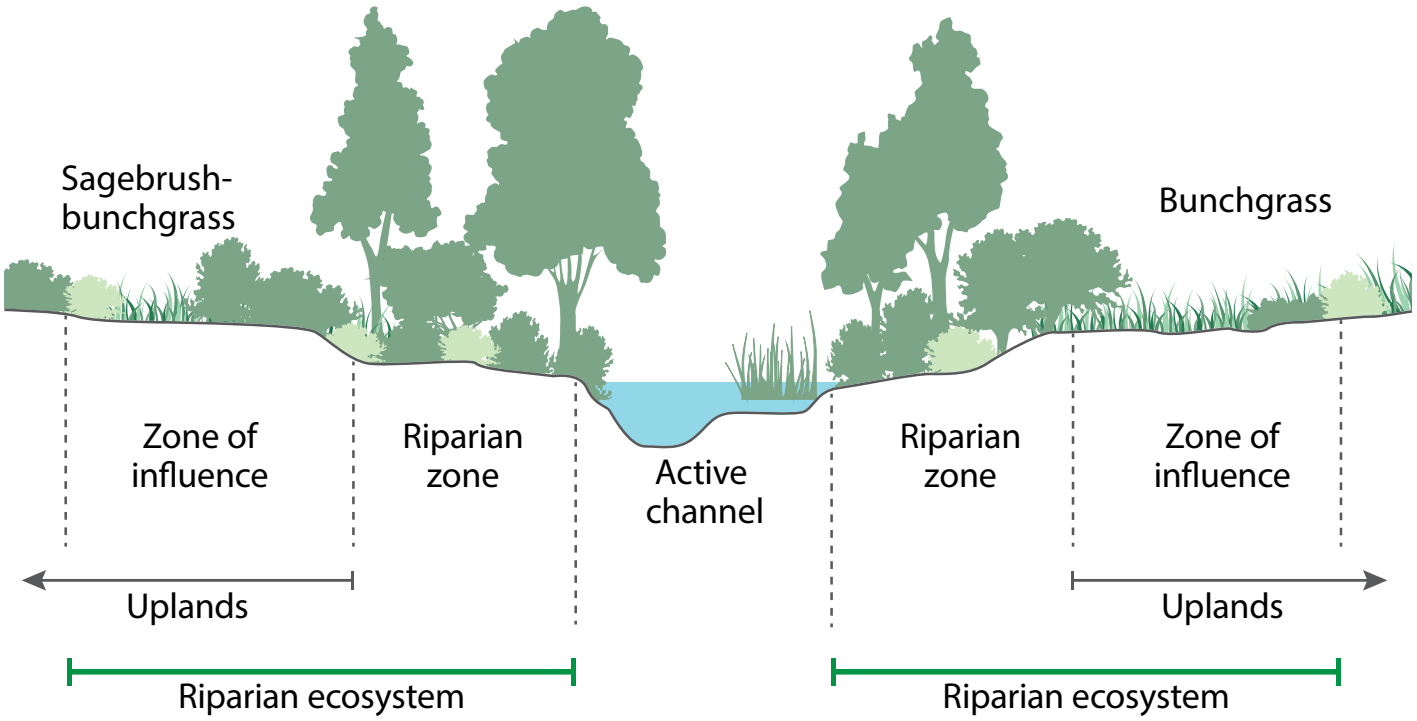


Figure 1.2. Dryland Riparian Ecosystem. The riparian ecosystem consists of two zones: riparian and zone of influence. The riparian zone extends from the edge of the active channel towards the uplands. This zone includes areas where terrestrial biota and soils are influenced, at least periodically, by surface or subsurface waters. Beyond this is the riparian "zone of influence." This includes areas where ecological processes significantly influence the stream (diagram modified from USFS 2004).

Department of Ecology, or areas bordering marine or estuarine (brackish) waters despite the potential applicability of this work to those environmental settings. A 2009 review of riparian functions of marine shorelines is available at https://wdfw.wa.gov/publications/00693.

1.2. Scope of Volume 1

1.2.1. Riparian Ecosystem Management

Riparian ecosystem management is often couched in terms of maintaining riparian functions thought to be important to fish and wildlife and their habitats (e.g., Bolton and Shellberg 2001, Everest and Reeves 2007). Some commonly identified riparian functions are described in FEMAT (1993) and the Forests and Fish Report (DNR 1999). The riparian ecosystem functions we discuss in this document, including some associated compositional and structural elements, are organized by chapter:

- Chapter 2. *Stream Morphology*—the interplay of water, sediment, and vegetation on channel form and riparian areas
- Chapter 3. *Wood*—effects of wood on channel morphology and habitat, and the recruitment of wood from riparian areas
- Chapter 4. *Stream Temperature*—effects of hydrology and shading on the thermal regime of streams
- Chapter 5. *Pollutant Removal*—the interception or filtration of fine sediments, excessive nutrients, pathogens, pesticides, and other contaminants in overland and shallow subsurface flows
- Chapter 6. *Nutrients Dynamics in Riparian Ecosystems*—dynamics and fate of the primary macro-nutrients: nitrogen, phosphorus, and carbon
- Chapter 7. *Riparian Areas of the Columbia Plateau*
- Chapter 8. *Watersheds*—relationship of watershed-scale management to the goal of achieving beneficial effects for fish and wildlife

Riparian functions are affected and in turn affect aquatic and terrestrial systems at multiple spatial scales. We focus much attention on riparian functions at the site (e.g., stream reach or land parcel) scale for three reasons. First, riparian areas are disproportionately important, relative to area, for fish and wildlife and other ecosystem services (Naiman and Bilby 1998; NRC 2002). Second, local governments and individual landowners, important users of WDFW's PHS guidance, typically manage at the parcel scale. Most land use activity, outside of public lands, occurs at the site-scale on ownership parcels that are relatively small compared to the watershed in which they occur. Third, effective and efficient conservation of fish and wildlife habitats requires management at multiple scales and thus good site-scale riparian management is an essential complement to good watershed management (Chapter 8), although approaches at different scales can vary dramatically.

1.2.2. Watershed Management

Even when all riparian functions are protected, rivers, streams, and riparian ecosystems are not immune to the effects of upland management. To varying degrees, riparian and stream structure, composition, and function reflect land uses and conditions throughout watersheds.

Regardless of its size, no ecosystem is entirely closed. Upslope activities can considerably alter the magnitude and timing of stream flows; the mobilization, routing, and storage of sediment, wood, and fine organic matter; and the quality of water, thereby influencing riparian ecosystem functions (NRC 2002; Figure 1.3). Thus, the management of riparian ecosystems at the site or reach scale should be considered just one important part, not

the sole requirement, of holistic watershed management for the protection of fish and wildlife and other values. We include Chapter 8, which focuses on watershed-scale issues that are important to the management of aquatic systems as a whole, with the intent of increasing the effectiveness of collective riparian conservation efforts. This chapter provides a conceptual framework that identifies the key watershed processes and their primary influences by, on, and through riparian areas and adjacent watercourses.

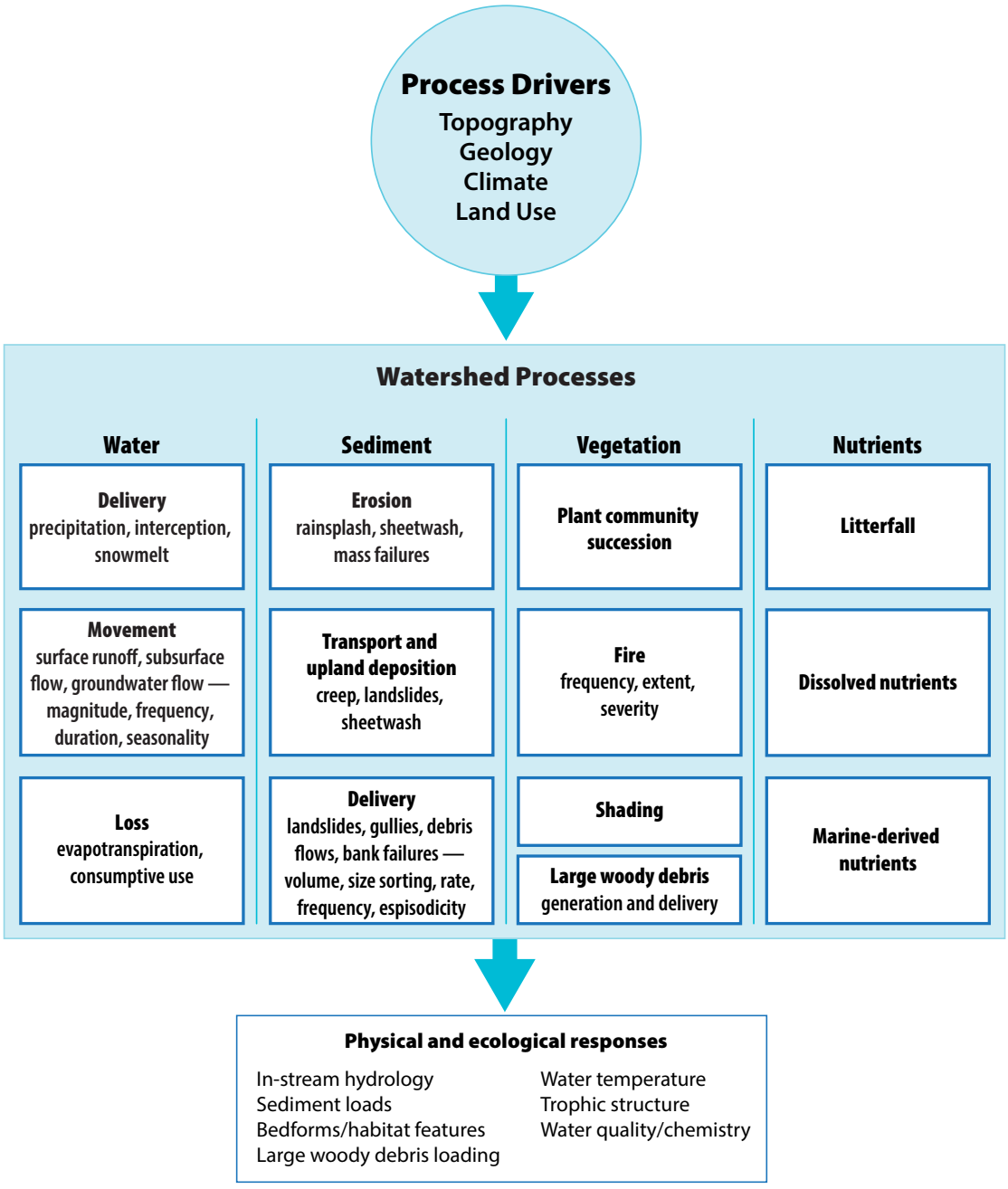


Figure 1.3. Conceptual framework for the hierarchical relationship of invariant, large-scale "process drivers," the suite of watershed processes that are determined by these drivers, and the instream physical and biological responses to those processes. Multiple additional interactions between elements and levels are not shown on this diagram to emphasize the primary influences; but in any given setting, one or more of these secondary interactions may temporarily achieve equivalent importance. This framework embraces the definition of watershed processes from Stanley et al. (2011): "[t]he dynamic physical and chemical interactions that form and maintain the landscape and ecosystems."



Devil's Club Oplopanax horridus *is common in wet soils of western Washington riparian areas/Ned Pittman, WDFW*

1.2.3. Science Synthesis

Chapter 9, *Science Synthesis to Management Implications,* of this volume summarizes important scientific finding from chapters 1-8 and provides a brief discussion of scientific themes that can inform thoughtful approaches to protecting aquatic systems.

1.2.4. Scope: Protection and Restoration

Protection and restoration of riparian ecosystems and watersheds are both essential for Washington's fish and wildlife, and especially for endangered and threatened salmonids. However, planning, management practices, regulations, and legal context for protection are different from those for restoration, and thoroughly covering both topics was beyond our scope. Thus, restoration is not explicitly incorporated in the scope of this document. Nevertheless, much of the science presented in this document can inform restoration activities. For instance, while this document does not review scientific literature on instream large wood placement, a common restoration activity, it does summarize large wood recruitment and reference conditions for the amount and size of instream large wood. Thus, the body of science that informs protection also helps to inform restoration, at least in terms of establishing resource goals and objectives.

1.3. Document Development

We employed the following approach to developing this document. We first established a Technical Advisory Group (TAG) of scientists from the region. Second, with guidance from the TAG, we conducted a literature review designed to inform the general state of knowledge regarding ecosystem protection and another literature review more focused on recent developments in riparian ecology and management. Third, we contracted with regional topic experts to author and co-author chapters. WDFW staff provided conceptual and technical guidance as possible. Finally, we subjected the draft final documents to several rounds of peer review. Each of these steps is discussed below.

1.3.1. Technical Advisory Group

The TAG helped provide overall science guidance, that is, contribute expertise and scientific perspective, provide important references and other sources of information, and review draft products. The TAG was composed of 13 individuals who were selected by virtue of their scientific expertise as opposed to affiliation with particular organization or stakeholder group. However, given the broad potential applicability of this document, it is conceivable that TAG members belong to one or more stakeholder groups. All TAG members were expected to attend three all-day meetings over the course of the project. Members of the TAG volunteered their time, except one who was paid a small stipend because she was employed by a non-profit organization. The first meeting was designed to introduce TAG members to the nature of the PHS update, to discuss different approaches to conducting a literature review and synthesizing new scientific information, and to

secure their ongoing commitment to helping WDFW meet high scientific standards. The second and third TAG meetings were designed to solicit review and feedback from TAG members on draft products. As part of their review process, we invited all TAG members to edit draft chapters and provide additional citations for WDFW's considerations. Although the TAG played a key role in advising WDFW on the science of riparian management and conservation, WDFW bears sole responsibility for the contents of this document.

1.3.2. Literature Review

We organized summaries around ecological functions including stream channel morphology, wood, pollution removal, nutrients, water temperatures, and watershed processes. Note that many of the issues we address here are directly or indirectly related to fish and wildlife habitats and other ecosystem services. We did not, however, explicitly consider cultural services that are important values for many stakeholders (e.g., spiritual, cultural and aesthetic values of riparian areas).

We enlisted the assistance of scientists with specific areas of expertise as technical advisors, authors, and informal and formal reviewers to help ensure that our summaries of pertinent scientific information were sufficiently accurate and inclusive. We were most interested in characterizing the state of knowledge and important, recent findings about each topic. That is, we tried to assesses what we know, how well we know it, and what we do not know. The summary statements in each chapter are important to the development of management recommendations because they often identify important management challenges that are not well described in the published literature (e.g., the importance of habitat connectivity to fish population persistence). To this end, when appropriate, we encouraged authors to consider the broad body of scientific information and how it might be extrapolated to unstudied locales; in other words, to consider the body of literature with regard to our ability to make reliable predictions.

Where information existed and as time allowed, we also attempted to summarize how riparian composition, structure, and functions differ among natural plant communities. In most cases, we used the broadest division called Major Vegetational Areas, which is made up of two groups in Washington State, i.e., Forested Regions and Steppe Regions (Franklin and Dyrness 1988). Regions can be further subdivided into forested zones (e.g., *Tsuga heterophylla* Zone) and steppe communities (e.g., shrub-steppe with *Artemisia tridentata*) that contain similar climax plant communities influenced by similar disturbance regimes. When information was available, for example, in the case of large wood in forested regions, we report that information at the finer division within the vegetation classification.

In addition, and as time and resources allowed, we summarized some potential effects of common land use activities on stream and riparian areas as a precursor to providing useful land use advice. We considered four general categories of land use: 1) urban, which includes commercial, industrial, urban, suburban, and rural development, 2) agricultural, which includes cultivated crops and grazing uses, 3) forestry, which includes timber management and associated activities such as

Chapter 9 summarizes scientific findings from chapters 1 through 8 and includes a brief discussion of scientific themes that can inform thoughtful approaches to protecting aquatic systems.

road building and maintenance, and 4) other activities (e.g., mining), which were not discussed due to the paucity of available research results.

We started this work by assembling topical literature reviews including Bolton and Shellberg (2001), Pizzimenti (2002), Bezener and Bishop (2005), Mayer et al. (2005), and Naiman et al. (2005). We compiled relevant literature cited in these review articles, from other reference materials we encountered, and from recommendations of TAG members. We also did an extensive literature search on computerized databases. We mostly focused our literature search on peer reviewed articles published after 1993, published in English, and conducted in proximity to Washington State. This last criterion was designed to focus on studies thought most relevant to Washington State's ecological conditions.



The North Fork Skokomish River runs through mature conifer forests of the Olympic National Park/Tim Quinn, WDFW

We also documented the type of review the study received according to RCW 34.05.271 (Appendix 1). Studies with no record of review were not considered further. As we (authors) reviewed the published literature, we noted important study findings that we believed would be especially useful for writing the PHS document. For empirical studies, our notes typically included the primary research questions or objectives, key results, management implications, and study limitations or assumptions. For literature reviews and syntheses, our notes summarized main conclusions by subject area. The intent here was to capture a sufficient level of detail for each paper so that we could use our collective notes as sources for writing the synthesis.

We found a massive quantity of literature related to riparian and watershed science despite focusing on information published after 1993. Due to the sheer volume of information, we could not cover all the literature in depth, so we covered those topics that were most relevant for management of riparian areas in Washington State. This document provides a comprehensive review on the current state of the science regarding certain riparian functions. Further, as described above, we enlisted the services of experts with specific areas of expertise as technical advisors, authors, and informal and formal reviewers to help ensure that our summaries of pertinent scientific information were sufficiently accurate and inclusive.

1.3.3. Peer Review

The peer review for Volume 1 consisted of a series of iterative steps, wherein we tried to gain as much agreement about the science synthesis as possible among those involved in the writing and reviewing process. Our intent was to provide the best available science. As described above, the TAG reviewed and often edited incomplete chapter drafts during the literature review and synthesis stage of the project. These draft syntheses were then given to topic experts to complete.

In cases, where WDFW lacked sufficient topic expertise, we provided stipends up to $10,000 to outside authors (i.e., contractors) for completing a chapter. The steps involved in completion of drafts included adding one or more conceptual models describing the system and its functioning and a synthesis or summary of the important findings over the last approximately 20 years. These steps often entailed a series of editing and reediting by WDFW staff and contractors. Once completed by contractors and returned to WDFW, the drafts were reviewed a final time by TAG members. This last review by TAG members was to ensure that completion of the chapters was consistent with their earlier guidance and with their understanding of the literature. WDFW attempted to resolve all disagreement that occurred between contractors and TAG members and provided a written description of how those issues were resolved to both the contractor and the TAG. After final WDFW review, the document was submitted for review by the Washington State Academy of Sciences (WSAS).

We enlisted the WSAS to conduct the final, independent peer review of the PHS document. Modeled after the National Academy of Science, which is charged with providing independent, objective advice to the nation on matters related to science and technology, the WSAS provides expert scientific analysis to inform public policy making at the state level (WSAS 2015). The final peer review with the WSAS was also iterative. That is, WDFW in consultation with authors and TAG members, addressed WSAS comments, made appropriate changes to the document, and then discussed those comments with the WSAS in an attempt to resolve differences. This process proceeded until we reached agreement about scientific contents and conclusions.

1.4. Literature Cited[1]

Beechie, T., and S. Bolton. 1999. An approach to restoring salmonid habitat-forming processes in Pacific Northwest watersheds. Fisheries 24:6-15. (i)

Bezener, A.M., and C.A. Bishop. 2005. Literature review of riparian habitat requirements for aquatic and terrestrial wildlife and its application to habitat restoration projects: a case example in the South Okanagan and Similkameen Valleys, British Columbia. Technical Report Series No. 379. Canadian Wildlife Service, Pacific and Yukon Region, British Columbia. (viii)

BLM (Bureau of Land Management). 2015. Riparian area management: proper functioning condition assessment for lotic areas. Technical Reference 1737-15. National Operations Center, Denver, Colorado. (viii)

Bolton, S.M., and J. Shellberg. 2001. Ecological issues in floodplains and riparian corridors. Center for Streamside Studies, University of Washington, Seattle. (viii)

Cummins, K.W. 1974. Structure and function of streams ecosystems. BioScience 24:631-641. (i)

DNR (Washington Department of Natural Resources). 1999. Forests and Fish Report. Forest Practices Division, Olympia. (viii)

Everest, F.H., and G.H. Reeves. 2007. Riparian and aquatic habitats of the Pacific Northwest and southeast Alaska: ecology, management history, and potential management strategies. PNW-GTR-692. U.S. Forest Service, Pacific Northwest Research Station, Portland, Oregon. (viii)

FEMAT (Forest Ecosystem Management Assessment Team). 1993. Forest ecosystem management: an ecological, economic and social assessment. U.S. Department of Agriculture and U.S. Department of the Interior, Portland, Oregon. (viii)

[1] References are classified according to RCW 34.05.271 (see Appendix 1) denoted by a lower case roman numeral (i – viii) in parentheses at the end of the citation.

Fetherston, K.L., R.J. Naiman, and R.E. Bilby. 1995. Large woody debris, physical process, and riparian forest succession in montane river networks of the Pacific Northwest. Geomorphology 13:133-144. (i)

Franklin, J.F., and C.T. Dyrness. 1988. Natural vegetation of Oregon and Washington. Oregon State University Press, Corvallis. (i)

Harris, R.R. 1987. Occurrence of vegetation on geomorphic surfaces in the active floodplain of a California alluvial stream. American Midland Naturalist 118:393-405. (i)

Hunter, M.L. Jr., G.L. Jacobson Jr., and T. Web III. 1988. Paleoecology and the coarse filter approach to maintaining biological diversity. Conservation Biology 2:375-385. (i)

Jax, K. 2005. Function and "functioning" in ecology: what does it mean? Oikos 111:641-648. (i)

Johnson, R.R., and S.W. Carothers. 1982. Riparian habitat and recreation: interrelationships and impacts in the southwest and Rocky Mountains region. Eisenhower Consortium Bulletin 12. Rocky Mountain Forest and Range Experiment Station, Fort Collins, Colorado. (viii)

Karr, J.R. 1996. Ecological integrity and ecological health are not the same. Pages 97-109 *in* P.C. Schulze, R. Frosch, and P. Risser, editors. Engineering within ecological constraints. National Academy of Engineering, Washington, D.C. (viii)

Knutson, K.L., and V.L. Naef. 1997. Management recommendations for Washington's priority habitats: Riparian. Washington Department of Fish and Wildlife, Olympia. (iv)

Lichvar, R.W., D.C. Finnegan, M.P. Ericsson, and W. Ochs. 2006. Distribution of ordinary high water mark (OHWM) indicators and their reliability in identifying the limits of "waters of the United States" in arid southwestern channels. ERDC/CRREL TR-06-5. U.S. Army Corps of Engineers, Washington, D.C. (viii)

Likens, G. 1992. An ecosystem approach: its use and abuse. Ecology Institute, Oldendorf/Luhe Germany. (i)

Mayer, P.M., S.K. Reynolds, M.D. McMutchen, and T.J. Canfield. 2005. Riparian buffer width, vegetative cover, and nitrogen removal effectiveness: a review of current science and regulations. EPA/600/R-05/118. USEPA, Office of Research and Development, Washington, D.C. (viii)

MEA (Millennium Ecosystem Assessment). 2005. Ecosystems and human well-being: synthesis. Island Press, Washington, D.C. (i)

Myster, R.W. 2001. What is ecosystem structure? Caribbean Journal of Science 37(1-2):132-134. (i)

Naiman, R.J., T.J. Beechie, L.E. Benda, D.R. Berg, P.A. Bisson, L.H. MacDonald, M.D. O'Conner, P.L. Olsen, and E.A. Steel. 1992. Fundamental elements of ecologically healthy watersheds in the Pacific Northwest Coastal Ecoregion. Pages 127-188 *in* R.J. Naiman, editor. Watershed management: balancing sustainability and environmental change. Springer, New York. (i)

Naiman R.J., and R.E. Bilby, editors. 1998. River ecology and management: lessons from the Pacific Coastal Ecoregion. Springer Science & Business Media, New York. (i)

Naiman, R.J., H. Decamps, and M.E. McClain. 2005. Riparia: ecology, conservation, and management of streamside communities. Elsevier Academic Press, San Francisco. (i)

Naiman, R.J., H. Decamps, and M. Pollock. 1993. The role of riparian corridors in maintaining regional biodiversity. Ecological Applications 3:209-212. (i)

Naiman, R.J., K.L. Fetherston, S.J. McKay, and J. Chen. 1998. Riparian forests. Pages 289-323 *in* R.J. Naiman and R.E. Bilby, editors. River ecology and management: lessons from the Pacific Coastal Ecoregion. Springer, New York. (i)

NOAA (National Oceanic and Atmospheric Administration). 2015. Pacific Coastal salmon recovery funds: project and performance metric database. Available: **https://www.webapps.nwfsc.noaa.gov/apex/f?p=309:13**. (January 2019). (viii)

Noss, R.F. 1992. The Wildlands Project: land conservation strategy. Wild Earth (Special Issue):10-25. (i)

NRC (National Research Council). 2002. Riparian areas: functions and strategies for management. National Academy Press, Washington, D.C. (i)

Odum, E.P. 1953. Fundamentals of ecology. W. B. Saunders, Philadelphia. (i)

Oxford Dictionary. 2015. Available: https://www.lexico.com/en/definition/structure. (January 2019). (viii)

Pizzimenti, J. 2002. Efficacy and economics of riparian buffers on agricultural lands, State of Washington. GEI Consultants, Inc., Englewood, Colorado. (viii)

Reid, L.M. 1998. Cumulative watershed effects and watershed analysis. Pages 476-501 *in* R.J Naiman and R. E. Bilby, editors. River ecology and management. Springer-Verlag, New York. (i)

Stanley, S., S. Grigsby, D.B. Booth, D. Hartley, R. Horner, T. Hruby, J. Thomas, P. Bissonnette, R. Fuerstenberg, J. Lee, P. Olson, and G. Wilhere. 2011. Puget Sound characterization. volume 1: the water resources assessments (water flow and water quality). Publication #11-06-016. Washington State Department of Ecology, Olympia. Available: https://fortress.wa.gov/ecy/publications/documents/1106016.pdf. (January 2019). (iv)

Steiner, F., S. Pieart, E. Cook, J. Rich, and V. Coltman. 1994. State wetlands and riparian area protection programs. Environmental Management 18:183–201. (i)

Sedell, J.R., F.H. Everest, and D.R. Gibbons. 1989. Streamside vegetation management for aquatic habitat. Pages 115-125 *in* Proceedings of the National Silviculture Workshop, U.S. Forest Service, Washington, D.C. (viii)

USFS (U.S. Forest Service). 2008. Stream simulation: an ecological approach to providing passage for aquatic organisms at road-stream crossings. National Technology and Development Program, San Dimas, California. (viii)

Ward, J.V., and J.A. Stanford. 1995. Ecological connectivity in alluvial river ecosystems and its disruption by flow regulation. Regulated Rivers: Research & Management 11:105-119. (i)

Williams, P.B., E. Andrews, J.J. Opperman, S. Bozkurt, and P.B. Moyle. 2009. Quantifying activated floodplains on a lowland regulated river: its application to floodplain restoration in the Sacramento Valley. San Francisco Estuary and Watershed Science 7(1). (i)

Wolman, M.G., and L.B. Leopold. 1957. River flood plains: some observations on their formation. Geological Survey Professional Paper 282-C. U.S. Government Printing Office, Washington, D.C. (i)

Wilhere, G.F., and T. Quinn. 2018. How wide is wide enough?: values, science, and law in riparian habitat conservation. Natural Resources Journal 58:279-318. (i)

WSAS (Washington State Academy of Science). 2015. Available: http://www.washacad.org/aboutus/. (January 2019). (v)

Chapter 2. Stream Morphology

By: Jane B. Atha, Mike Liquori, Kirk L. Krueger, George F. Wilhere, and Timothy Quinn

2.1. Introduction

The composition, structure, and functions of lotic systems are largely due to dynamic interactions of water, sediment, wood, and riparian vegetation. The nature of these interactions is affected by topography (e.g., channel slope), flow regime, sources and characteristics of sediment, the size, strength, and density of riparian vegetation (Naiman and Bilby 1998), and the actions of some animal species, most notably the American Beaver *Castor canadensis* and salmon. The influences of water and channel slope on sediment results in channel patterns (i.e., straight, meandering, braided) (Leopold and Wolman 1957) and geomorphic zones (i.e., source, transport, depositional) (Schumm 1977) that occur somewhat predictably from headwaters to river mouth. Furthermore, variation in fluvial processes (e.g., frequency and intensity of floods) and controls (e.g., lithology, large wood, riparian vegetation) result in a wide range of channel forms or reach types that are often described based on their bedform (e.g., slope, sinuosity, distribution of sediment sizes, etc.) (Montgomery and Buffington 1997). These channel forms can be useful descriptors of aquatic species' habitats. Tributary junctions (Kiffney et al. 2006), natural disturbances (Frissell et al. 1986), and artificial structures (Stanford and Ward 2001) can create discontinuities in these general patterns.

The composition and structure of riparian vegetation affects channel morphology, which in turn affects riparian vegetation (Hupp and Osterkamp 1996; Corenblit et al. 2007; Osterkamp and Hupp 2010; Gurnell 2014). Additionally, channel morphology and the processes that shape it can be impacted by human activities (e.g., levees, dams, Beaver trapping), usually resulting in loss of habitats, reduced habitat diversity, and diminished habitat functions for aquatic species. Management actions such as bank armoring, channelization, and riparian vegetation removal tend to reduce natural variability of geomorphic processes, often amounting to stream habitat degradation greater than the sum of its parts.



Yakima River/Justin Haug, WDFW

Knowledge of the fluvial processes that affect riparian and aquatic systems is important for making sound policy and management decisions. This chapter provides an overview of water and sediment in fluvial processes, their interactions with riparian vegetation, and potential alterations of fluvial processes by human activities. We first describe a general conceptual model for considering how physical processes affect channel morphology. Next, we describe stream flow and sediment processes in more detail. We then consider the watershed-scale context that directly influences fluvial processes. Lastly, we review impacts of human activities on stream functioning, introduce the "riverscape" concept for the management of fish habitats, and describe some physical stream habitat associations of herpetofauna. Some related topics are discussed in other chapters. For example, see Chapter 3 for a description of fluvial process interactions with large wood and Chapter 8 for a thorough examination of influences and management that occur at the watershed scale.

2.2. Conceptual Context

The concept of equilibrium is one of the most important ideas in fluvial geomorphology (Thorn and Welford 1994; Grant et al. 2013). The equilibrium concept posits that rivers tend to work toward long-term equilibrium (Gilbert 1877 as cited by Grant et al. 2013). *Dynamic equilibrium* describes a state of relative stability that results from the interaction of opposing forces (e.g., flowing water and substrate resistance). That is, over the long term and assuming that process drivers like climate and land use remain unchanged (see Chapter 8), overall progression of the composition and structure of stream reaches in a watershed remains largely unchanged. A stream network may undergo significant changes during an extreme flood event, and yet return to equilibrium as smaller flows rework the sediment distributed by floodwaters to re-establish roughly the same relative abundance of stream reach types that existed prior to the flood event.

Lane (1955) conceptualized equilibrium within a stable channel as a balance among stream discharge, channel slope, sediment load, and sediment size (Figure 2.1). Lane's conceptual model was described by Heede (1980) as:

$$Q_s D \propto Q_w S$$

where Q_s is sediment load (i.e., sediment discharge), Q_W is water discharge, D is sediment size, and S is channel slope.

What remains "in balance" over time are the processes of streambed degradation (erosion) and aggradation (sediment deposition). If an increase occurs in stream discharge, for instance, then the resulting increase in stream power can cause an increase in streambed degradation. The channel "adjusts" by decreasing channel slope, which reduces stream power and causes a return to the balance between degradation and aggradation. If a shift in stream discharge or sediment supply occurs, then the channel returns to equilibrium through adjustments in one or more other variables. However, persistent changes in one or more variables of sufficient magnitude may exceed a threshold that causes an abrupt shift to a new equilibrium state (Schumm 1979).

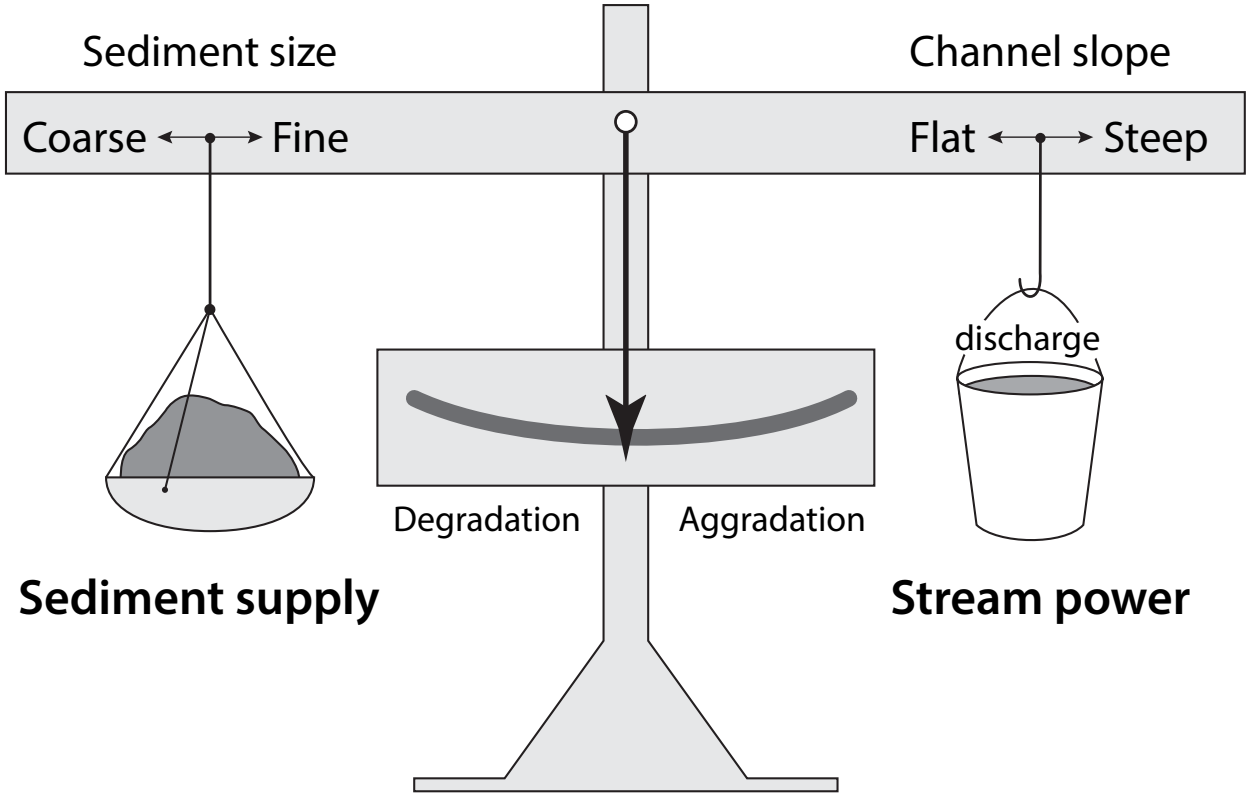


Figure 2.1. Lane's Balance illustrating the concept of channel adjustment (i.e., vertical aggradation or degradation of the streambed) in response to changes in water or sediment yield (from Dust and Wohl 2012).

While Lane's Balance is a useful conceptual model, it does not address complexity at the watershed scale nor the interactions between fluvial processes and riparian vegetation that affect channel morphology (Corenblit et al. 2007; Gurnell 2014) (Figure 2.2). These interactions are reciprocal and feedbacks exist between fluvial processes and vegetation composition and structure (Hupp and Osterkamp 1996; Osterkamp and Hupp 2010). Vegetation influences channel form and channel forming processes help shape riparian plant communities. Human activities that alter these interactions can cause significant changes to channel morphology and fish habitats.

Many geomorphic and ecosystem processes are coupled and occur in parallel at similar spatial and temporal scales. This results in mutual dependence between processes (Renschler et al. 2007). While such processes have received much attention from the scientific community in the last fifteen years, a theoretical synthesis within a holistic conceptual framework is still needed to address how riparian management interacts with this complex system (Smith et al. 2002; Stallins 2006). Interdisciplinary research of these interactions could result in better predictability of impacts caused by management. From an ecosystem management perspective, the choice of spatiotemporal boundaries—often dictated by geomorphic processes—is of profound importance to conceptualization of the system and its ecologic processes (Post et al. 2007).

We frame the hydrologic and physical processes as they shape the riverscape from the context of equilibrium and mutual dependence among water, sediment, and vegetation.

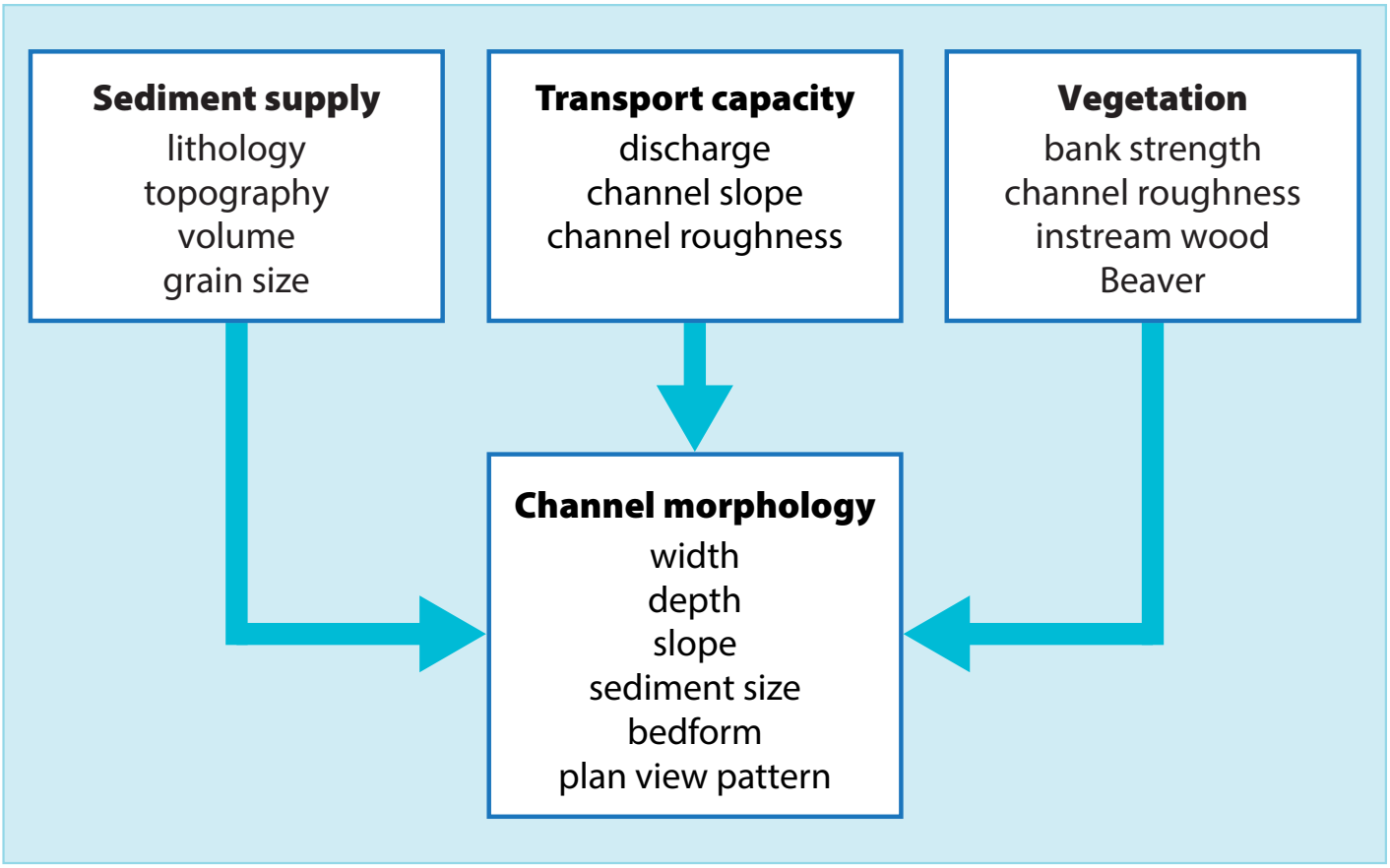


Figure 2.2. Influences on channel morphology (modified from Naiman and Bilby 1998).

2.3. Streamflow Processes

The pathways that water takes to reach a river exert a strong influence on the amount and timing of streamflow in the channel (Figure 2.3). Differences in the relative contributions of these pathways among locations and seasonal variability (e.g., presence or absence of snow) in environmental conditions produce a wide range of stream flow responses to precipitation events.

The fate of precipitation that is not lost through evaporation and transpiration is highly dependent on soil cover. Rain or melted snow that infiltrates the soil can flow downslope in the vadose zone (unsaturated), above the water table as through flow, or below the water table as groundwater in the phreatic zone (saturated).

When precipitation rates exceed soil infiltration rates (Horton 1933) or when local soils are saturated (Dunne and Black 1970a, 1970b; Dunne 1978), water moves downslope as surface runoff. Surface runoff or overland flow remains outside the confines of a channel, and is most common where vegetation is sparse. Human activities that compact soil or destroy permeable, near-surface soil layers reduce infiltration capacity and promote overland flow. A second type of runoff, saturated overland flow, occurs at convergent zones (such as hillslope concavities) and is a combination of direct precipitation onto saturated areas and return flow from the subsurface as it becomes saturated (Wohl 2014) (Figure 2.3).

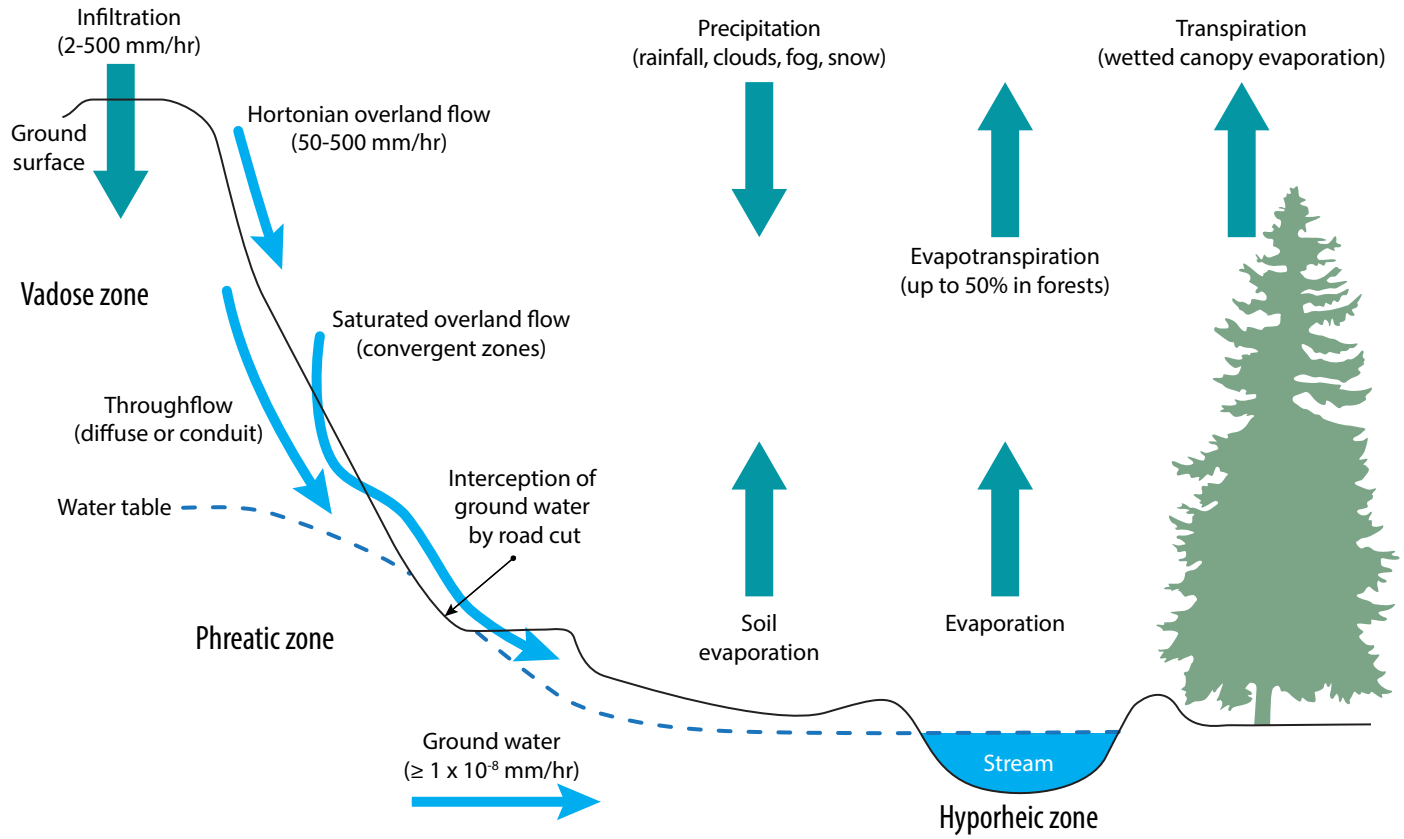


Figure 2.3. Illustration of different types and rates of downslope movement of water on a hillslope (modified from Ziemer and Lisle 1998, and Wohl 2014).

Runoff originates from variable source areas in response to precipitation and soil saturation conditions (Betson 1964; Hewlett and Nutter 1970). Conceptually, the amount of runoff within a single small drainage basin can be highly varied in space and time because many factors influence water infiltration and movement. Much of the variability in areas contributing water to the channel reflects the groundwater levels and activation[1] thresholds for lateral subsurface flow existing immediately after a precipitation event (McDonnell 2003).

Riparian vegetation influences preferential flow pathways in both surface and subsurface environments (Swanson et al. 1998; McDonnell 2003) and the manner in which surface flows create and maintain channel and floodplain morphology. During periods of active runoff, riparian areas quickly become saturated, and become the first areas within the watershed to contribute runoff into the channel (McDonnell 2003). Riparian areas account for the majority of the runoff at the beginning of a flood event, whereas hillslopes contribute more as the runoff tapers off at the end of an event. Flow resistance provided by riparian vegetation and related organic material slows water velocities, reduces peak discharge, and lengthens a flood's duration (Tabacchi et al. 2000; Nilsson and Svedmark 2002).

In a reciprocal manner, stream hydrology plays a large role in shaping riparian vegetation communities. The rate at which the river water surface lowers after a spring freshet influences seedling germination and recruitment (Mahoney and Rood 1998). Thus vegetation species composition and age structure vary due to flow frequencies that determine sediment mobilization and effective discharge (Pike and Scatena 2010).

[1] Activation of subsurface water means that subsurface water is flowing, i.e., the velocity deviates significantly from zero. Activation threshold often refers to the amount of precipitation needed to activate subsurface flow.

Interactions between stream water and groundwater occur in the hyporheic zone. In other words, the *hyporheic zone* is the ecotone between a surface stream and deeper groundwater (Boultan et al. 1998). The extent of the hyporheic zone is determined by the volume of sediment stored within the channel and active floodplain (Moore and Wondzell 2005). Two-way exchanges of water occurring in the hyporheic zone are important in regulating hydrological, biogeochemical, and thermal processes (Krause et al. 2011), which strongly influence the volume, chemistry, and temperature of streamflow. Along this ecotone, upwelling subsurface water supplies the stream ecosystem with mineral nutrients while downwelling stream water provides dissolved oxygen and organic matter to organisms inhabiting the interstitial spaces of alluvial sediments (Boultan et al. 1998). The hyporheic zone can account for a fifth of the invertebrate production in an aquatic ecosystem (Smock et al. 1992). Water flows laterally from the hyporheic zone into alluvial sediment deposits, and can extend out more than 1.2 miles (2 km) in wide valleys and to depths of 33 ft (10 m) (Stanford and Ward 1988). Hyporheic flows can also affect riparian vegetation, although the interactions between riparian communities and hyporheic conditions are not well understood (NRC 2002).



Cape Creek, Lane County, Oregon/Jane Atha, WDFW

2.4. Erosion and Sedimentation Processes

2.4.1. Sediment Sources and Delivery

Sediment sources and delivery within a watershed can vary significantly depending upon geology, climate, landform, soil erodibility, vegetation, and the magnitude and frequency of dominant disturbances. Delivery of sediment to channels by surface erosion is generally low in undisturbed watersheds, but can vary greatly by year (Swanston 1991). Annual differences are caused by variation in weather patterns, changes in exposed surface area, and changes in the amount of erodible material. Sediment can move downslope in aggregates through mass wasting (mass movement, mass failure, or slope movement) categorized as landslides, debris flows, or heaves. Mass wasting events are typically seasonal as a function of soil moisture and freeze-thaw processes (Hales and Roering 2009). Soil on a hillslope will remain stable if the sum of the applied shear stresses does not exceed the sum of the shear strengths of slope materials (soils, roots, etc.). Mass wasting is initiated when shear stress on a material exceeds its shear strength threshold (Ritter et al. 2002). The volume of material generated from hillslope mass wasting events can be very large, and is often the predominant source of sediment and large wood delivered to streams in the Pacific Northwest (Swanson et al. 1982).

Sediment can also move downslope through gradual, diffuse processes such as rainsplash and rills that form from overland flow. Rainsplash takes place when raindrops loosen the soil particles making them more



Skagit Valley agriculture/Jane Atha, WDFW

susceptible to entrainment by overland flow (Furbish et al. 2009; Dunne et al. 2010). Overland flow can be concentrated into small, narrow, shallowly incised micro-channels that are carved into hillslope soils (Selby 1993). These channels, termed rills and gullies (with gullies being deeper) can form effective conduits for sediment erosion into stream channels (Wohl 2014).

Sediment delivered from riparian areas can be generated by mechanisms other than direct streambank erosion. Riparian sediment sources can be associated with treefall that results in the uprooting of trees (root throw; Hairston-Strang and Adams 2000; Liquori 2006). The primary causes of treefall include wind along newly created edges in riparian forest (Liquori 2006; Reid and Hilton 1998), undercutting streambank erosion, and large-scale disturbances such as fire or pest infestation. Root throw can provide direct sediment inputs to the channel (Lewis 1998; Reid and Hilton 1998; Gomi et al. 2005). Harris (1977) found that windthrow-related sediment production along a stream in coastal Oregon was responsible for 33 tons of sediment per mile of stream per year (18.6 metric tons per kilometer per year) (as cited in Gomi et al. 2005).

Riparian vegetation can effectively trap and store sediment transported downslope from overland flow (Naiman et al. 2010). This topic is fully explored in Chapter 5, Pollutant Removal. Once the sediment is deposited in riparian areas, plant roots facilitate stabilization and continued storage of sediment (Allmendinger et al. 2005; Tal and Paola 2007).

2.4.2. Instream Sediment Transport and Deposition

Sediment that has entered the stream channel can be transported downstream as dissolved load, suspended load, or bed load. Dissolved load carries sediment within solution, which can be substantial in some rivers (Knighton 2014). The concentration of solute is highest in water entering the channel through subsurface pathways because slower rates of subsurface water

movement allow for longer reaction times with the surrounding environment. Solute concentrations through subsurface pathways tend to lessen with greater discharge (Wohl 2014). Suspended load refers to sediment carried as suspended particulates in the water, and originates predominantly from bank erosion and surface erosion from upland areas. The finest size fractions of suspended transport, known as wash load, are more likely to be supply limited, i.e., the amount in transport is limited by the amount available. In contrast, the coarser bed load, which consists of larger rocks that bounce along the channel bed, is typically limited by transport capacity of flowing water (stream energy). Bed load may not get suspended; it can roll and slide during low flows, saltate (bounce) at intermediate flows, and move as sheetflow during high flows (Wohl 2014). Bed load transport processes are surprisingly complicated because many factors, some of which interact, determine the threshold for movement. These factors include the range of sediment sizes, their spatial arrangement, and channel form within a reach (Knighton 1984).

Bedforms are bed undulations that result from sediment transport and deposition. Montgomery and Buffington (1997) classified stream channels based on common bedforms (i.e., cascade, step-pool, plane-bed, pool-riffle, and dune-riffle), their dominant sediment transport process, and behaviors of debris flows and instream wood. The role that sediment plays in aquatic habitat can differ dramatically among those classes. For example, sediment in headwater channels (often classified as cascade or step-pool) tends to be stored behind boulder and wood obstructions. In lower gradient channels, sediments become sorted into pools and riffles depending on instream wood load, gradient, and a wide variety of other factors (Benda et al. 2005; Gomi et al. 2005).

All bedforms are depositional features. Deposition occurs when the flow or shear velocity in the stream falls below the settling threshold velocity of the sediment particle. Settling thresholds are lower than entrainment thresholds, and deposition can be localized or extended across a channel length depending on fluctuations in flow velocity (Wohl 2014). Riparian vegetation can be especially instrumental in facilitating deposition within channels and along banks (Tal et al. 2004). Establishment of riparian vegetation can initiate a positive feedback process as plants trap and stabilize sediments and organic matter that provides sites for germination of plants, which can then reinforce the development of floodplains, instream islands, and other landforms.

Erosional forces in the streambed can be increased due to topographic constrictions or locally steep gradients. Where hydraulic forces overcome surface resistance, channel incision can occur (Wells et al. 2009). Channel incision that occurs at the channel head, known as a headcut, results in vertical faces that separate upslope unchanneled environments from downslope channels. Headcuts that destabilize or incise an otherwise stable channel bed result in significant increases in sediment yield (Meyer et al. 1975; Bryan 1990). Headcuts can also occur as an upstream-migrating "step" in the channel bed that forms as a result of hydraulic scour, often from manipulations to the channel or flow conditions (e.g., culverts, diversions, etc.). This type of headcut can migrate upstream and change channel form for long distances.

Establishment of riparian vegetation can initiate a positive feedback process as plants trap and stabilize sediments and organic matter that provide sites for germination of plants, which can then reinforce the development of floodplains, instream islands, and other landforms.

A combination of field, experimental, and theoretical research has dramatically advanced our understanding of sediment transport dynamics as well as the role of vegetation in stream morphology. Sophisticated flume experiments and computational models have confirmed the importance and complexity of interactions among water, sediment, wood, and vegetation (Gurnell 2014). Recent modeling efforts have placed these phenomena on solid theoretical footings and have allowed researchers to explore scale dependence. We know much less about these interactions at small scales (single plant), however, understanding smaller scale phenomena is crucial to fully understanding longer-term and larger-scale geomorphic form and process (Gurnell 2014).



Bank erosion along the upper Chehalis River/Jane Atha, WDFW

2.4.3. Streambank Erosion

Streambank erosion is a geomorphic process that is integral to a watershed's natural disturbance regime and necessary for long-term ecological sustainability (Florsheim et al. 2008). Bank erosion is a key process for maintaining the structural diversity of aquatic and riparian habitats; it initiates community succession that promotes ecological diversity of riparian areas, and contributes coarse sediment to streambeds that is an essential habitat element for benthic invertebrates and spawning salmon. Bank erosion commonly occurs on the outside of river bends, but it can also occur in straight channels where changes in water or sediment supply cause channel incision. Instream large wood or mid-channel gravel bars that divert flows toward a bank (Florshiem et al. 2008) can also cause bank erosion. Local bank erosion is a naturally occurring process that is often indicative of a channel in dynamic equilibrium. Despite this fact, bank erosion at any scale is commonly misinterpreted as a sign of channel instability. Human disturbances can increase rates of bank erosion, and thus, understanding whether bank erosion is triggered by human activities or natural geomorphic processes is important for site-scale management (Polvi et al. 2014).

Two types of processes result in bank erosion: fluvial erosion and mass wasting (ASCE 1998). Fluvial erosion is the separation of sediments from a streambank's surface by the forces of flowing water. Fluvial erosion may destabilize riparian vegetation by exposing plant roots or undercutting vegetation (Florsheim et al. 2008). Fluvial erosion can eventually lead to mass wasting ("bank failure"). Mass wasting at streambanks is caused by scour of the streambed and bank toe that increases bank height and angle. When gravitational forces on the bank (weight of soil, water, and overlying vegetation) exceed the shear strength of the bank material, a portion of the bank collapses along a failure plane (Simon et al. 2000). Both types of bank erosion occur mainly during peak flows, but the association between flow magnitude and amount of bank erosion varies greatly among



Building in danger from streambank erosion on Newaukum River/Kaysie Cox, WDFW

watersheds. Wolman (1959, as cited in ASCE 1998), for instance, reported that significant bank erosion on a creek in Maryland occurred more than ten times per year during relatively small but frequent peak flow events. Studies of other alluvial systems have found that significant bank erosion was caused mostly by large floods with recurrence intervals of decades or more (ASCE 1998).

The stability of streambanks is influenced by soil characteristics, groundwater, and vegetation (Hickin 1984; NRC 2002). Mass wasting failure mechanics, for example, are quite different for cohesive and noncohesive soils (ASCE 1998). Adjacent surface waters or ground water affects pore water pressure, and positive pore water pressure destabilizes banks by reducing cohesion and friction amongst soil particles. Water in soil also adds mass, thereby increasing gravitational forces acting on a streambank. Bank failure often occurs shortly after flood waters recede because soils are at or near saturation and the laterally confining hydraulic pressure of the floodwaters decreases to zero (Rinaldi et al. 2004).

Vegetation may have mechanical and hydrologic effects on bank stability, and these effects can be stabilizing or destabilizing (Simon and Collison 2002; Langendoen et al. 2009; Pollen-Bankhead and Simon 2010). Soil is generally strong in compression, but weak in tension. Woody and herbaceous plant roots are strong in tension, but weak in compression. Consequently, the root-permeated soil of streambanks behaves as a composite material with enhanced strength (Simon and Collision 2002; Pollen and Simon 2005). However, the additional bank strength provided by roots is species dependent (Polvi et al. 2014). Simon et al. (2006), for instance, found that Lemmons's Willow *Salix lemmonii* provided an order of magnitude more root reinforcement of streambanks than Lodgepole Pine *Pinus contorta*. Dense root networks also physically restrain or bind soil particles. In addition, exposed roots on the bank surface increase channel roughness, which dampens stream flow velocities, thereby reducing fluvial erosion (Griffin et al. 2005; Gorrick and Rodríguez 2012). In fact, fluvial erosion of well-vegetated banks is 10 to 100 times less than erosion of unvegetated banks (ASCE

1998). Reduction of stream velocities by roots may also cause sediment deposition, which further stabilizes streambanks.

Vegetation has destabilizing mechanical effects as well (ASCE 1998; Simon and Collison 2002). The weight of vegetation adds a "surcharge"[2] load to soil. Hence, the weight of vegetation increases the vertical shear stress near a streambank and adds to the lateral earth pressure[3] at the streambank surface, however, these effects can be minimal relative to soil's weight (Simon et al. 2006). Additionally, tall, stiff vegetation may impose destabilizing forces on streambanks during windstorms (ASCE 1998).

The hydrologic effects of plants on streambank stability are those that influence soil moisture. Through canopy interception, vegetation reduces the amount of precipitation that reaches soil. Transpiration, which extracts water from the soil column within the root zone, creates negative pore water pressures (matric suction) that increase soil shear strength (Simon and Collison 2002). Plants destabilize streambanks by facilitating infiltration of water into soil via flow pathways ("macropores") created by live and decayed roots. In addition, stemflow tends to concentrate precipitation around the base of stems, creating higher local pore water pressure. The net hydrological effect of vegetation can be significant. Simon and Collision (2002), for instance, found in their study conducted in northern Mississippi that following a very dry period the stabilizing hydrological effect of tree cover was two times greater (220%) than tree cover's stabilizing mechanical effect. However, this result was reversed following a wet period; the stabilizing mechanical effect of tree cover was 159% of tree cover stabilizing hydrological effect.

The bank stability function of riparian vegetation has important implications for riparian area management. FEMAT (1993:V-27) created a generalized curve of root strength versus distance from channel based on expert opinion informed by scientific literature. The radius of Douglas-fir *Pseudotsuga menziesii* root networks are highly correlated with tree crown radius (Smith 1964).[4] Hence, FEMAT (1993) assumed the contribution of root strength to maintaining streambank integrity declines at distances greater than one-half a crown diameter. Using linear regression, Roering et al. (2003) derived a power-law relationship for coniferous trees between root network radius and tree diameter. This relationship suggests that large diameter conifers (36 to 48 inches [91 to 122 cm] diameter breast height) have root network radii that measure 16 to 33 ft (5 to 10 m). Hence, in an undisturbed old-growth riparian forest, the full contribution of root strength to streambank stability is provided by trees within approximately 33 ft (11 m) of the streambank.

2.4.4. Lateral Channel Migration

Lateral channel migration affects sediment erosion and deposition, local topographic relief, flood inundation patterns, river planform, alluvial architecture, and riparian vegetation patterns, which in turn results in a complex arrangement of aquatic and riparian habitats across a river's floodplain (Naiman et al. 1993). Lateral channel migration occurs through the processes of meander bend development, avulsions, and channel widening and narrowing (Rapp and Abbe 2003). These processes occur through fluvial erosion of intact bank material and mass failure of streambanks under gravity, followed by mobilization and transport of the disturbed material (Burckhardt and Todd 1998).

2 A surcharge load is any load imposed upon the soil surface close enough to a streambank to cause lateral pressure to act on the bank. "Surcharge" denotes an extra force in addition to the weight of the soil.

3 Lateral earth pressure is the pressure (i.e., force per area) that soil exerts in the horizontal direction.

4 The ratio of root spread to crown width for small Douglas-fir and Western Hemlock *(Tsuga heterophylla)* (mean dbh about 13 inches [33 cm]) was reported by Smith (1964) to be about 1. Data in Eis (1987) for these same tree species suggest a ratio of about 2.

One mechanism of channel migration is meandering, which is one of the most common river-channel patterns (Güneralp and Marston 2012). Given time, and lacking physical obstructions, a natural unimpeded meandering channel can swing and shift across its valley in the downstream direction, completely disturbing the floodplain (Schumm 1977). The floodplains of meandering rivers are low-lying depositional features that store large volumes of sediment, and reflect the history of erosion and deposition of a river occupying the valley floor (Dunne and Leopold 1978). The time needed for a channel to migrate and occupy its entire floodplain is expressed as a "floodplain turnover rate," which may take tens to thousands of years in western Washington. Beechie et al. (2006) found, for example, that braided channels in rivers of the Cascades and Olympic mountains had a turnover rate of 25 years. In contrast, O'Connor et al. (2003) estimated turnover rates for two large rivers on the Olympic Peninsula to be approximately 200 to 2000 years. The channel migration rates for the rivers in O'Connor et al.'s study ranged from 13 ft (4.0 m) to 42 ft (12.7 m) per year.

Sediment erosion and deposition patterns that result in channel migration are caused by complex flow patterns along meander bends. Water tends to develop a horizontal swirling flow as a result of greater roughness along the banks than in the center of the channel. This swirling flow, termed "helical flow", is generated by the super elevation of the water's surface as it flows along the outside of a bend (Callander 1978). Helical flow creates large cross-stream variation in velocity (Dietrich et al. 1984), and the reduced velocity and bed shear stress at the inside of a bend creates pointbar deposition. In addition, pointbars deflect flow laterally toward the cutbank, creating topographically driven secondary flow that further induces an outward velocity shift toward the cutbank (Güneralp and Marston 2012).

Movements of individual meanders are described as: 1) simple migration (or translation), which is a downstream shift without significant shape change; 2) extension (or growth), where the amplitude of the bend extends by migrating across the valley; 3) rotation, in which the bend axis changes orientation; and 4) lobing and compound growth, where the bends become less regular and symmetrical (Hooke 1984). Individual bends along a meandering channel can have different styles and rates of migration, and typically deform and become asymmetrical with migration. Meander migration that increases the amplitude and tightness of bends can lead to a cutoff channel that creates a shorter flow path across the inside of a pointbar or a neck cutoff at the base of the bend. The increase in channel gradient from the cutoff causes it to become the main channel, and the longer flow path becomes a secondary or overflow channel on the floodplain. Secondary channels may function as side channels that are important rearing habitat for juvenile salmonids (Rosenfeld et al. 2008) or



Chehalis River meander bend/Jane Atha, WDFW



Mid-channel bar/Jane Atha, WDFW

oxbow lakes, which are habitat for amphibians (Henning and Schirato 2006). The increased habitat diversity for aquatic and riparian organisms can persist for decades to centuries depending on rates of sediment filling.

Another mechanism for channel migration is avulsion, which is the rapid abandonment of a river channel and the formation of a new river channel. Avulsions can occur with little erosion of the land between the old and new channel locations (Allen 1965; Butler 2004). An avulsion can cause rapid, dramatic shifts in channel location from one side of the valley bottom to the other, and can occur during a single flood event. Avulsions are often associated with aggrading channels, but this is not a necessary requirement (Tooth et al. 2007). Meander cutoffs, for example, are a type of avulsion not derived from aggradation. In the Pacific Northwest, wood jams often cause and mediate avulsions, acting to maintain a multiple-channel pattern. Wood jams can cause avulsions by plugging channels and diverting flow into a relict channel that then becomes the main channel (Collins and Montgomery 2002).

Along alluvial rivers, spatial and temporal patterns of riparian vegetation composition and structure are controlled by rates of channel migration and vegetation response to disturbance (Figure 2.4). As channels migrate laterally, pointbars create conditions for recruitment of early successional plant species. Over long periods, pointbar growth is followed by the succession of terrestrial plant communities. Consequently, a pointbar may support a chronological series of successional stages arranged from youngest closest to the active channel to oldest farthest from the channel (Shankman 1993). A limited number of species consistently dominate the accreting edge of pointbar landforms, while progressively more species establish as the pointbar aggrades to a higher surface elevation (Meitzen 2009). Opposite these pointbars, eroding cutbanks expose and remove previously established mature vegetation, but also open edge habitat for colonization by new plant species. Kupfer and Malanson (1993) found that cutbank edge forests have higher stem densities and greater species richness than floodplain interior forests.

Lateral channel migration and related streambank erosion processes can pose risks to human communities located near rivers and large streams. Likewise, human actions intended to limit channel migration can degrade aquatic and riparian habitats. For these reasons, geomorphologists have developed protocols for determining the channel migration zone (CMZ). A CMZ includes the outer extent of historical channels, plus the area where future channel migration could occur over some time period (e.g., 100 years). CMZ delineation considers the historical migration zone, i.e., the area encompassing all historical channels; the avulsion hazard zone, i.e., areas not in the historical record that are at risk of avulsion; and the erosion hazard area, i.e., the area at risk of bank erosion from stream flow or mass wasting over the time horizon of the CMZ (Rapp and Abbe 2003). The CMZ typically encompass floodplains and some portion of terraces (landform remnants of the former floodplain). The CMZ also includes channels and terrace banks that are at risk of mass wasting due to erosion of the toe.

Lateral channel migration produces a spatially dynamic riparian ecosystem. Because the riparian ecosystem (i.e., the riparian zone and zone of influence) is defined by proximity to water, as the active channel moves back

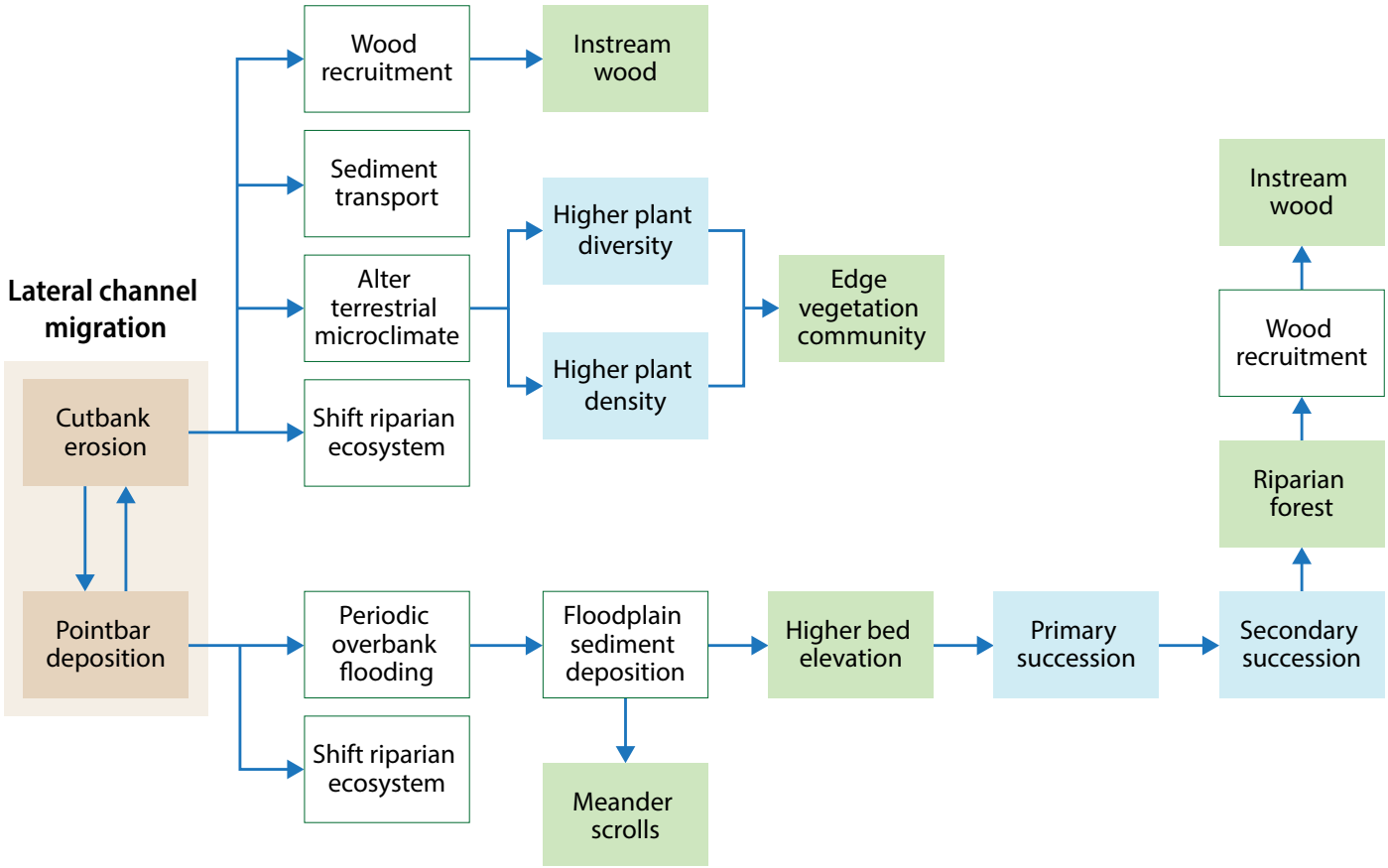
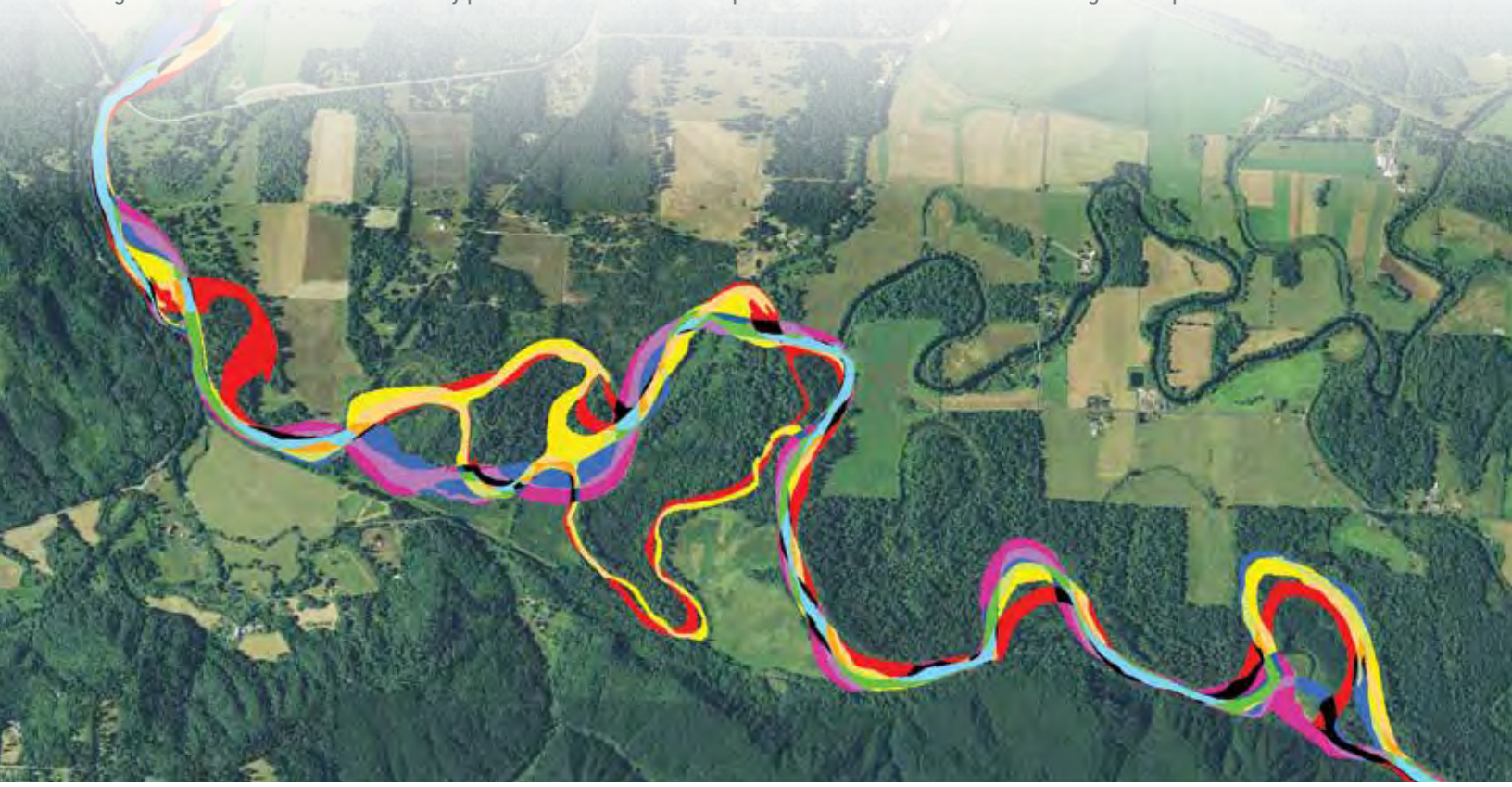


Figure 2.4. A conceptual model of lateral channel migration processes and riparian forest responses (modified from Meitzen 2009). Arrows indicate the hypothesized directions of causal relationships. Brown boxes represent proximal processes leading to channel migration. White boxes are secondary processes. Green boxes depict structures. Blue boxes are biological responses.



Chehalis River meander paths between 1938 and 2013/Ken Pierce, WDFW

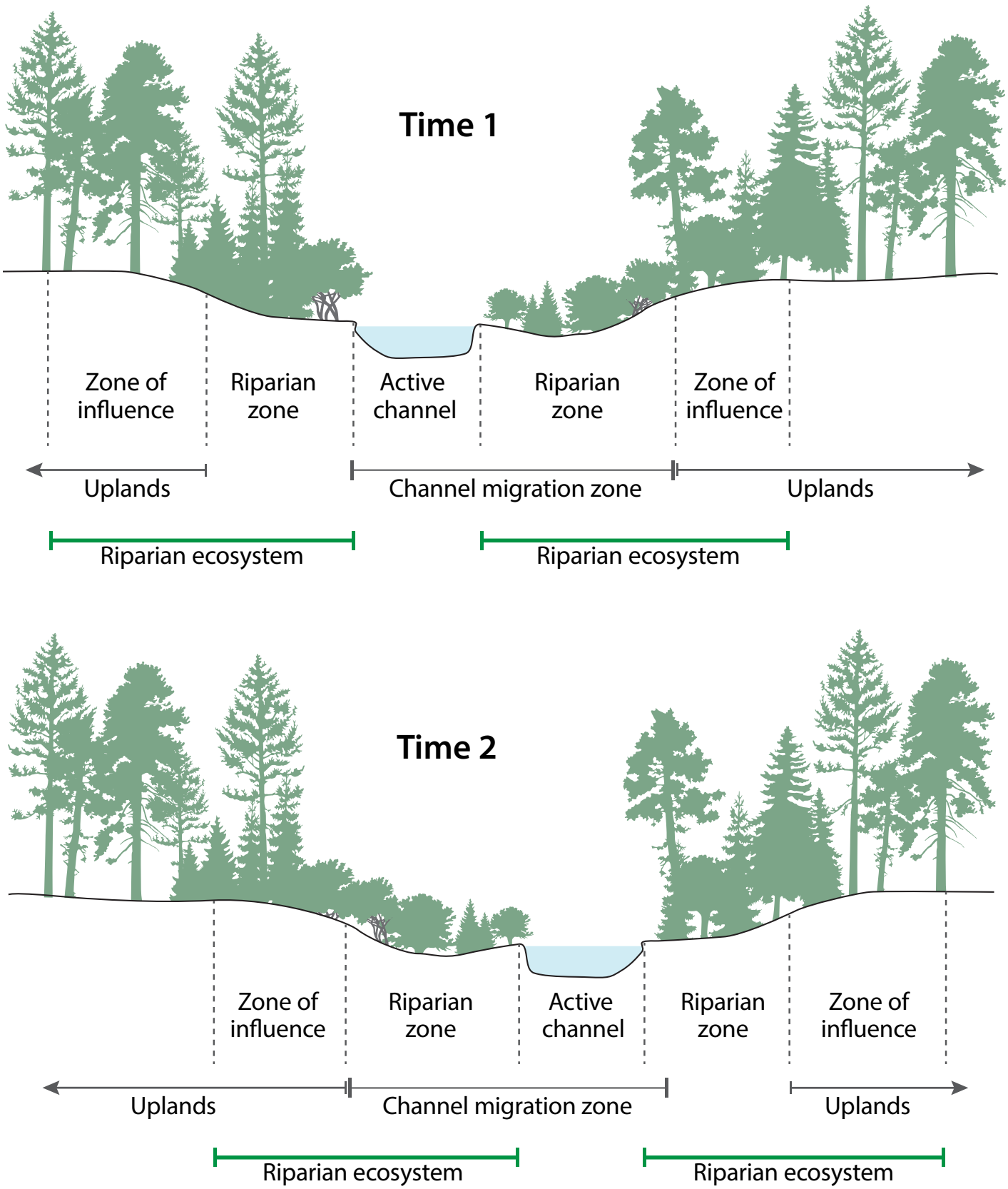


Figure 2.5. Spatial relationships between the riparian ecosystem and channel migration zone (CMZ) over time. As the active channel moves laterally within the CMZ the riparian ecosystem moves with it. Time 1 and time 2 could be separated by days or centuries.



Quinault River/Jane Atha, WDFW

and forth across the CMZ, the riparian ecosystem moves with it (Figure 2.5). Consequently, over long periods of time, a riparian ecosystem will occupy different parts of the CMZ. Furthermore, when an active channel reaches the outside limit of its CMZ, the riparian ecosystem lies outside and adjacent to the CMZ. Hence, to maintain riparian ecosystem functions, management must anticipate and protect future locations of the riparian ecosystem.

2.5. Disturbances

2.5.1. Geomorphic Process Domains

The spatial variability of sediment sources and the varying capacity of water to transport sediment result in a mosaic of different channel forms within a watershed. Channel forms can be described by attributes such as bed and bank sediment size distributions, pool and riffle depths, bankfull widths, gradient, and sinuosity. The classification of channel forms has been refined over the last 30-40 years beginning with Schumm (1977), who distinguished a headwater production zone, mid-basin transfer zone, and downstream depositional zone. This longitudinal arrangement is also reflected in more recent work that defines geomorphic *process domains*. Process domains characterize differences in the types and frequency of disturbance events, and provide a way to represent spatial differences in disturbance regimes (Montgomery 1999).

Six common geomorphic process domains have been identified for forested watersheds of Washington State: hillslope, unchanneled hollows, debris-flow channels, bedrock-fluvial channels, coarse-bed alluvial channels, and fine-bed alluvial channels (Montgomery et al. 1996; Sklar and Dietrich 1998; Montgomery 1999). These process domains are important to distinguish since they

each function differently in terms of sediment dynamics and transport capacity. Note that although geomorphic process domains often occur in a regular longitudinal sequence, there are many exceptions in Washington State where this is not the case.

Hillslopes are unchannelized and are typically dominated by diffusive transport or rain-facilitated transport of sediment downslope. Unchanneled hollows are hillslope concavities that serve as sediment storage sites and source zones for hillslope mass movement (Dietrich and Dunne 1978; Montgomery et al. 2009). Debris-flow channels are dominated by mass wasting sediment dynamics but channel geometry may still be influenced by fluvial processes. Bedrock-fluvial channels have underlying exposed bedrock that limits boundary erosion. In these channels, overlying alluvium is transported by scour during higher flows, and transport capacity exceeds sediment supply, resulting in exposed bedrock. Coarse-bed alluvial channels are dominated by unconsolidated gravels, cobbles, and boulders and are more likely to be supply limited, rather than stream energy limited. Lastly, fine-bed alluvial channels have non-cohesive sand-sized sediment and are more likely to be transport limited by flow energy rather than sediment supply (Wohl 2014).

Using process domains, it is possible to identify within a watershed where different geomorphic processes, disturbance regimes, and responses to disturbance dominate, and predict riparian vegetation dynamics (Naiman et al. 2000; Polvi et al. 2011). Channel morphology correlates well with bed gradient and sediment supply (Montgomery and Buffington 1997). The differences in the balance of hydraulic forces and available sediment among these channels likely lead to differences in overbank processes that can affect vegetation establishment, growth, and mortality. For example, in higher gradient channels, energy is expended on transporting sediment downstream and is not available to reshape the riparian area.

Disturbances are relatively discrete disruptive events that change the physical environment or resource availability, and are essential for developing habitat to support native biota.

2.5.2. Natural Disturbance Regimes

From an ecological perspective, disturbances are relatively discrete disruptive events that change the physical environment or resource availability (Pickett and White 1985); thereby creating opportunities for other species to become established (Nakamura and Swanson 2003). Natural disturbances result in dynamic habitats of varying physical conditions that allow for a variety of species to coexist. Community succession theory recognizes that large-scale disturbances, such as low frequency, high magnitude floods, continually reinitiate community succession in riparian areas (Pickett et al. 1987; Corenblit et al. 2007). The cycle of disturbance and succession occurring throughout a watershed maintains compositional and structural diversity in aquatic and riparian ecosystems. Disturbances that influence streams and riparian areas include wildfire, floods, landslides, tree infestations by insects, and human-induced disturbances such as residential development, timber harvest, and road construction.

Disturbance processes are essential for developing the range of habitat conditions necessary to support native biota (Swanson et al. 1998; Tabacchi et al. 2000). For example, the coarse sediments and large wood delivered to streams via mass wasting are thought to be essential components of freshwater salmonid habitats (Reeves et al. 1995). A natural disturbance regime can be characterized by frequency (how often), magnitude

(how big), duration (how long), and predictability. Wildfires of a given magnitude, for example, occur with a particular statistical probability in the absence of human manipulation of a watershed (Agee 1993). In general, smaller, frequent, and varied disturbances increase the heterogeneity of channel forms, leading to an environment that is more diverse and species rich (Kauffman and Martin 1989; Malanson 1993; Tabacchi et al. 2000; Everett et al. 2003). For example, the dynamics of stream channels that result from frequent, low intensity wildfires determine short-term patterns such as seed germination and animal foraging behavior (Hughes 1997). The influence of moderate and frequent disturbances such as fire (Wright and Bailey 1992) or insect-induced tree mortality (Mattson and Addy 1975) may lead to minor reductions in the riparian canopy, but more diverse habitat conditions that are generally beneficial for salmonids (Naiman and Bilby 1998). By contrast, disturbances that are large and infrequent tend to lead to widespread alterations that have larger and longer-lasting physical impacts. Large disturbances could cause a geomorphic threshold to be exceeded, and the resulting fluvial response could manifest a new geomorphic state with different physical conditions that support a different biological community (Hughes 1997).

Human activities can either dampen or amplify disturbance processes. While natural disturbance processes are ongoing, they are modified by human alterations (e.g., dams eliminate or dampen flood flows and land management can reduce the frequency and severity of fires). Too little or too much disturbance may have detrimental impacts on the physical structure of streams and riparian areas. For example, too little flooding can lead to cementation of the streambed or loss of riparian vegetation, especially in arid regions. Conversely, too much flooding caused by land cover change, for example, can lead to less habitat complexity due to excessive scouring of the channel. The past and current management of a site–and of its greater watershed–may alter the natural disturbance regime resulting in ecosystem states that did not exist historically.

Process domains within a watershed exhibit different disturbance regimes which manifest different aquatic and riparian ecosystems. Disturbances, and where they occur within a watershed, play key roles in structuring ecosystems. Important advances have shifted focus from single channel reaches and disturbance events to processes occurring at larger geographic extents over longer periods of time, that establish linkages between watershed-scale conditions and natural disturbance regimes (Naiman and Bilby 1998; Nakamura and Swanson 2003).

2.5.3. Human Alteration Impacts

Thus far, this chapter has largely focused on the hydrologic and geomorphic processes and their interactions with riparian area vegetation as they naturally occur within a watershed. However, human influences on channel form are ubiquitous, and therefore should be considered in management of riparian areas.

How a channel responds to human alterations of the landscape or riparian areas depends on its sensitivity and resilience (Brunsden and Thornes 1979).



Narrow riparian buffers along Badger Creek/Jennifer Nelson, WDFW

A sensitive channel reach changes in response to human alterations. A resilient channel reach also changes in response to human alterations but will return to its prior condition at some later time. The idea that some parts of a river are more or less sensitive or resilient is critical to predicting channel adjustments. For example, stream reaches with high transport capacity may adjust relatively quickly to an increase in upstream sediment yield but a similar change in sediment yield may cause significant changes in channel morphology in reaches with low transport capacity. The shape, hydraulics, and natural disturbance regime of a reach may indicate its sensitivity to anthropogenic disturbance. For example, a channel that is degrading (lowering bed elevation) may be more sensitive to riparian large wood additions than a channel that is in equilibrium. In addition, sensitivity to changes in hydrology is inversely proportional to channel gradient (Wohl et al. 2007). Hence, managers should anticipate that high gradient streams will be more sensitive to changes in stream flow than lower gradient streams. Other drivers such as the flow regime or controls such as lithology might also be used to determine a reach's sensitivity and resilience, and thereby inform management decisions.

Forestry

An extensive body of scientific literature documents the effects of forestry on stream channels (see Foley et al. 2005; Scanlon et al. 2007; and Wohl 2013 for thorough reviews). Cutting of trees and road building associated with forestry can greatly increase sediment yields and affects water yields over multiple decades as vegetation recovers (Wohl 2014). Impacts from road networks—for logging and otherwise—are numerous and are discussed below. Changes in sediment supply and water yield due to logging can alter the streamflow, stream chemistry, and channel morphology of a stream reach (Liquori et al. 2008). In addition, the resilience of channels in response to such alterations can be quite variable. For example, Madej and Ozaki (1996) found that channel recovery (defined as returning to a former bed-elevation) after a sediment wave following extensive logging in Redwood Creek basin, Northern California varied from 8 years in one creek to 15 years in another. A third channel had not yet recovered.



Clearcut hillslope/Jane Atha, WDFW



Big Beef Creek, Kitsap Peninsula/Ned Pittman, WDFW

There is substantial agreement among scientists as to the potential magnitude and consequences of peak flow changes due to forestry. Grant et al. (2008) assessed the effects of forestry on peak flows and consequent channel response in the Pacific Northwest in a state of the science report. Their findings, primarily synthesized from long-term monitoring, show that responses are complex, and vary with runoff type (snowmelt, rainfall or rain-on-snow), local hydrology, harvest treatment, and channel type. The authors generally noted that geomorphic changes from harvest-related peak flow effects are limited to low-gradient channels (below 2% grade) and are generally minor as compared to other anthropomorphic impacts. Other literature reviews (e.g., Liquori et al. 2008; Grant et al. 1999) had similar conclusions.

The degree to which forestry practices alter water and sediment yields depends on where the logging occurs within a drainage basin. In one study, logging at lower elevations in snowmelt-dominated basins of southwestern Canada caused little to no change in peak flow because of relatively small snowpack, whereas in the higher elevations the peak flow changed significantly (Whitaker et al. 2002). Similarly, characteristics such as climate, topography, and soils also determine landscape sensitivity to forestry. Several studies have shown that mean annual precipitation is a reasonable indicator of impact (e.g. Anderson et al. 1976; Coe 2006; CBOF-TAC 2008). A road network may deliver 20% of sediment to stream channels in areas with 22 in (500 mm) per year average precipitation compared with 50% of the sediment when precipitation exceeds 118 in (3,000 mm) per year (Coe 2006). In areas of high topographic relief, it is particularly challenging for researchers to differentiate channel adjustments induced by logging from change that would have occurred without interference (Marston 2008).

Conversion of riparian areas from forest to other land uses can cause channel narrowing and deepening (Anderson et al. 2004; Sweeney et al. 2004; Faustini et al. 2009). Furthermore, streams without riparian forests often exhibit channels with less wood that are narrower, deeper, have fewer obstructions, less variability in active channel width, higher proportions of run and glide habitats, and lower habitat diversity (Jackson et al. 2014).

Road Infrastructure

Road networks are similar to stream networks in that they are often widely distributed, transport energy and material across a landscape, and have a high edge length per unit area enabling interaction with adjacent hillslopes (Jones et al. 2000). Stream networks and road networks commonly occur in similar densities in wet-climate forested mountains where logging has occurred (Wemple et al. 1996).

The biggest impact of unpaved roads on aquatic systems is sedimentation. Road construction and maintenance disturbs a layer of soil on the road tread, adjacent drainage ditch, and cutslopes that becomes easily eroded material (Megahan 1974). In conjunction with other loose material on roads, higher erodibility increases the total sediment yield from a road segment (Luce and Black 1999). In managed forests of Washington State, unpaved roads and trails are the most significant management activity that affects

sediment production and delivery into streams (Lewis 1998; Gomi et al. 2005; CBOF TAC 2008). Roads can initiate mass movements that tend to result in longer runout zones and more sediment than their naturally occurring counterparts do (May 2002). Sediment generated from roads can be delivered to streams via ditches and gullies below cross-draining culverts that concentrate and route runoff. Road sediment production varies substantially with the type of surfacing material, road slope, mean annual precipitation, geology, traffic type and volumes, and road area (Cafferata and Munn 2002; MacDonald et al. 2004; Coe 2006). Roads and water crossings with improper design or maintenance are often the most significant sources of erosion and sediment delivery to streams in forested watersheds (Madej 2001; Cafferata and Munn 2002). Jones et al. (2000) found that unpaved roads continue to contribute sediment fines to channels long after harvested vegetation has reestablished.

Agriculture

Agriculture, in the form of livestock grazing or crop production, can reduce and alter vegetation cover, compact soils,and reduce water infiltration. It can also increase runoff and sediment yield, and cause associated changes in streamflow, channel morphology, and channel stability.

Cattle grazing can severely degrade riparian areas particularly through vegetation reduction and trampling of streambanks. Grazing animals can create ramps along streambanks and trails along the floodplain that enhance localized erosion (Trimble and Mendel 1995). Grazing-disturbed streams are usually characterized by a lack of overhanging banks, wide and shallow channels, smaller pool area, high sediment yields and turbidity, steep gradients, and channel beds typified by long stretches of glides or runs. Along streams with enclosures that kept cattle out of riparian areas, Magilligan and McDowell (1997) found that channel widths became narrower due to increased roughness by grassy riparian vegetation, which ultimately traps sediment leading to width reductions. The channel narrowing effects of grassy vegetation were also reported by Sweeney et al. (2004) and Allmendinger et al. (2005).

Understanding a channel's state of equilibrium (or disequilibrium) and its potential future states is critical for restoration and protection of salmon habitats.

A common effect of planting crops is increased sediment yield and associated changes in channel pattern and stability (Wohl 2014). The magnitude of these changes is dependent on the type and extent of crops, as well as the topographic and soil characteristics at a site. Numerous case studies indicate that soil erosion from conventional agriculture exceeds rates of natural erosion by up to several orders of magnitude (Montgomery 2007).

Urban/Suburban

Research on the effects of urbanization on sediment yield and channel response date back almost 50 years and is global in reach (Wolman 1967). The results of this research draw similar conclusions regarding the sequence of changes that occur within a drainage basin, with differences occurring only in the magnitude and timing (Chin 2006).

Erosion rates can reach up to 40,000 times pre-disturbance rates on land surfaces cleared for building that remain bare for up to a year (Harbor 1999). Construction sites can dramatically increase sediment yield from an urbanizing basin (Fusillo et al. 1977). For example, sediment production from Issaquah Creek



Mill Creek, Walla Walla, Washington/Jane Atha, WDFW

watershed in western Washington had two- to five-fold increases when only 0.3% of its 55.6 mi^2 (144 km^2) drainage area was under construction (Nelson and Booth 2002). Upon completion of construction, sediment yield usually decreases to negligible amounts as urbanizing areas are stabilized beneath roads, buildings, and lawns.

Research on the effects of urbanization on hydrology and flooding is also extensive, and dates back at least 50 years. Collectively, this research clearly shows that urban development, and associated increases in impervious surfaces, leads to larger and more frequent floods (Leopold 1968). The key metrics of change are peak discharge, lag time, flood frequency, and total runoff or water yield. Morphological adjustments have been studied in response to hydrologic changes, with most studies showing increases in channel width (Chin 2006).

Stream Channel Modifications

Humans have been directly altering stream flow and channel form for centuries (Poff et al. 1997). Flow regulation, through dams, reduces the size and variation of annual peak flows (Williams and Wolman 1984), increases minimum flows (Hirsch et al. 1990), shifts the timing of seasonal flows, and can alter diurnal flow fluctuations if the dam is used for hydroelectric power generation (Magilligan and Nislow 2001).

Dams can have dramatic effects on aquatic and riparian systems (Nilsson et al. 1997; Nilsson and Berggren 2000; Katz et al. 2005; Merritt and Wohl 2006). Dams disconnect the channel from the floodplain by reducing peak flows. This decreases or eliminates freshly scoured surfaces necessary for seedling establishment in riparian areas. Flow regulation can disrupt downstream transport of seeds to germination sites, and seedlings established on gravel bars may die from prolonged submersion when managed flows are higher than natural flows. Changes in sediment size distributions and moisture content can also adversely impact riparian vegetation. The cumulative effects on riparian communities downstream of dams can result in fewer plant species and lower plant density (Jansson et al. 2000).

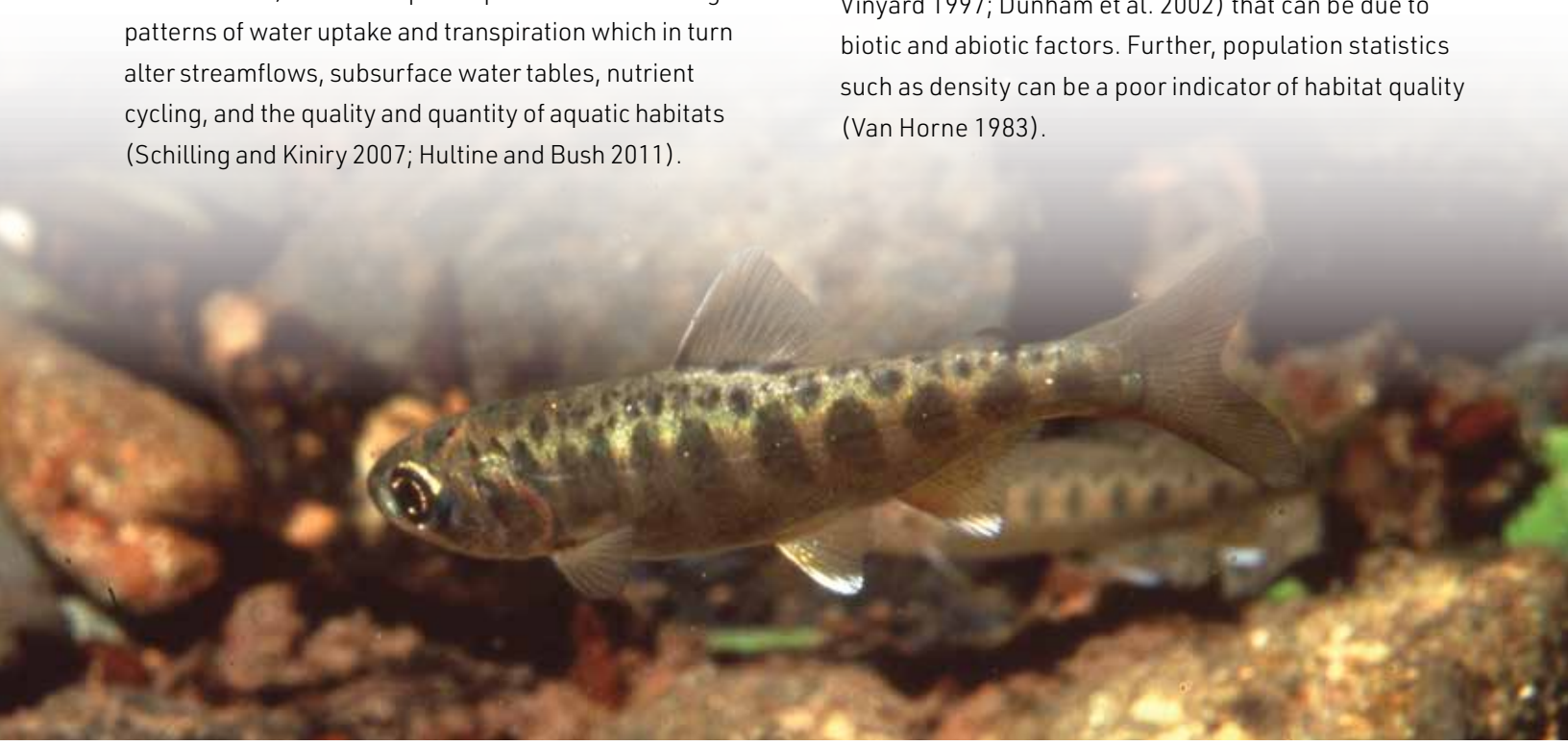
Humans regularly alter channel form through dredging, channel straightening, removing instream wood or Beaver dams, building check dams, extending channel networks via canals, burying or laterally shifting inconvenient channels, and simply reconfiguring a channel to be more esthetically pleasing. (Wohl 2014). Levees are a direct form of channel alteration particularly ubiquitous in lowland rivers. Levees are mounds built parallel to stream channels that limit overbank flooding, and are also known as dikes or embankments (Petroski 2006). Levees severely reduce or eliminate channel-floodplain exchanges, facilitate higher magnitude floods, and exacerbate flooding in downstream areas without levees. Disconnection between the channel and floodplain reduces deposition of sediment and organic matter in floodplains, leading to loss of habitat, reduced animal abundance, and lower biodiversity in riparian areas (Hohensinner et al. 2004).

Lastly, humans can indirectly and severely alter channel form by introducing invasive, exotic species to riparian areas. Invasive plants may displace native riparian plants and thus impact streambank resistance to erosion and overbank sedimentation dynamics (Graf 1978; Allred and Schmidt 1999). Invasive riparian plants can also change patterns of water uptake and transpiration which in turn alter streamflows, subsurface water tables, nutrient cycling, and the quality and quantity of aquatic habitats (Schilling and Kiniry 2007; Hultine and Bush 2011).

2.6. Fish and Wildlife Habitat

2.6.1. Fish

The fisheries and fish ecology literature are replete with studies that report relationships between fish and physical habitat conditions. Such studies demonstrate the profound importance of instream conditions for fish and they have helped guide habitat management and restoration. For example, Nickelson et al. (1992) found seasonal differences in the use of pool and riffle habitat by juvenile Coho Salmon *Oncorhynchus kisutch* and suggested that additional pool habitats might improve their survival. Such correlative approaches have been expanded by considering shifts in habitat use within species and differential habitat requirements among species in attempts to identify optimal habitat type configurations (Rosenfeld 2003; Bain and Jai 2012). However, the success of such approaches has been limited by high spatiotemporal variability in, for example, habitat-density relations among streams (Dunham and Vinyard 1997; Dunham et al. 2002) that can be due to biotic and abiotic factors. Further, population statistics such as density can be a poor indicator of habitat quality (Van Horne 1983).



Juvenile Chinook Salmon Oncorhynchus tshawytscha/*David Price, WDFW*

Recent scientific advances regarding the protection and restoration of fish habitats (and habitats for other vagile aquatic species) include the following: 1) acknowledgement of the importance and frequency of fish movement (Schlosser 1991, 1995; Gowan et al. 1994), 2) greater acknowledgement of the importance of habitat heterogeneity and spatial variability in fish-habitat relationships (Torgersen et al. 2006), and 3) the concept of riverscapes (Ward 1998; Fausch et al. 2002; Allan 2004), which describes a dynamic mosaic of habitat types and environmental gradients that are characterized by high connectivity and complexity.

The riverscape concept expands on the classic stream continuum concept of Vannote et al. (1980) mostly by explicitly incorporating spatial and temporal heterogeneity, discontinuities, and connectivity between stream reaches (longitudinal), the stream and uplands (lateral), and the stream and groundwater (vertical). Fausch et al. (2002) provide several principles for effective research and management given the riverscape concept. These include: 1) conduct research (and management) at appropriate scales for the question, 2) the importance of physical and ecological processes are revealed at different spatiotemporal scales and processes will interact among scales, 3) rare or unique features can be very important, and 4) unintended consequences of habitat degradation propagate in all directions, including upstream. Cumulatively, these principles and the vast research that supported their development suggest that the spatial extent and temporal duration of research and management must be matched to the scales at which populations of species use habitat and at which suitable habitat conditions are created and maintained. Further, they emphasize the importance of maintaining and restoring longitudinal and lateral connectivity of stream systems (Sedell et al. 1989) to allow for proper functioning of habitat forming processes and maintenance and restoration of supplementary and complimentary habitats to account for expected variability in local suitability.

Conducting research and management that incorporates the riverscape concept is challenging because it often requires study at large spatial and long temporal extents as well as monitoring biotic and abiotic processes at fine spatial and temporal resolutions. Perhaps the best examples of such work in Washington are the Intensively Monitored Watersheds (IMW) projects that are designed to assess the efficacy of stream restoration for increasing the freshwater survival and production of salmon (Bilby et al. 2005). The IMW projects are conducted at the spatial extent of watersheds and over the course of several salmon life cycles. Important physical and ecological processes are monitored within and among individual stream reaches with the intent of identifying rare features and measuring changes in habitat complexity and connectivity (Bennett et al. 2016). This approach should yield reliable inferences regarding the efficacy of restoration efforts that can be used to inform decisions via adaptive management (Bennett et al. 2016).

2.6.2. Amphibians and Reptiles

Amphibians are less conspicuous inhabitants of instream habitats than fish, but in much of the Pacific Northwest, particular groups of stream-breeding amphibian species that include giant salamanders (*Dicamptodon* spp.), tailed frogs (*Ascaphus* spp.), and torrent salamanders (*Rhyacotriton* spp.) dominate fishless headwater

The riverscape concept expands on Vannote et al.'s (1980) classic stream continuum concept by including lateral and vertical connectivity and incorporating spatial and temporal heterogeneity.



Coastal Tailed Frog Ascaphus truei *in metamorphosis/Marc Hayes, WDFW*

streams. Headwater streams represent a large majority (up to 80%) of the overall stream network based on its length (Meyer and Wallace 2001). Stream-breeding amphibian dominance in headwaters partly reflects the flow conditions in headwater habitats and the suitable physical conditions those flows create. Amphibian abundance is highest in step-pool and cascade reach morphologies characterized by armored beds, stable bedforms, refuge spaces amongst coarse bed material, and reduced tractive forces as a result of tumbling flow (Dupuis and Friele 2006). For example, torrent salamanders, the only stream-breeding amphibian group that does not attach their eggs to rocky substrates, deposit and conceal them in the lowest flow headwater ends of streams and their tributaries; higher flow habitats will dislodge or damage their eggs. In contrast, giant salamanders and tailed frogs, which glue their eggs to coarse rocky substrates, use concealed oviposition sites in stable step structures typically found further downstream in the headwater network (Hayes et al. 2006). Stream-breeding amphibians seem to become less abundant below headwater streams at least in part because substrate and flow conditions that provide either oviposition or refuge sites become less frequent (Brummer and Montgomery 2003). Other conditions, such as predation by fishes, also play a role.

The freshets (high water events) in larger streams or rivers that have an alluvial floodplain, when coupled with wood, are also critical to both creation and maintenance of off-channel amphibian habitats (Amoros and Bornette 2002). Off-channel habitats comprise among the most important lowland stillwater habitats representing key breeding and rearing areas for the largest group of native amphibians (stillwater breeders) (Richter 2005) and the garter snakes (*Thamnophis* spp.) that feed on them. Such off-channel habitats are also critical rearing and foraging habitat for native turtles (Holland 1994).

2.7. Conclusions

The interactions of water, sediment, wood, and riparian vegetation create complex channel morphologies and diverse aquatic habitat conditions. Reach-scale differences in sediment erosion, transport, and deposition result in a mosaic of aquatic habitat conditions within and among stream reaches.

Understanding a channel's state of equilibrium (or disequilibrium) and its potential future states is critical for restoration and protection of salmon habitats. Consistent with the idea of process domains, not all stream reaches within a watershed are equally sensitive or resilient to human land uses or other anthropogenic disturbances. Describing a channel's historical range of natural variability can aid in understanding a reach's potential response to human disturbance. A historical perspective may also aid in identifying biological communities that are in most need of habitat restoration (McDonald et al. 2004; Brierley and Fryirs 2009). By adopting a historical perspective, we may be able to move closer to the ecosystem composition and structure, and the resulting habitat heterogeneity, essential for fish and wildlife.

Historically, disturbance and successional processes were key drivers for the creation of aquatic habitats (Reeves et al. 1995). Now and into the future, both natural and anthropogenic disturbances will affect the creation, maintenance, destruction, and recreation of aquatic habitats. Management may most reliably result in high quality habitat when it emulates historical disturbances and their effects on a watershed (Poff et al. 1997). An idea offered by Naiman et al. (2000) is to base management on historical patterns of watershed conditions and natural disturbances. If flooding was a major natural disturbance in a watershed, then with empirical data and/or models on the extent to which flooding has affected the watershed, one could describe the dynamic equilibrium conditions of channels and floodplains over time, and then tailor riparian management to the unique conditions of that watershed. If wildfires followed by landslides were the historical disturbance pattern in a watershed, then watershed-scale, long-term forest management plans might schedule timber harvests such that historical natural patterns are partially emulated (Reeves et al. 1995; Bisson et al. 2009). Emulating flood or wildlife disturbances for the benefit of salmon and other aquatic species will be a much more complicated project in residential (i.e., rural, suburban, urban) areas.

The importance of riparian ecosystems in maintaining channel, off-channel, and floodplain habitats is increasingly well supported by the scientific literature. In particular, the importance of longitudinal, lateral, and vertical connectivity to the quality of habitat conditions and the importance of riparian vegetation to stream channel stability are increasingly emphasized. Management of riparian ecosystems should consider connectivity among the geomorphic process domains, the influences of natural disturbance, the historical range of natural variability, and the inextricable influence that riparian vegetation has on geomorphic processes.



Bridge on Strait of Juan de Fuca Highway/Ned Pittman, WDFW

2.8. Literature Cited[5]

Agee, J.K. 1993. Fire ecology of Pacific Northwest forests. Island Press, Washington, D.C. (i)

Allan, J.D. 2004. Landscapes and riverscapes: the influence of land use on stream ecosystems. Annual Review of Ecology, Evolution, and Systematics 35:257-284. (i)

Allen, J.R.L. 1965. A review of the origin and characteristics of recent alluvial sediments. Sedimentology 5:89-191. (i)

Allmendinger, N.E., J.E. Pizzuto, N. Potter, T.E. Johnson, and W.C. Hession. 2005. The influence of riparian vegetation on stream width, eastern Pennsylvania, USA. Geological Society of America Bulletin 117:229-243. (i)

Allred, T.M., and J.C. Schmidt. 1999. Channel narrowing by vertical accretion along the Green River near Green River, Utah. Geological Society of America Bulletin 111:1757-1772. (i)

Amoros, C., and G. Bornette. 2002. Connectivity and biocomplexity in waterbodies of riverine floodplains. Freshwater Biology 47:761-776. (i)

Anderson, J.R., E.E. Hardy, J.T. Roach, and R.E. Witmer. 1976. A land use and land cover classification system for use with remote sensor data. Geological Survey Professional Paper 964. U.S. Geological Survey, Arlington, Virginia. (viii)

Anderson, R.J., B.P. Bledsoe, and W.C. Hession. 2004. Widths of streams and rivers in response to vegetation, bank material, and other factors. Journal of the American Water Resources Association 40:1159-1172. (i)

ASCE (American Society of Civil Engineers Task Committee on Hydraulics, Bank Mechanics, and Modelling of River Width Adjustment). 1998. River width adjustment. I: processes and mechanisms. Journal of Hydraulic Engineering 124:881-902. (i)

Bain, M.B., and H. Jai. 2012. A habitat model for fish communities in large streams and small rivers. International Journal of Ecology 2012:962071. (i)

Beechie, T.J., M. Liermann, M.M. Pollack, S. Baker, and J. Davies. 2006. Channel pattern and river-floodplain dynamics in forested mountains river systems. Geomorphology 78:124-141. (i)

Benda, L., M.H. Hassan, M. Church, and C.L. May. 2005. Geomorphology of steepland headwaters: the transition from hillslopes to channels. Journal American Water Resources Association 41:835-851. (i)

Bennett, S., G. Pess, N. Bouwes, P. Roni, R.E. Bilby, S. Gallagher, J. Ruzycki, T. Buehrens, K. Krueger, W. Ehinger, J. Anderson, C. Jordan, B. Bowersox, and C. Greene. 2016. Progress and challenges of testing the effectiveness of stream restoration in the Pacific Northwest using intensively monitored watersheds. Fisheries 41:92-103. (i)

Betson, R.P. 1964. What is watershed runoff? Journal of Geophysical Research 69:1541–1552. (i)

Bisson, P.A., J.B. Dunham, and G.H. Reeves. 2009. Freshwater ecosystems and resilience of Pacific salmon: habitat management based on natural variability. Ecology and Society 14(1):45. (i)

Bilby, R., W. Ehinger, T. Quinn, G. Volkhardt, K. Krueger, D. Seiler, G. Pess, C. Jordan, M. McHenry, and D. Poon. 2005. Study evaluates fish response to management actions. Western Forester 50:14-15. (i)

Boulton, A.J., S. Findlay, P. Marmonier, E.H. Stanley, and H.M. Valett. 1998. The functional significance of the hyporheic zone in streams and rivers. Annual Review Ecology and Systematics 29:59-81. (i)

Brierley, G., and K. Fryirs. 2009. Don't fight the site: three geomorphic considerations in catchment-scale river rehabilitation planning. Environmental Management 43:1201-1218. (i)

Brummer, C.J., and D.R. Montgomery. 2003. Downstream coarsening in headwater channels. Water Resources Research 39:1-13. (i)

Brunsden, D., and J.B. Thornes. 1979. Landscape sensitivity and change. Transactions of the Institute of British Geographers 4:463-484. (i)

Bryan, R. 1990. Knickpoint evolution in rillwash. Catena Supplement 17:111-132. (i)

[5] References are classified according to RCW 34.05.271 (see Appendix 1) denoted by a lower case roman numeral (i – viii) in parentheses at the end of the citation.

Burckhardt, J.C., and B.L. Todd. 1998. Riparian forest effect on lateral stream channel migration in the glacial till plains. Journal of the American Water Resources Association 34:179-184. (i)

Butler, B. 2004. Channel migration zones. Chapter 4 *in* Best available science, volume 1: a review of science literature. King County, Seattle. (viii)

Cafferata, P.H., and J.R. Munn. 2002. Hillslope monitoring program: monitoring results from 1996 through 2001. Monitoring Study Group Final Report prepared for the California State Board of Forestry and Fire Protection. Sacramento, California. (viii)

Callander, R.A. 1978. River meandering. Annual Review of Fluid Mechanics 10:129-158. (i)

CBOF-TAC (California Board of Forestry and Fire Protection Technical Advisory Committee). 2008. Primer on water riparian exchanges related to forest management in the western U.S., Version 2.0. Sacramento, California. (viii)

Chin, A. 2006. Urban transformation of river landscapes in a global context. Geomorphology 79:460-487. (i)

Coe, D. 2006. Sediment production and delivery from forest roads in the Sierra Nevada, California. Master's thesis. Colorado State University, Fort Collins. (i)

Collins, B.F., and D.R. Montgomery. 2002. Forest development, wood jams, and restoration of floodplain rivers in the Puget Lowland, Washington. Restoration Ecology 10:237-247. (i)

Corenblit, D., E. Tabacchi, J. Steiger, and A.M. Gurnell. 2007. Reciprocal interactions and adjustments between fluvial landforms and vegetation dynamics in river corridors: a review of complementary approaches. Earth-Science Reviews 84:56-86. (i)

Dietrich, W., and T. Dunne. 1978. Sediment budget for a small catchment in a mountainous terrain. Pages 31- 48 *in* O. Slaymaker, editor. Fluvial geomorphology. Rutledge, New York. (i)

Dietrich, W.E., J.D. Smith, and T. Dunne. 1984. Boundary shear stress, sediment transport, and bed morphology in a sand-bedded river meander during high and low flow. Pages 632-639 *in* C.M. Elliot, editor. River meandering: proceedings of the conference rivers '83. American Society of Civil Engineers, New York. (viii)

Dunham, J.B., B.S. Cade, and T.W. Terrell. 2002. Influences of spatial and temporal variation on fish-habitat relationships defined by regression quantiles. Transactions of the American Fisheries Society 131:86-98. (i)

Dunham, J.B., and G.L. Vinyard. 1997. Incorporating stream level variability into analyses of site level fish habitat relationships: some cautionary examples. Transactions of the American Fisheries Society 126:323-329. (i)

Dunne, T. 1978. Field studies of hillslope flow processes. Pages 227-293 *in* M.J. Kirby, editor. Hillslope hydrology. John Wiley, Chichester, United Kingdom. (i)

Dunne, T., and R.D. Black. 1970a. Partial-area contributions to storm runoff in a small New England watershed. Water Resources Research 6:1296-1311. (i)

Dunne, T., and R.D. Black. 1970b. An experimental investigation of runoff production in permeable soils. Water Resources Research 6:170-191. (i)

Dunne, T., and L.B. Leopold. 1978. Water in environmental planning. WH Freeman and Company, San Francisco. (i)

Dunne, T., D.V. Malmon, and S.M. Mudd. 2010. A rain splash transport equation assimilating field and laboratory measurements. Journal of Geophysical Research 115:F01001. (i)

Dupuis, L, and P. Friele. 2006. The distribution of the Rocky Mountain Tailed Frog (*Ascaphus montanus*) in relation to the fluvial system: implications for management and conservation. Ecological Research 21:489-502. (i)

Dust, D., and E. Wohl. 2012. Conceptual model for complex river responses using an expanded Lane's relation. Geomorphology 139:109-121. (i)

Eis, S. 1987. Root systems of older immature hemlock, cedar and Douglas-fir. Canadian Journal of Forest Research 17:1348-1354. (i)

Everett, R., R. Schellhaas, P. Ohlson, D. Spurbeckand, and D. Keenum. 2003. Continuity in fire disturbance between riparian and adjacent sideslope Douglas-fir forests. Forest Ecology and Management 175:31-47. (i)

FEMAT (Forest Ecosystem Management Assessment Team). 1993. Forest ecosystem management: an ecological, economic and social assessment. U.S. Department of Agriculture and U.S. Department of the Interior, Portland, Oregon. (viii)

Fausch, K.D., C.E. Torgersen, C.V. Baxter, and H.W. Li. 2002. Landscapes to riverscapes: bridging the gap between research and conservation of stream fishes. BioScience 52:1-16. (i)

Faustini, J.M., Kaufmann, P.R., and A.T. Herlihy. 2009. Downstream variation in bankfull width of wadeable streams across the conterminous United States. Geomorphology 108:292-311. (i)

Florsheim, J.L., J.F. Mount, and A. Chin. 2008. Bank erosion as a desirable attribute of rivers. BioScience 58:519-529. (i)

Foley, J.A., R. DeFries, G.P. Asner, C. Barford, G. Bonan, S.R. Carpenter, F.S. Chapin, M.T. Coe, G.C. Daily, and H.K. Gibbs. 2005. Global consequences of land use. Science 309:570-574. (i)

Frissell, C.A., W.J. Liss, C.E. Warren, and M.D. Hurley. 1986. A hierarchical framework for stream classification: Viewing streams in a watershed context. Environmental Management 10:199-214. (i)

Furbish, D.J., E.M. Childs, P.K. Haff, and M.W. Schmeeckle. 2009. Rain splash of soil grains as a stochastic advection dispersion process, with implications for desert plant soil interactions and land surface evolution. Journal of Geophysical Research 114:F00A03. (i)

Fusillo, T.V., G. Nieswand, and T. Shelton. 1977. Sediment yields in a small watershed under suburban development. Pages 34-88 *in* Proceedings from the international symposium on urban hydrology, hydraulics, and sediment control. University of Kentucky Press, Lexington. (viii)

Gilbert, G.K. 1877. Report on the geology of the Henry Mountains. U.S. Government Printing Office, Washington, D.C. (viii)

Gomi, T., R.D. Moore, and M. Hassan. 2005. Suspended sediment dynamics in small forest streams of the Pacific Northwest. Journal of the American Water Resources Association 41:877-898. (i)

Gorrick, S., and J.F. Rodrígue. 2012. Sediment dynamics in a sand bed stream with riparian vegetation. Water Resources Research 48:W02505. (i)

Gowan, C., M.K. Young, K.D. Fausch, and S.C. Riley. 1994. Restricted movement of resident stream salmonids: a paradigm lost. Canadian Journal of Fisheries and Aquatic Sciences 51:2626-2637. (i)

Graf, W.L. 1978. Fluvial adjustments to the spread of tamarisk in the Colorado Plateau region. Geological Society of America Bulletin 89:1491-1501. (i)

Grant, G.E., S.L. Lewis, F.J. Swanson, J.H. Cissel, and J.J. McDonnell. 2008. Effects of forest practices on peak flows and consequent channel response: a state-of-the-science report for western Oregon and Washington. PNW-GTR-760. U.S. Forest Service, Pacific Northwest Research Station, Portland, Oregon. (viii)

Grant, G., W. Megahan, and R. Thomas. 1999. A re-evaluation of peak flows: do forest roads and harvesting cause floods? Paper presented at the 1999 NCASI west coast regional meeting. National Council for Air and Stream Improvement, Corvallis, Oregon. (viii)

Grant G.E., J.E. O'Connor J.E., and M.G. Wolman. 2013. A river runs through it: conceptual models in fluvial geomorphology. Pages 6-21 *in* J.F. Shroder, editor. Treatise on geomorphology, volume 9. Academic Press, San Diego, California. (i)

Griffin, E., J. Kean, K. Vincent, J. Smith, and J. Friedman. 2005. Modeling effects of bank friction and woody bank vegetation on channel flow and boundary shear stress in the Rio Puerco, New Mexico. Journal of Geophysical Research: Earth Surface 110:F04023. (i)

Güneralp, I., and R.A. Marston. 2012. Process-form linkages in meander morphodynamics: bridging theoretical modeling and real world complexity. Progress in Physical Geography 36:718-746. (i)

Gurnell, A. 2014. Plants as river system engineers. Earth Surface Processes and Landforms 39:4-25. (i)

Hairston-Strang, A.B., and P.W. Adams. 2000. Riparian management area condition for timber harvests conducted before and after the 1994 Oregon water protection rules. Western Journal of Applied Forestry 15:147-153. (i)

Hales, T., and J. Roering. 2009. A frost "buzzsaw" mechanism for erosion of the eastern Southern Alps, New Zealand. Geomorphology 107:241-253. (i)

Harbor, J. 1999. Engineering geomorphology at the cutting edge of land disturbance: erosion and sediment control on construction sites. Geomorphology 31:247-263. (i)

Harris, D.D. 1977. Hydrologic changes after logging in two small Oregon coastal watersheds. Water Supply Paper 2037. U.S. Geological Survey, Washington, D.C. (i)

Hayes, M., T. Quinn, D. Dugger, T. Hicks, M. Melchiors, and D. Runde. 2006. Dispersion of Coastal Tailed Frog (*Ascaphus truei*): a hypothesis relating occurrence of frogs in non-fish-bearing headwater basins to their seasonal movements. Journal of Herpetology 40:533-545. (i)

Heede, B.H. 1980. Stream dynamics: an overview for land managers. PNW-GTR-72. U.S. Forest Service. Rocky Mountain Research Station, Fort Collins, Colorado. (viii)

Henning, J.A., and G. Schirato. 2006. Amphibian use of Chehalis River floodplain wetlands. Northwestern Naturalist 87:209-214. (i)

Hewlett, J.D., and W.L. Nutter. 1970. The varying source area of streamflow from upland basins. Pages 65-83 *in* Proceedings of the symposium on interdisciplinary aspects of watershed management. American Society of Civil Engineers, New York. (viii)

Hickin, E.J. 1984. Vegetation and river channel dynamics. Canadian Geographer 28:111-126. (i)

Hirsch, R., J. Walker, J. Day, and R. Kallio. 1990. The influence of man on hydrologic systems. Pages 329–359 *in* M.G. Wolman and H.C. Riggs, editors. Surface water hydrology. Geological Society of America, Boulder, Colorado. (viii)

Hohensinner, S., H. Habersack, M. Jungwirth, and G. Zauner. 2004. Reconstruction of the characteristics of a natural alluvial river-floodplain system and hydromorphological changes following human modifications: the Danube River (1812-1991). River Research and Applications 20:25-41. (i)

Holland, D.C. 1994. The Western Pond Turtle: habitat and history. Final Report to the U.S. Department of Energy, Bonneville Power Administration, Portland, Oregon. (viii)

Hooke, J.M. 1984. Changes in river meanders: a review of techniques and results of analyses. Progress in Physical Geography 8:473-508. (i)

Horton, R.E. 1933. The role of infiltration in the hydrologic cycle. Transactions American Geophysical Union, 14:446-460. (i)

Hultine, K., and S. Bush. 2011. Ecohydrological consequences of non-native riparian vegetation in the southwestern United States: a review from an ecophysiological perspective. Water Resources Research 47:W07542. (i)

Hughes, F.M.R. 1997. Floodplain biogeomorphology. Progress in physical geography 21:501–529. (i)

Hupp, C.R., and W.R. Osterkamp. 1996. Riparian vegetation and fluvial geomorphic processes. Geomorphology 14:277-295. (i)

Jackson, C., D. Leigh, S. Scarbrough, and J. Chamblee. 2014. Herbaceous versus forested riparian vegetation: narrow and simple versus wide, woody and diverse stream habitat. River Research and Applications 31:847-857. (i)

Jansson, R., C. Nilsson, M. Dynesius, and E. Andersson. 2000. Effects of river regulation on river-margin vegetation: a comparison of eight boreal rivers. Ecological applications 10:203-224. (i)

Jones, J.A., F.J. Swanson, B.C. Wemple, and K.U. Snyder. 2000. Effects of roads on hydrology, geomorphology, and disturbance patches in stream networks. Conservation Biology 14:76-85. (i)

Katz, G.L., J.M. Friedman, and S.W. Beatty. 2005. Delayed effects of flood control on a flood-dependent riparian forest. Ecological Applications 15:1019-1035. (i)

Kauffman, J.B., and R.E. Martin. 1989. Fire behavior, fuel consumption, and forest floor changes following prescribed understory fires in Sierra Nevada mixed conifer forests. Canadian Journal of Forest Resources 19:455-462. (i)

Kiffney, P.M., C.M. Greene, J.E. Hall, and J.R. Davies. 2006. Tributary streams create spatial discontinuities in habitat, biological productivity and diversity in mainstem rivers. Canadian Journal of Fisheries and Aquatic Sciences 63:2518-2530. (i)

Knighton, D. 2014. Fluvial forms and processes: a new perspective. Routledge, London. (i)

Krause, D., D.M. Hannah, J.H. Fleckenstein, C.M. Heppell, D Kaeser, R. Pickup, G. Pinay, A.L. Robertson, and P.J. Wood. 2011. Inter-disciplinary perspectives on processes in the hyporheic zone. Ecohydrology 4:481-499. (i)

Kupfer, J., and G.P. Malanson. 1993. Observed and modeled directional change in riparian forest composition at a cutbank edge. Landscape Ecology 8:185-199. (i)

Lane, E.W. 1955. The importance of fluvial morphology in hydraulic engineering. Proceedings of American Society of Civil Engineers 81:1-17. (i)

Langendoen, E.J., R.R. Lowrance, and A. Simon. 2009. Assessing the impact of riparian processes on streambank stability. Ecohydrology 2:360-369. (i)

Leopold, L.B. 1968. Hydrology for urban land planning: A guidebook on the hydrologic effects of urban land use. Geological Survey Circular 554. U.S. Geological Survey, Reston, Virginia. (i)

Leopold, L.B., and G. Wolman. 1957. River channel patterns: braided, meandering and straight. U.S. Geological Survey Professional Paper 282-B. U.S. Government Printing Office, Washington, D.C. (i)

Lewis, J. 1998. Evaluating the impacts of logging activities on erosion and sediment transport in the Caspar Creek watersheds. Pages 55-69 *in* R.R. Ziemer, technical coordinator. Proceedings of the conference on coastal watersheds: the Caspar Creek story. PSW-GTR-168. U.S. Forest Service, Pacific Southwest Research Station, Albany, California. (viii)

Liquori, M.K. 2006. Post-harvest riparian buffer response: implications for wood recruitment modeling and buffer design. Journal of American Water Resources Association 42(1):177-189. (i)

Liquori, M.K., D. Martin, R. Coats, L. Benda, and D. Ganz. 2008. Scientific literature review of forest management effects on riparian functions for anadromous salmonids. Sound Watershed Consulting, Oakland, California. (viii)

Luce, C.H., and T.A. Black. 1999. Sediment production from forest roads in western Oregon. Water Resources Research 35:2561-2570. (i)

MacDonald, L.H., D.B. Coe, and S.E. Litschert. 2004. Assessing cumulative watershed effects in the central Sierra Nevada: hillslope measurements and catchment-scale modeling. Pages 149-157 *in* D.D. Murphy and P.A. Stine, editors. Proceedings of the Sierra Nevada science symposium. PSW-GTR-193. U.S. Forest Service, Pacific Southwest Research Station, Albany, California. (viii)

Madej, M.A. 2001. Erosion and sediment delivery following removal of forest roads. Earth Surface Processes and Landforms 26:175-190. (i)

Madej, M.A., and V. Ozaki. 1996. Channel response to sediment wave propagation and movement, Redwood Creek, California, USA. Earth Surface Processes and Landforms 21:911-927. (i)

Magilligan, F.J., and P.F. McDowell. 1997. Stream channel adjustments following elimination of cattle grazing. Journal of the American Water Resources Association 33:867-878. (i)

Magilligan, F.J., and K.H. Nislow. 2001. Long-term changes in regional hydrologic regime following impoundment in a humid-climate watershed. Journal of the American Water Resources Association 37:1551-1569. (i)

Mahoney, J.M., and S.B. Rood. 1998. Streamflow requirements for cottonwood seedling recruitment -an integrative model. Wetlands 18:634-645. (i)

Malanson, G.P. 1993. Riparian Landscapes. Cambridge University Press, Cambridge, United Kingdom. (i)

Marston, R.A. 2008. Land, life, and environmental change in mountains. Annals of the Association of American Geographers 98:507-520. (i)

Mattson, W.J., and N.D. Addy. 1975. Phytophagous, insects as regulators of forest primary production. Science 190:515-522. (i)

May, C.L. 2002. Debris flows through different forest age classes in the central Oregon Coast Range, Journal of the American Water Resources Association 38:1097-1113. (i)

McDonald, A., S.N. Lane, N.E. Haycock, and E. Chalk. 2004. Rivers of dreams: on the gulf between theoretical and practical aspects of an upland river restoration. Transactions of the Institute of British Geographers 29:257-281. (i)

McDonnell, J.J. 2003. Where does water go when it rains? Moving beyond the variable source area concept of rainfall-runoff response. Hydrological Processes 17:1869-1875. (i)

Megahan, W.F. 1974. Erosion over time on severely disturbed granitic soils: a model. INT-156. U.S. Forest Service, Intermountain Forest & Range Experiment Station, Ogden, Utah. (i)

Meitzen, K.M. 2009. Lateral change migration effects on riparian forest structure and composition, Congaree River, South Carolina, USA. Wetlands 29:465-475. (i)

Merritt, D.M., and E.E. Wohl. 2006. Plant dispersal along rivers fragmented by dams. River Research and Applications 22:1-26. (i)

Meyer, L., G. Foster, and S. Nikolov. 1975. Effect of flow rate and canopy on rill erosion. Transactions of the American Society of Agricultural Engineers 18:905-911. (i)

Meyer, J.L., and J.B. Wallace. 2001. Lost linkages and lotic ecology: rediscovering small streams. Pages 295-317 *in* M.C. Press, N.J. Huntly, and S. Levin, editors. Ecology: achievement and challenge. Blackwell Science, Oxford, United Kingdom. (i)

Montgomery, D.R. 1999. Process domains and the river continuum. Journal of the American Water Resources Association 35:397-410. (i)

Montgomery, D.R. 2007. Is agriculture eroding civilization's foundation? GSA Today 17(10):4-9. (i)

Montgomery, D.R., T.B. Abbe, J.M. Buffington, N.P. Peterson, K.M. Schmidt, and J.D. Stock. 1996. Distribution of bedrock and alluvial channels in forested mountain drainage basins. Nature 381:587-589. (i)

Montgomery, D.R., and J.M. Buffington. 1997. Channel-reach morphology in mountain drainage basins. Geological Society of America Bulletin 109:596-611. (i)

Montgomery, D.R., K.M. Schmidt, W.E. Dietrich, and J. McKean. 2009. Instrumental record of debris flow initiation during natural rainfall: implications for modeling slope stability. Journal of Geophysical Research 114:F01031. (i)

Moore, R.D., and S.M. Wondzell. 2005. Physical hydrology and the effects of forest harvesting in the Pacific Northwest: a review. Journal of the American Water Resources Association 41:763-784. (i)

Naiman, R.J., and R.E. Bilby. 1998. River ecology and management: lessons from the Pacific Coastal Ecoregion. Springer-Verlag, New York. (i)

Naiman, R.J., R.E. Bilby, and P.A. Bisson. 2000. Riparian ecology and management in the Pacific coastal rain forest. BioScience 50:996-1011. (i)

Naiman, R.J., H. Decamps, and M.E. McClain. 2010. Riparia: ecology, conservation, and management of streamside communities. Academic Press, London. (i)

Naiman, R.J., H. Decamps, and M. Pollock. 1993. The role of riparian corridors in maintaining regional biodiversity. Ecological Applications 3:209-212. (i)

Nakamura, F., and F.J. Swanson. 2003. Dynamics of wood in rivers in the context of ecological disturbance. Pages 279-298 *in* S.V. Gregory, K.L. Boyer, and A.M. Gurnell, editors. The ecology and management of wood in world rivers. American Fisheries Society, Bethesda, Maryland. (i)

NRC (National Research Council). 2002. Riparian areas: strategies for management. National Academies Press, Washington, D.C. (i)

Nelson, E.J., and D.B. Booth. 2002. Sediment sources in an urbanizing, mixed land-use watershed. Journal of Hydrology 264:51-68. (i)

Nickelson, T.E., J.D. Rodgers, S.L. Johnson, and M.F. Solazzi. 1992. Seasonal changes in habitat use by juvenile Coho Salmon (*Oncorhynchus kisutch*) in Oregon coastal streams. Canadian Journal of Fisheries and Aquatic Sciences 49:783-789. (i)

Nilsson, C., and K. Berggren. 2000. Alterations of riparian ecosystems caused by river regulation. BioScience 50:783-792. (i)

Nilsson, C., R. Jansson, and U. Zinko, U., 1997. Long-term responses of river-margin vegetation to water-level regulation. Science 276:798-800. (i)

Nilsson, C., and M. Svedmark. 2002. Basic principles and ecological consequences of changing water regimes: riparian plant communities. Environmental Management 30:468-80. (i)

O'Connor, J.E., M.A. Jones, and T.L. Haluska. 2003. Floodplain and channel dynamics of the Quinault and Queets Rivers, Washington, USA. Geomorphology 51:31-59. (i)

Osterkamp, W.R., and C.R. Hupp. 2010. Fluvial processes and vegetation – glimpses of the past, the present, and perhaps the future. Geomorphology 116:274-285. (i)

Petroski, H. 2006. Levees and other raised ground. American Scientist 94(1):7-11. (i)

Pickett, S., S. Collins, and J. Armesto. 1987. A hierarchical consideration of causes and mechanisms of succession. Vegetatio 69:109-114. (i)

Pickett, S.T., and P.S. White. 1985. The ecology of natural disturbance and patch dynamics. Academic Press, San Diego, California. (i)

Pike, A.S., and F.N. Scatena. 2010. Riparian indicators of flow frequency in a tropical montane stream network. Journal of Hydrology 382:72-87. (i)

Poff, N.L., J.D. Allan, M.B. Bain, J.R. Karr, K.L. Prestegaard, B. Richter, R. Sparks, and J. Stromberg. 1997. The natural flow regime: a new paradigm for riverine conservation and restoration. BioScience 47:769-784. (i)

Pollen, N., and A. Simon. 2005. Estimating the mechanical effects of riparian vegetation on stream bank stability using a fiber bundle model. Water Resources Research 41:W07025. (i)

Pollen-Bankhead, N., and A. Simon. 2010. Hydrologic and hydraulic effects of riparian root networks on streambank stability: is mechanical root-reinforcement the whole story? Geomorphology 116:353–362. (i)

Polvi, L.E., E.E. Wohl, and D.M. Merritt. 2011. Geomorphic and process domain controls on riparian zones in the Colorado Front Range. Geomorphology 125:504-516. (i)

Polvi, L.E., E.E. Wohl, and D.M. Merritt. 2014. Modeling the functional influence of vegetation type on streambank cohesion. Earth Surface Processes and Landforms 39:1245-1258. (i)

Post, D.M., M.W. Doyle, J.L. Sabo, and J.C. Finlay. 2007. The problem of boundaries in defining ecosystems: a potential landmine for uniting geomorphology and ecology. Geomorphology 89:111-126. (i)

Rapp, C.F., and T.B. Abbe. 2003. A framework for delineating channel migration zones. Ecology Publication #03-06-027. Washington State Department of Ecology and Washington State Department of Transportation, Olympia. (viii)

Reeves, G.H., L.E. Benda, K.M. Burnett, P.A. Bisson, and J.R. Sedell. 1995. A disturbance-based ecosystem approach to maintaining and restoring freshwater habitats of evolutionarily significant units of anadromous salmonids in the Pacific Northwest. American Fisheries Society Symposium 17:334-349. (i)

Reid, L.M., and S. Hilton. 1998. Buffering the buffer. Pages 71-80 *in* R.R. Ziemer, technical coordinator. Proceedings of the conference on coastal watersheds: the Caspar Creek story. PSW-GTR-168. U.S. Forest Service, Pacific Southwest Research Station, Albany, California. (i)

Renschler, C.S., M.W. Doyle, and M. Thomas. 2007. Geomorphology and ecosystems: challenges and keys for success in bridging disciplines. Geomorphology 89:1-8. (i)

Richter, K.O. 2005. Wetlands. Pages 22-23 *in* L.L.C. Jones, W.P. Leonard, and D.J. Olson, editors. Amphibians of the Pacific Northwest. Seattle, Audubon Society, Seattle. (vi)

Rinaldi, M., N. Casagli, S. Dapporto, and A. Gargini. 2004. Monitoring and modelling of pore water pressure changes and riverbank stability during flow events. Earth Surface Processes and Landforms 29:237-254. (i)

Ritter, D.F., R.C. Kochel, and J.R. Miller. 2002. Process geomorphology. McGraw-Hill, Boston. (i)

Roering, J.J., K.M. Schmidt, J.D. Stock, W.E. Dietrich, and D.R. Montgomery. 2003. Shallow landsliding, root reinforcement, and the spatial distribution of trees in the Oregon Coast Range. Canadian Geotechnical Journal 40:237-253. (i)

Rosenfeld, J. 2003. Assessing the habitat requirements of stream fishes: an overview and evaluation of different approaches. Transactions of the American Fisheries Society 132:953-968. (i)

Rosenfeld J.S., E. Raeburn, P.C. Carrier, and R. Johnson. 2008. Effects of side channel structure on productivity of floodplain habitats for juvenile Coho Salmon. North American Journal of Fisheries Management 28: 1108–1119. (i)

Scanlon, B.R., I. Jolly, M. Sophocleous, and L. Zhang. 2007. Global impacts of conversions from natural to agricultural ecosystems on water resources: quantity versus quality. Water Resources Research 43:W03437. (i)

Schilling, K., and J. Kiniry. 2007. Estimation of evapotranspiration by Reed Canarygrass using field observations and model simulations. Journal of Hydrology 337:356-363. (i)

Schlosser, I.J. 1991. Stream fish ecology: a landscape perspective. BioScience 41:704-712. (i)

Schlosser, I.J. 1995. Critical landscape attributes that influence fish population dynamics in headwater streams. Hydrobiologia 303:71-81. (i)

Schumm, S.A. 1977. The fluvial system. Wiley, New York. (i)

Schumm, S.A. 1979. Geomorphic thresholds: the concept and its applications. Transactions of the Institute of British Geographers 4:485-515. (i)

Sedell, J.R., J.E. Richey, and F.J. Swanson. 1989. The river continuum concept: a basis for the expected ecosystem behavior of very large rivers? Pages 49-55 *in* D.P. Dodge, editor. Proceedings of the international large river symposium. Department of Fisheries and Oceans, Ottawa, Canada. (i)

Selby, M.J. 1993. Hillslope forms and processes, 2nd edition. Oxford University Press, United Kingdom. (i)

Shankman, D. 1993. Channel migration and vegetation patterns in the Southeastern Coastal Plain. Conservation Biology 7:176-183. (i)

Simon, A., and A.J.C. Collison. 2002. Quantifying the mechanical and hydrologic effects of riparian vegetation on streambank stability. Earth Surface Processes and Landforms 27:527-546. (i)

Simon, A., A. Curini, S.E. Darby, and E.J. Langendoen. 2000. Bank and near-bank processes in an incised channel. Geomorphology 35:193-217. (i)

Simon, A., N. Pollen, and E. Langendoen. 2006. Influence of two woody riparian species on critical conditions for streambank stability: upper Truckee River, California. Journal of the American Water Resources Association 42:99-113. (i)

Sklar, L., and W.E. Dietrich. 1998. River longitudinal profiles and bedrock incision models: stream power and the influence of sediment supply. Geophysical Monograph Series 107:237-260. (i)

Smith, J.H.G. 1964. Root spread can be estimated from crown width of Douglas-fir, Lodgepole Pine, and other British Columbia tree species. Forestry Chronicle 40:456-473. (i)

Smith, B., P. Warkeand, and W. Whalley. 2002. Landscape development, collective amnesia and the need for integration in geomorphological research. Area 34:409-418. (i)

Smock, L.A., J.E. Gladden, J.L. Riekenberg, L.C. Smith, and C.R. Black. 1992. Lotic macroinvertebrate production in three dimensions: channel surface, hyporheic, and floodplain environments. Ecology 73:876-886. (i)

Stallins, J.A. 2006. Geomorphology and ecology: unifying themes for complex systems in biogeomorphology. Geomorphology 77:207-216. (i)

Stanford, J.A., and J.V. Ward. 1988. The hyporheic habitat of river ecosystems. Nature 335:64-66. (i)

Stanford, J.A., and J.V. Ward. 2001. Revisiting the serial-discontinuity concept. Regulated Rivers: Research & Management 17:303-310. (i)

Swanson, F.J., R.L. Fredriksen, and R.M. McCorison. 1982. Material transfer in a western Oregon forested watershed. Pages 233-266 *in* R.L. Edmonds, editor. Analysis of coniferous forest ecosystems in the western United States. Hutchinson Ross, Stroudsburg, Pennsylvania. (viii)

Swanson, F.J., S.L. Johnson, S.V. Gregory, and S.A. Acker. 1998. Flood disturbance in a forested mountain landscape. BioScience 48:681-689. (i)

Swanston, D.N. 1991. Natural Processes. Pages 139-179 *in* W. Meehan, editor. Influences of forest and rangeland management on salmonid fishes and their habitats. American Fisheries Society, Bethesda, Maryland. (i)

Sweeney, B.W., T.L. Bott, J.K. Jackson, L.A. Kaplan, J.D. Newbold, L.J. Standley, W.C. Hession, and R.J. Horwitz. 2004. Riparian deforestation, stream narrowing, and loss of stream ecosystem services. Proceedings of the National Academy of Sciences101:14132-14137. (i)

Tabacchi, E., L. Lambs, H. Guilloy, A.M. Planty-Tabacchi, E. Muller, and H. Decamps. 2000. Impacts of riparian vegetation on hydrological processes. Hydrological Processes 14:2959-2976. (i)

Tal, M., K. Gran, A.B. Murray, C. Paola, and D.M Hicks. 2004. Riparian vegetation as a primary control on channel characteristics in multi-thread rivers. Pages 43-58 *in* A.J. Bennet and A. Simon, editors. Riparian vegetation and fluvial geomorphology. American Geophysical Union, Washington, D.C. (i)

Tal, M., and C. Paola. 2007. Dynamic single-thread channels maintained by the interaction of flow and vegetation. Geology 35:347-350. (i)

Thorn, C.E., and M.R. Welford. 1994. The equilibrium concept in geomorphology. Annals of the Association of American Geographers 84:666-696. (i)

Tooth, S., H. Rodnight, G.A. Duller, T.S. McCarthy, P.M. Marren, and D. Brandt. 2007. Chronology and controls of avulsion along a mixed bedrock-alluvial river. Geological Society of America Bulletin 119:452-461. (i)

Torgersen, C., E., C.V. Baxter, and H.W. Li. 2006. Landscape influences on longitudinal patterns of river fishes: spatially continuous analysis of fish-habitat relationships. American Fisheries Society Symposium 48:473-492. (i)

Trimble, S.W., and A.C. Mendel. 1995. The cow as a geomorphic agent—a critical review. Geomorphology 13:233-253. (i)

Van Horne, B. 1983. Density as a misleading indicator of habitat quality. Journal of Wildlife Management 47:893-901. (i)

Vannote, R.L., G.W. Minshall, K.W. Cummins, J.R. Sedell, and C.E. Cushing. 1980. The river continuum concept. Canadian Journal of Fisheries and Aquatic Sciences 37:130-137. (i)

Ward J.V. 1998. Riverine landscapes: biodiversity patterns, disturbance regimes, and aquatic conservation. Biological Conservation 83:269-278. (i)

Wells, R.R., C.V. Alonso, and S.J. Bennett. 2009. Morphodynamics of headcut development and soil erosion in upland concentrated flows. Soil Science Society of America Journal 73:521-530. (i)

Wemple, B.C., J.A. Jones, and G.E. Grant. 1996. Channel network extension by logging roads in two basins, western Cascade, Oregon. Journal of the American Water Resources Association 32:1195-1207. (i)

Whitaker, A., Y. Alila, J. Beckers, and D. Toews. 2002. Evaluating peak flow sensitivity to clear-cutting in different elevation bands of a snowmelt-dominated mountainous catchment. Water Resources Research 38:1172. (i)



School of Bull Trout Salvelinus confluentus*/William Meyer, WDFW*

Williams, G.P., and M.G. Wolman. 1985. Effects of dams and reservoirs on surface-water hydrology – changes in rivers downstream from dams. U.S. Geological Survey, Washington, D.C. (i)

Wohl, E. 2013. Mountain rivers revisited. American Geophysical Union, Washington, D.C. (i)

Wohl, E. 2014. Rivers in the landscape: science and management. Wiley, Hoboken, New Jersey (i)

Wohl, E., D. Cooper, L. Poff, F. Rahel, D. Staley, and D. Winters. 2007. Assessment of stream ecosystem function and sensitivity in the Bighorn National Forest, Wyoming. Environmental Management 40:284-302. (i)

Wolman, M.G. 1959. Factors influencing erosion of cohesive river banks. American Journal of Science 25:204-216. (i)

Wolman, M.G. 1967. A cycle of sedimentation and erosion in urban river channels. Geografiska Annaler 49A:385-395. (i)

Wright H.A., and A.W. Bailey. 1982. Fire ecology: United States and southern Canada. Wiley, New York. (i)

Ziemer, R.R., and T.E. Lisle. 1998. Hydrology. Pages 43-68 *in* R.J. Naiman and R.E. Bilby, editors. River ecology and management: lessons from the Pacific Coastal Ecoregion. Springer-Verlag, New York. (i)

Chapter 3. Wood

By: George F. Wilhere and Anne Marshall

3.1. Introduction

The scientific study of wood in rivers and streams began about 50 years ago (Gregory 2003) and the vital ecological role of instream wood has been known for at least 40 years (Swanson et al. 1976). Over that 50 year period, the substantial quantity of research on instream wood has motivated numerous authoritative reviews of the scientific literature, such as Bisson et al. (1987), Maser et al. (1988), Gurnell et al. (1995), Bilby and Bisson (1998), Gurnell et al. (2002), Naiman et al. (2002a), and Hassan et al. (2005). A comprehensive, in-depth review of the ecology of wood in aquatic ecosystems is provided by Gregory et al. (2003). Although we have a solid understanding of wood's role in aquatic ecosystems and the pathways through which wood enters and moves through a stream network, some important questions remained unanswered.



Wood, rocks, and roots – roughness elements that enhance habitat diversity by increasing hydraulic complexity/Jane Atha, WDFW

This chapter focuses on the roles and recruitment of wood in aquatic ecosystems. It does not cover stream restoration using large wood. For information on that, see Dominguez and Cederholm (2000), Reich et al. (2003), Bisson et al. (2003), Carah et al. (2014), and Roni et al. (2014). For information on riparian forest management see Boyer et al. (2003) and Spies et al. (2013).

3.2. The Ecological Role of Instream Wood

Wood plays critical roles in the composition, structure, and function of riparian and aquatic ecosystems. In forested regions, wood is an important determinant of channel form and dynamics, especially in small streams (Montgomery and Buffington 1997; Bilby and Bisson 1998). However, the importance of wood's effects differs with channel dimensions, slope, sediment supply, and stream discharge (Gurnell et al. 1995). Large wood causes widening and narrowing, deepening and shallowing, stabilization and destabilization at different points along a stream or river channel (Swanson et al. 1976). The many effects of large wood create a variety of channel morphologies–dam pools, plunge pools, riffles, glides, undercut banks, and side channels–which provide a diversity of aquatic habitats. Pools are deposition sites for sediment and fine organic matter. Sediment is essential substrate for salmonid spawning, and stored sediments become mobilized over time to replenish downstream spawning areas.

Sediment and fine organic matter deposits are productive areas for invertebrates and are important food production sites for juvenile salmonids (Bisson et al. 1987). Pools provide rearing habitats and essential refuge from high flows for fish and other aquatic fauna. Instream large wood provides fish with cover from predators, and by increasing a water body's effective space, wood structures may increase fish densities (Bisson et al. 1987).

3.2.1. Small Wood

Wood is often divided into large and small size categories. Large wood is usually defined as having diameter greater than 4 in (10 cm) and length greater than 6 ft (≈2 m) (Bilby and Ward 1991; Schuett-Hames et al. 1999).[1] Small wood[2] consists of branches and other woody material not classified as large wood. Small wood plays essential and unique roles in lotic ecosystems. For instance, accumulations of small wood enhance a stream's retention of leaves and particulate organic matter (Gregory et al. 1991), which are vital food sources for many aquatic invertebrates. Small wood also effects channel morphology. Plunge and dammed pools are often associated with accumulations of small wood, and large wood with dense accumulations of small wood retain sediment significantly more frequently than large wood with sparse small wood accumulations (Bilby and Ward 1991).

Small wood exerts tremendous effects on hydrology and channel morphology through actions of the American Beaver *Castor canadensis* (Naiman et al. 1988). Beaver dams can store large quantities of sediment, reduce channel incision, remove excess nutrients from water, increase water retention and base flows, reduce peak flows, and by spreading flow events over longer periods, increase groundwater recharge, and increase the salmonid habitat capacity of small streams (Pollock et al. 2015). Beaver dams consist mainly of mud and small wood. Published information on small wood sizes in dams of Beaver is lacking. However, Beaver most often forage on trees ranging from 1.2 - 3.2 in (3 - 8 cm) in diameter (Collen and Gibson 2001), and a large proportion of woody stems used as food are also used in dam construction (Barnes and Mallik 1996). In Maryland, Blersch and Kangas (2014) found that 98% of sticks (i.e., small wood) in a Beaver dam were less than 4 in (10 cm) in diameter and that 46% of those sticks were probably placed in the dam by Beaver. The other 54% of sticks in the dam were due to passive capture of transported wood. For more information on the role of Beaver and Beaver dams in aquatic ecosystems, see Pollock et al. (2015).

3.2.2. Roles of Instream Large Wood

The main role of large wood in aquatic ecosystems is large roughness elements (Bisson et al. 1987) (Figure 3.1). Roughness elements are obstacles in a channel that deflect flow and change its velocity. The size, shape, and strength of large wood make it very effective at redirecting hydraulic forces and the flow of materials (Figure 3.2), such as sediment and fine organic matter. Instream large wood increases hydraulic complexity, i.e., creates a wider range of flow velocities, which causes pool formation, streambed scour, sediment deposition, and channel migration. The net result is a diversity of aquatic habitats.

[1] Large wood is also known as large woody debris (LWD) or coarse woody debris. There is no universal definition of LWD. Another definition is greater than 4 in (10 cm) in diameter and greater than 3 ft (≈1 m) in length. The system of measurement used effects the size of large wood. The definition using English units (4 in wide and 6 ft long) results in a piece of smaller volume than the definition using metric units (10 cm wide and 2 m long).
[2] Small wood is also known as small woody debris or fine woody debris

The influences of instream large wood on aquatic ecosystems are a function of wood size relative to channel size. For instance, as much as 80% of pools in small streams can be associated with wood (Montgomery et al. 1995); however, the frequency of wood-associated pools decreases with increasing stream size (Bilby and Ward 1989, 1991; Montgomery et al. 1995). The latter relationship is due to the increased capacity of larger streams to transport large wood downstream.

In low order streams, "key pieces" of large wood affect channel morphology. Key pieces are defined as large wood that is independently stable within the bankfull channel (i.e., not held or trapped by other material) and have the potential to retain other pieces of large wood (WFPB 2011). Key piece size increases as channel width increases (Table 3.1). In large rivers, wood influences channel morphology through tangled accumulations of wood known as woody debris jams.

Stable structural features can promote channel stability (Sullivan et al. 1987). In large rivers, for instance, woody debris jams contribute to floodplain stabilization by initiating the formation of mid-channel bars that eventually become forested islands (Fetherston et al. 1995; Abbe and Montgomery 1996). In small streams, persistent large wood structures trap sizable amounts of sediment thereby increasing channel stability (Figure 3.3). Of all structures capable of storing sediment (i.e., wood, boulders) in small non-fish-bearing streams of northwest Washington, 93% were composed of large wood (Grizzel and Wolff 1998). Thirty to 80% of a stream's drop in elevation can be influenced by large wood (Keller and Swanson 1979), and log steps can reduce average channel gradients by 8 to 22% (Heede 1972). Reducing channel gradient dissipates stream power which mobilizes less sediment and increases sediment storage which can subsequently increase channel stability.

Table 3.1. Minimum volume of large wood key pieces for different channel widths. Example dimensions for key piece length and diameter yield minimum volume. Diameter is measured at piece midpoint. One meter is approximately 3.3 ft.

		Example dimensions (m)	
Bankfull width (m)	Minimum volume (m^3)	Length	Diameter
0-5[a]	1	2.5	0.71
5-10[a]	2.5	7.5	0.65
10-15[a]	6	12.5	0.78
15-20[a]	9	17.5	0.81
20-30[b]	9.75	17.5	0.84
30-50[bc]	10.5	17.5	0.87
50-100[bc]	10.75	17.5	0.88

[a] WFPB (2011), [b] Fox and Bolton (2007), [c] Must have an attached root wad.

Studies where wood has been experimentally removed from streams further reveal the significant role of large wood for storing sediment. For instance, Bilby (1981) measured a 72% reduction in sediment storage following removal of large wood from 575 ft (175 m) of streambed. Beschta (1979) observed a similar effect after woody debris dams were removed from a moderate gradient headwater stream in western Oregon where 6,500 yd^3 (5,000 m^3) of sediment was lost from 820 ft (250 m) of streambed over a period of about 10 months.

Large wood can also cause transient channel instability. Keller and Swanson (1979) and Nakamura and Swanson (1993) describe stream reaches where large wood caused local erosion that increased channel width by more than 50%. In one case a woody debris jam increased channel width by 230%. These two studies also describe reaches where large wood caused lateral migration of the main channel and formation of side

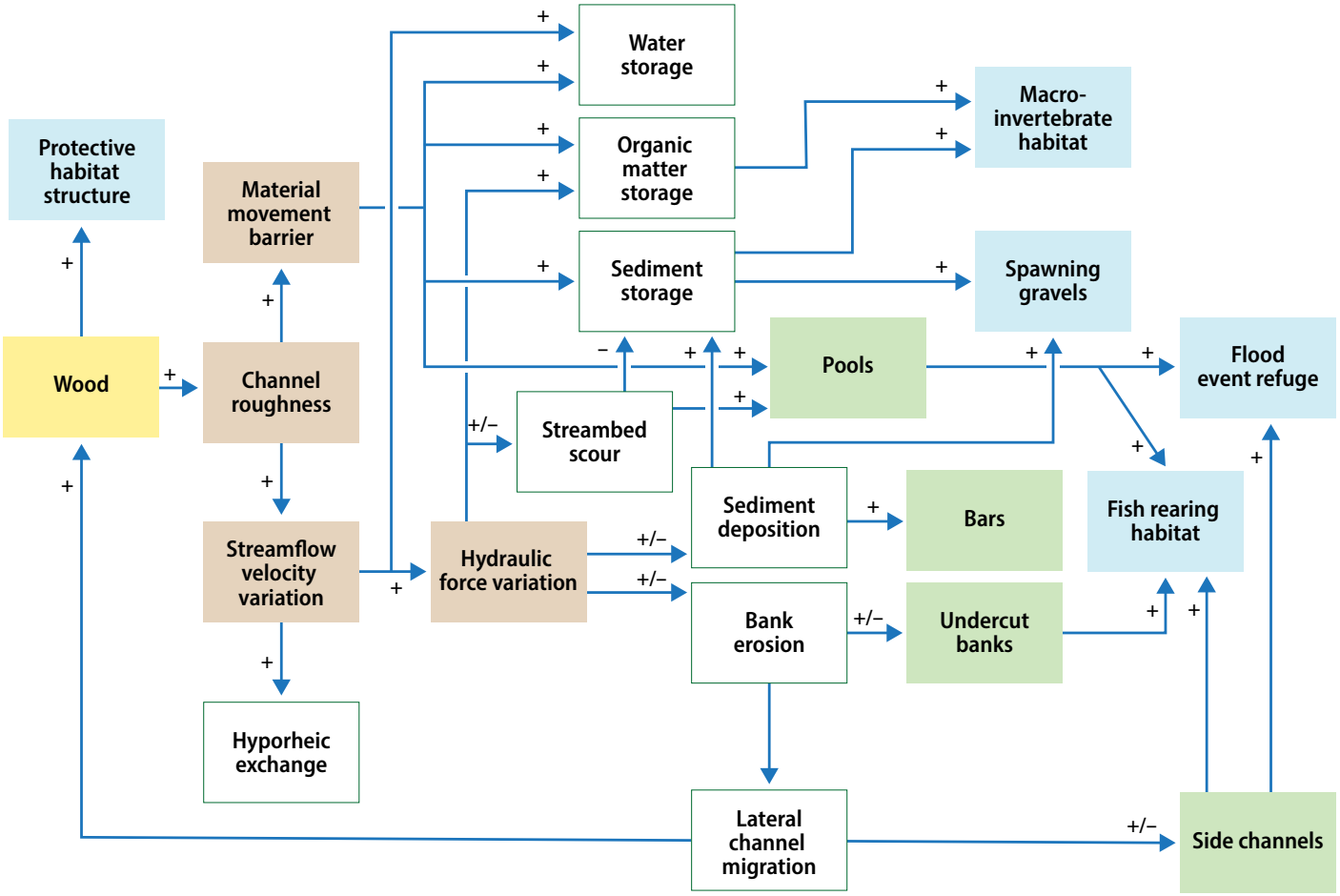


Figure 3.1. Conceptual model depicting the effects of wood on fluvial systems and fish habitats. Arrows indicate the hypothesized directions of causal relationships; pluses and minuses indicate the hypothesized slope of each relationship. Brown boxes represent direct effects of wood on fluvial processes. White boxes are secondary processes. Green boxes depict channel structures. Blue boxes are habitat features. Diagram does not include most feedback loops.

channels. Over time, these types of disturbances create a shifting mosaic of aquatic and riparian habitats.

Wood influences nutrient dynamics in two major ways: wood contains nutrients that are released through decomposition, and large wood influences the rate and timing of organic materials transport (Bilby 2003). The latter is the more important effect. Instream large wood traps and retains organic matter, such as leaves and other plant detritus, which are essential to the aquatic food web. Trapped organic materials are food sources for aquatic microorganisms, such as bacteria and certain fungi, and invertebrates, such as insects, crustaceans, and mollusks.



Figure 3.2. Sediment and nutrient storage and gravel bar formation behind large wood/Jane Atha, WDFW



Figure 3.3. Large wood altering channel morphology by creating dam pool, step drop, and plunge pool/Jane Atha, WDFW

The relationship between instream large wood and nutrient storage is well established. Larger quantities of wood per unit area in small streams lead to higher rates of storage of fine organic matter (Bilby and Likens 1980; Bilby and Bisson 1998; Brookshire and Dwire 2003). The mass of coarse particulate organic matter in streams in the McKenzie River watershed of Oregon was positively related to amounts of instream wood (Naiman and Sedell 1979). Bilby (1981) reported dramatic increases in downstream export of fine particulates during periods of high discharge following woody debris removal.

Carcasses of adult anadromous salmon provide nutrients to aquatic ecosystems (Cederholm et al. 1989; Reimchen et al. 2003). On the Olympic Peninsula, a positive correlation was observed between the number of Coho Salmon *Oncorhynchus kisutch* carcasses retained in streams and the amount of large wood in the stream (Cederholm and Peterson 1985).

By creating dams, instream large wood regulates water flow and storage. For example, surface water volume increased by 168%, five years after restoration of instream large wood in a coastal Oregon stream (Crispin et al. 1993), and third-order streams in Indiana with woody debris dams held surface water 1.5 to 1.7 times longer than those with minimal large wood (Ehrman and Lamberti 1992, cited by Gurnell et al. 1995). Hydrological effects such as these may alter high flow events by reducing peak discharge and increasing the event's duration (Gurnell et al. 1995). Pools created by woody debris dams raise the water table in adjacent streambanks (Gurnell et al. 1995), and that affects riparian vegetation composition. For instance, at some sites, wet riparian soils may be maintained through seepage from pools, and wet soils are more suitable for Red Alder *Alnus rubra,* Red Ceder *Thuja plicata,* and Alaska Yellow Ceder *Chamaecyparis nootkatensis* than other tree species. Red Alder is known to contribute enormous amounts of beneficial nitrogen to soils and streams (Naiman et al. 2002b).

The hyporheic zone is the saturated sediment beneath stream channels and riparian areas where groundwater and instream water mix. Large wood diverts surface water flow into the hyporheic zone, and by trapping and storing sediments, large wood increases the volume of the hyporheic zone (Naiman et al. 2000). Greater hyporheic exchange can also reduce a streams thermal sensitivity (Chapter 4).

3.3. Recruitment of Instream Large Wood

The quantity of instream large wood is determined by the processes of wood recruitment, decomposition, and transport (Figure 3.4). "Recruitment" refers to the process of wood moving from the terrestrial environment to the stream channel. "Transport" refers to wood import to, movement within, and export from stream reaches. For comprehensive reviews of the dynamics of instream large wood, including decomposition and transport, see Benda et al. (2003), Bilby (2003), Gurnell (2003), and Piegay (2003).

3.3.1. Wood Recruitment Mechanisms

Large wood recruitment is often caused by bank erosion, windthrow, landslides, debris flows, snow avalanches, and tree mortality due to fire, ice storms, insects, and disease (Swanson et al. 1976; Maser et al. 1988). At any given site, more than one mechanism may contribute to recruitment. However, the dominant mechanism is determined by channel morphology, slope steepness, slope stability, forest composition and structure, and local wind patterns (Murphy and Koski 1989; McDade et al. 1990; May and Gresswell 2003; Johnston et al. 2011; Benda and Bigelow 2014). In large low-gradient rivers, for instance, wood is commonly recruited via bank erosion. Steep-sloped riparian forests along confined streams can recruit instream large wood via several mechanisms; however, landslides and windthrow are the dominant recruitment mechanisms in such settings (Nakamura and Swanson 1993; May and Gresswell 2003). Fox (2001) reported that smaller channels are likely to obtain a significant proportion of instream large wood by stem breakage and individual tree mortality due to insects or disease because smaller streams recruit less wood through lateral bank avulsion. Beaver recruit small wood to small, low-gradient streams (Pollock et al. 2003).

Instream wood originating from bank erosion increases as channel confinement decreases (Murphy and Koski 1989; Nakamura and Swanson 1993; Martin and Benda 2001; Johnston et al. 2011). In relatively unconfined third-order channels surrounded by mature and old-growth forests in British Columbia, bank erosion was the dominant route of large wood delivery, especially in wider channels (Johnston et al. 2011). Along Alaska's southeastern coast, bank erosion dominated large wood recruitment in alluvial channels, while windthrow was dominant in bedrock channels (Murphy and Koski 1989). Over a 63 year period, the Queets River (bankfull width = 420 ft [128 m]) recruited 95% of wood pieces ≥ 3 ft (1 m) in diameter through bank erosion that occurred as its channel meandered across its wide floodplain (Latterell and Naiman 2007).

The relative importance of each instream wood recruitment mechanism is highly variable (Table 3.2). Johnston et al. (2011) found tree mortality was the most common recruitment mechanism followed by (in descending order) bank erosion, windthrow, and landslides. In contrast, Murphy and Koski (1989) found that tree mortality was the third most common mechanism, and their rank ordering was bank erosion, windthrow, tree mortality, and landslides. Johnston et al. (2011) found that windthrow contributed 4% of instream large wood, but May and Gresswell (2003) found windthrow contributed 59%, on average. Benda et al. (2003) found that landslides contributed, on average, 17% of instream wood volume, but at the site-level, the contribution from landslides ranged from 0 to 66%. In the Oregon Coast Range, 65% of instream pieces of large wood and 46% of wood volume in a fourth order stream were delivered by landslide or debris flow (Reeves et al. 2003).



Large wood suspended over water creates a refuge for fish from avian predators/Jane Atha, WDFW

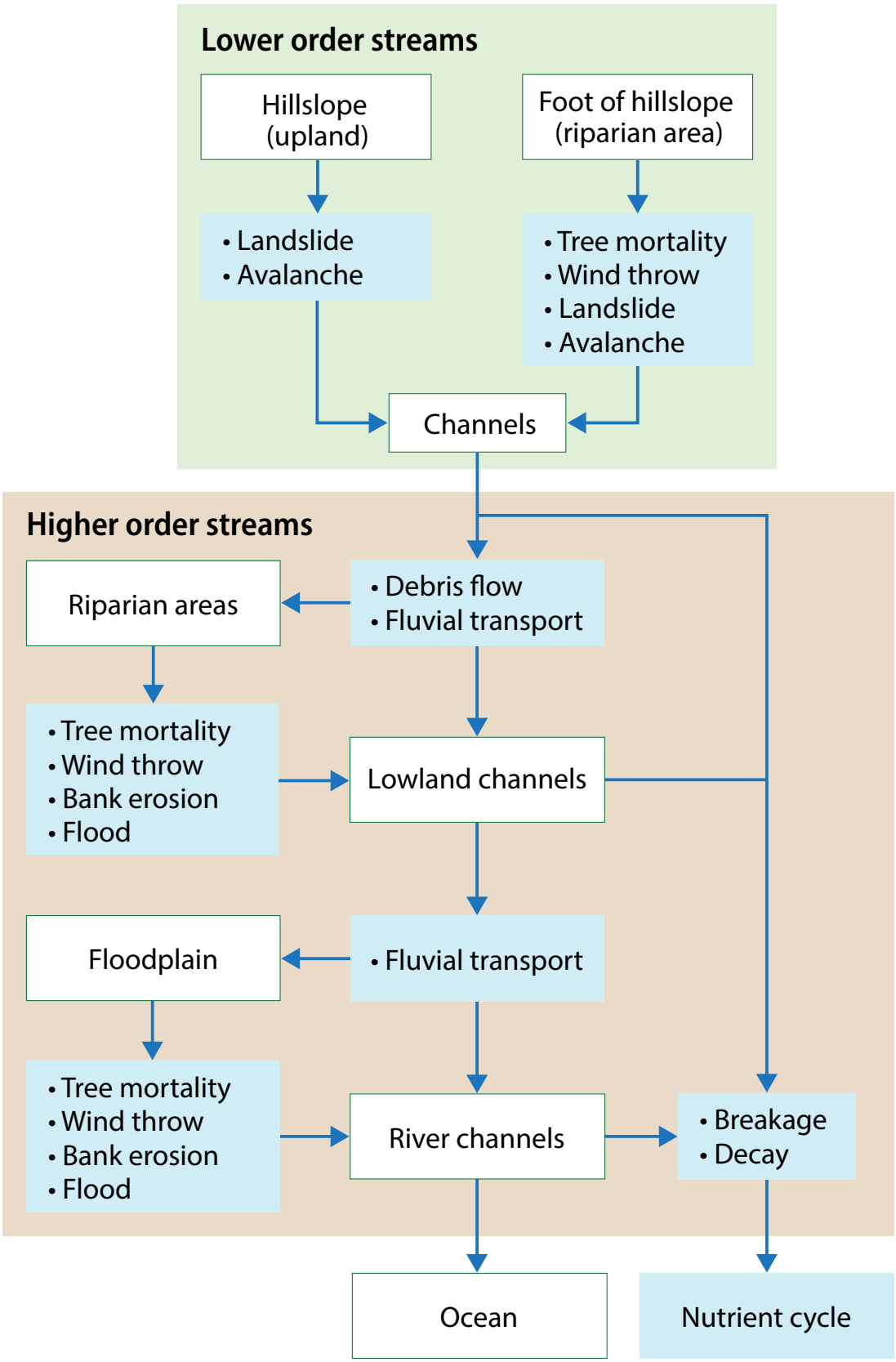


Figure 3.4. Wood recruitment mechanisms and wood transport pathways (adapted from Hassan et al. 2005). Lower order streams are first and second order headwaters. White and blue boxes are ecosystem structures and processes, respectively.

Table 3.2. Mean percentage of instream large wood contributed by various recruitment mechanisms in unmanaged old-growth conifer forests. For Johnston et al. (2011), stem breakage could be lumped with the windthrow or tree mortality categories. One meter is approximately 3.3 feet.

		Southeast Alaska[1]	South & Central British Columbia[2]	Coast Range Oregon[3]	Northern California[4]
	Stream length (m)	10,280	8,129	3,220	4,470
	Wood units	% of wood pieces	% of wood pieces	% of wood pieces	% of wood volume
Recruitment mechanism	bank erosion	42	18	6	29
	windthrow	33	4	59	--
	tree mortality	22	65	6	53
	stem break	--	12	--	--
	landslide	3	1	29	17

1 = Murphy and Koski 1989, 2 = Johnston et al. 2011, 3 = May and Gresswell 2003, 4 = Benda et al. 2003

A site's recruitment mechanisms determine the magnitude and timing of wood recruitment events. Recruitment can be continual or episodic. In large, meandering rivers wood may be recruited through continual bank erosion. Soil creep along the eroding base of a hillslope may also contribute to continual wood recruitment. However, most wood recruitment occurs through episodic events such as floods, landslides, debris flow, or windstorms. For example, if a 100-year flood causes a river to migrate across its floodplain, then a huge volume of wood that would have taken decades to be recruited under smaller flows could be recruited overnight. In smaller confined streams, the main recruitment mechanism may be windthrow, which can recruit wood incrementally (single tree per event) or catastrophically (100s of trees per event).

3.3.2. Recruitment Distances

Forests adjacent to streams provide the majority of large wood delivered to stream channels (Murphy and Koski 1989; McDade et al. 1990), however, trees far removed from riparian areas may also be delivered via landslides (Reeves et al. 2003) or channel migration (Latterell and Naiman 2007). Johnston et al. (2011) found that mean recruitment distances were greatest for wood entering by way of landslides, followed by (in descending order by distance) windthrow, stem breakage, falling of dead trees, and bank erosion.

Source distances are affected by channel geomorphology. The source distance of instream large wood differed significantly ($P < 0.05$) when comparing alluvial streams to colluvial channels draining steep hillslopes in Oregon's Coast Range (May and Gresswell 2003). In this study, 80% of wood pieces and total wood volume originated from forests within 160 ft (50 m) of colluvial channels confined by steep hillslopes, whereas in unconfined alluvial channels, 80% of instream large wood originated from within 98 ft (30 m) of the channel (May and Gresswell 2003). Along steep second growth redwood forests in northern California, landslides resulted in recruitment distances extending over 197 ft (60 m) (Benda et al. 2002). In the Oregon Coast Range, large wood from pristine steeply sloped conifer-deciduous forest was delivered to a fourth order stream by landslide or debris flow from distances of more than 295 ft (90 m) upslope of the channel (Reeves et al. 2003).

Table 3.3. Recruitment distances of instream large wood from unmanaged old-growth conifer riparian forests.

Location	Stream order or width	Maximum recruitment distance	Dominant recruitment process	Recruitment from intermediate distances	Source*
Southeast Alaska	second- to fifth-order	> 100 ft > 30 m	bank erosion	99% of pieces from < 100 ft (30 m). 45% of pieces from within 3 ft (1 m) of streambank. Average tree height = 130 ft (40 m)‡.	1
Western Oregon & Washington	first- to third-order	180 ft 55 m	not reported	50% of pieces from within 33 ft (10 m) of streambank; 85% from within 100 ft (30 m); 90% from within 128 ft (39 m), horizontal distance. Average tree height = 189 ft (57.6 m).	2
Northern California	45-55 ft 14-17 m	180 ft 55 m	variable	90% of wood from < 100 ft (30 m), slope distance. Longer recruitment distances due to landsliding.	3
Coast Range Oregon	second- and third-order	230 < d < 262 ft 70 < d < 80 m	windthrow	In alluvial stream 80% of pieces from ≤ 100 ft (30 m). In colluvial streams ≈50% of pieces from ≤ 100 ft (30 m). For both types ≈75% of volume from ≤ 165 ft (50 m).	4
Coast Range Oregon	fourth-order	> 300 ft > 90 m	landslide & debris flow	About 65% of pieces and 46% of wood volume were from upslope sources by landslides or debris flows.	5
Olympic Peninsula	sixth-order	> 1,475 ft > 450 m	channel migration	95% of wood from < 870 ft (265 m). 50% of pieces from within 300 ft (92 m).	6
Southeast Alaska	16-94 ft 5-30 m	115 < d < 130 ft 35 < d < 40 m	variable	96% of all large wood from within 65 ft (20 m) and 89% of from within 33 ft (10 m). Average tree height = 74 ft (22.6 m).	7
South & Central British Columbia	3-55 ft 1-17 m	425 ft 65 m	tree mortality	90% of large wood pieces and volume delivered to stream channels from within 33 and 30 ft (10 and 9 m), respectively. Average tree height = 120 ft (37 m).	8

* 1 = Murphy and Koski 1989, 2 = McDade et al. 1990, 3 = Benda et al. 2002; 4 = May and Gresswell 2003; 5 = Reeves et al. 2003, 6 - Latterell and Naiman 2007, 7 - Martin and Grotefendt 2007, 8 - Johnston et al. 2011.

‡ Tree height from Spence et al. (1996).

Source distances are affected by tree size. In one study, source distances for approximately 90% of instream large wood from mature and old-growth conifer riparian forest in western Washington and Oregon were within 85 and 130 ft (26 m and 40 m) of the streambank, respectively (McDade et al. 1990). The difference in source distances was largely attributed to taller trees in old-growth riparian forest (mean height = 189 ft [58 m]) compared to trees in mature riparian forest (mean height = 157 ft [48 m]). Likewise, recruitment distances measured in Alaska (e.g., Murphy and Koski 1989; Martin and Grotefendt 2007) are generally shorter than those measured in Oregon (e.g., McDade et al. 1990; May and Gresswell 2003) because trees of the same species are generally shorter in Alaska than in Oregon (Table 3.3). Johnston et al. (2011) also found that large wood source distances increased with increasing tree height. For a more thorough discussion of factors affecting source distances see Benda and Bigelow (2014).

The stereotypic recruitment function describing the amount of instream wood versus recruitment distance is nonlinear (Figure 3.5). That is, areas closer to the

stream channel provide relatively more wood than areas farther from the stream channel. In southeast Alaska, for instance, 100% of large wood was recruited from within 98 ft (30 m) of the streambank, but 45% of large wood originated from within 3.3 ft (1 m) (Murphy and Koski 1989). Likewise, in a study from Oregon and Washington, 100% of large wood with an identified source was recruited from within 180 ft (55 m), but 50% of large wood with an identified source originated from 33 ft (10 m; McDade et al. 1990) (Table 3.3). The shape of the wood recruitment function, and in particular, the shape under different watershed and site-level conditions, is an important question for riparian forest management.

Although most wood is recruited from areas close to a stream (Table 3.2), areas farther from a stream cannot be discounted, especially along larger alluvial streams. Along a fourth order stream in Oregon, the sources for 65% of large wood originated on hillslopes prone to landslides and lay beyond 295 ft (90 m) from the stream channel (Reeves et al. 2003). In Washington, 50% of large wood in a fifth-order river was recruited by lateral channel migration from forests on floodplains and fluvial terraces that lay beyond 300 ft (92 m) from the riverbank (Latterell and Naiman 2007).

3.3.3. Wood Recruitment in Intensively Managed Forests

An important question for riparian area management is how does wood recruitment in second-growth or intensively managed forests differ from recruitment in unmanaged, "natural" riparian forests? The answer to this question is essential for understanding the effects of contemporary forest management on fish habitats, however, useful answers are difficult to obtain because forest practices today are much different from those of the past.

The current conditions of instream wood and riparian areas in second-growth forests are the result of past management, and over the past 100 years management practices have changed dramatically. In the early 20th century splash dams were built on small streams to sluice logs downstream (Bisson et al. 1987), a practice that flushed naturally occurring large wood from the channel. During the 1950s and 1960s wood was routinely removed from streams to "improve" fish passage (Sedell et al. 1988), and this practice continued until the 1980s (Bilby 1984). Until the 1970s, logging to the streambank was common in Oregon

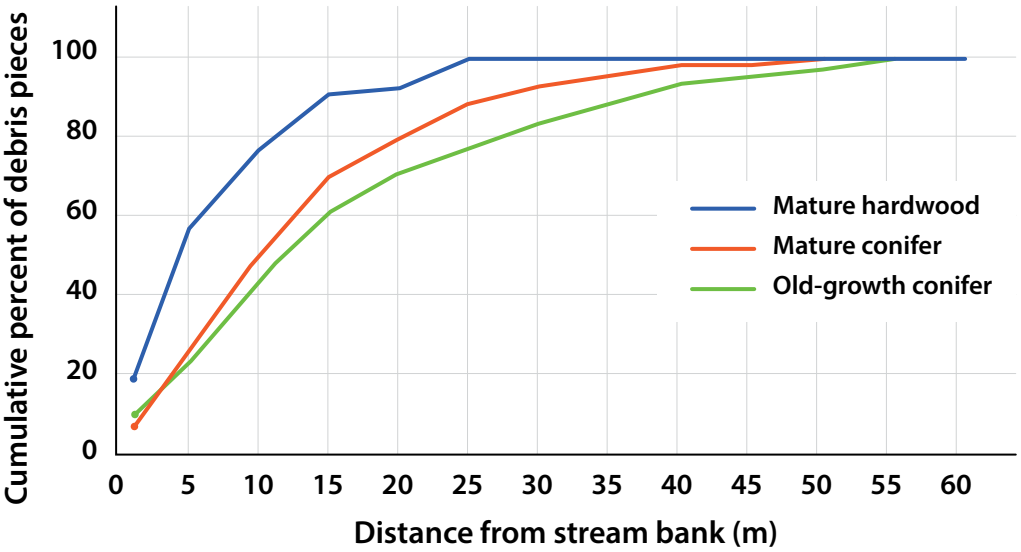


Figure 3.5. Distribution of source distances from tree origin to streambank. Empirically derived curves for old-growth conifer, mature conifer, and mature hardwood stands in western Oregon and Washington (from McDade et al. 1990). Empirically derived curves based on large wood with an identified source. One meter is equivalent to 3.3 feet.

and Washington; a practice that changed shortly after passage of the Clean Water Act of 1972. From 1987 to 2000, the Washington Forest Practices Rules required 23 to 65 trees per acre in riparian areas (WFPB 1987). In contrast, old-growth riparian areas may have 160 or more trees per acre (Acker et al. 2003). The current forest practices rule (WDNR 2005) require much wider stream-side buffers with much higher tree densities in riparian areas than pervious rules. The current regulations should result in a stand basal area equal to that of a mature conifer forest when the riparian stand is 140 years old. In short, over the past 100 years, riparian areas in intensively managed forests of Washington have been subjected to many different types of management, and over the next 100 years these same riparian areas will change dramatically.

Past forest practices are known to have severely degraded instream wood (Bilby and Ward 1991; Ralph et al. 1994), but current forest practice regulations are expected to improve instream wood (WDNR 2005). Whether current regulations will result in enough instream wood to create fish habitats that meet policy goals is unknown, and resolving that issue will be difficult until riparian areas attain their desired future conditions a century or more from now. Nevertheless, theoretical and empirical evidence suggest two main differences in large wood recruitment between second-growth, intensively managed forests and unmanaged mature and old-growth riparian forests.

Past forest practices are known to have severely degraded instream wood, but current forest practice regulations are expected to improve instream wood. Whether current regulations will result in enough instream wood to create fish habitats that meet policy goals is unknown.

First, the size of wood recruited from intensively managed forests is smaller than wood recruited from old-growth forests. Benda et al. (2002) found that the diameter of wood recruited from old-growth sites was, on average, up to twice the diameter of wood found in 50-year-old second-growth sites. Czarnomski et al. (2008) found significantly higher numbers of large wood pieces in stream segments adjacent to unmanaged mature and old-growth sites than in segments adjacent to 30- to 50-year-old intensively managed sites. From a theoretical perspective, these results are unsurprising—the dominant trees in a 200-year-old stand are much larger than the dominant trees in a 50-year-old stand. A similar relationship was also reported by McDade at al. (1990) who found that the size, both length and diameter, of instream large wood was related to forest age—wood was significantly smaller in younger forests (i.e., unmanaged mature forest versus old-growth forest).

Second, both theoretical models and empirical evidence show that maximum wood recruitment distances for intensively managed forest are less than the maximum recruitment distance for old-growth forests (McDade at al. 1990; Robison and Beschta 1990; Benda and Bigelow 2014). Again, these results are due to relative tree sizes—taller trees can contribute large wood from longer distances. The models show that the maximum recruitment distance for large wood is slightly less than the height of dominant trees; however, these models do not incorporate the recruitment processes of landslides and lateral channel migration which could substantially lengthen the maximum recruitment distance. For instance, in Benda et al. (2002) the theoretical maximum recruitment distance for their sixteen 50-year-old second-growth sites was about 98 ft (30 m), but due to landslides two sites had large wood recruited from beyond that distance—105 ft (32 m) and 210 ft (65 m). The results of Benda et al. (2002) and Benda and



Bank erosion recruits large wood into stream/Ned Pittman, WDFW

Bigelow (2014) also show that regardless of stand age or management, recruitment distances are primarily determined by recruitment processes. Riparian areas where bank erosion is the dominant process will, on average, have shorter recruitment distances, riparian areas where landslides dominate will have longer recruitment distances, and areas where other forms of tree mortality (e.g., windthrow, suppression, disease) dominate will have intermediate recruitment distances. In short, spatial variability in large wood recruitment is a function of many factors, including stream size and channel morphology, forest management, and natural disturbances such as landslides, floods, and windthrow.

3.4. Abundance of Instream Wood

3.4.1. Forested Regions of Washington

The abundance of instream large wood was much greater historically than it is today, especially in large rivers. One hundred fifty years ago, some woody debris jams on large rivers were nearly 1-mile-long (Sedell and Luchessa 1981), but

these impressive natural structures were cleared for purposes of river navigation. For instance, during the latter part of the 19th century, over 5,500 pieces of wood between 5 and 9 ft (1.5 and 2.7 m) in diameter were pulled from a 50-mile (80-km) section of the Willamette River (Sedell and Luchessa 1981). Collins et al. (2002) estimated that wood in some lowland Puget Sound rivers was 10 to 100 times greater prior to European settlement.

In contrast to large rivers, the abundance of large wood in small streams of unmanaged watersheds may still be representative of historical conditions. Fox and Bolton (2007) studied the quantities of instream large wood in natural, unmanaged forested watersheds in Washington. Ninety-six percent of their 150 sites had a stand age between 200 and 800 years (Fox 2001). In these watersheds, the processes of recruitment, decomposition, and transport were presumably undisturbed by human activities. Their findings, which are presented for forest zones and channel widths, could serve as reference or target conditions for instream large wood (Table 3.4).

3.4.2. Non-forested Regions of Washington

Fox and Bolton (2007) studied forested watersheds in forested regions (sensu Franklin and Dryness 1988), and, in fact, nearly all we know about instream wood is based on studies conducted in forested watersheds. This is unfortunate because our knowledge of instream wood for non-forested regions of Washington, such as semi-arid grasslands (i.e., steppe or Palouse) and shrub-steppe, is limited. Nevertheless, instream wood was likely to have been more abundant than it is today for two reasons.

First, in basins with headwaters in forested regions, such as the Yakima, Wenatchee, and Walla Walla basins, wood was transported downstream to shrub-steppe and grassland streams. This process is known to have occurred in other semi-arid and arid regions of the United States. Minckley and Rinne (1985) present historical evidence for the movement of large wood in rivers of the desert southwest: wood originated in forested headwaters, moved sporadically through desert riparian areas during flood events, and was ultimately deposited at the mouth of the Colorado River in Mexico. Minckley and Rinne (1985) identify interception of large wood by dams as a major cause of large wood reduction in semi-arid and arid river basins. At artificial reservoirs in eastern Washington, such as Keechelus, Kachess, Cle Elum, Bumping, Clear, and Rimrock lakes, large wood that could potentially interfere with dam operations is removed and burned (W. Meyer and B. Renfrow, Washington Department of Fish and Wildlife, personal communications). Some small water diversion dams do the same with large wood. This practice diminishes the quantity and quality of fish habitat in the Yakima and Tieton rivers, especially in their semi-arid shrub-steppe sections.

Second, riparian areas in grassland and shrub-steppe regions are inhabited by a wide variety of woody plants—Black Cottonwood *Populus balsamorhiza*, Quaking Aspen *Populus tremuloides*, White Alder *Alnus rhombifolia*, Thinleaf Alder *Alnus incana*, Water Birch *Betula occidentalis*, Black Hawthorne *Crataegus douglasii*, and Yellow Willow *Salix lutea* (Crawford 2003), and the historical abundance of woody plants in riparian areas is thought to have been much greater than it is today (Wissmar et al. 1994; Kauffman et al. 1997; Wissmar 2004). Reductions in woody plant abundance are mainly due to hydrological changes caused by water diversions for irrigation (Jamieson and Braatne 2001) and livestock grazing. Restoration projects can indicate the density of woody plants that historically existed in riparian areas prior to intensive livestock grazing. Only two years after the cessation of grazing within riparian areas in northeastern Oregon, the mean crown volume of willows and Thinleaf Alder tripled in size and that of Black Cottonwood increased 9-fold (Case and Kauffman

1997). Furthermore, shrub density increased by 50%. One possible reason for the severe impacts of grazing is that riparian vegetation in the semi-arid grassland and shrub-steppe regions of Washington evolved with little grazing by large herbivores (Mack and Thompson 1982).

With the exception of Black Cottonwood, woody plants in grassland and shrub-steppe regions do not contribute key pieces of large wood to stream channels (Table 3.1).

Historically, much wood in stream channels of semi-arid regions was likely to have been small wood, and much of that small wood may have been recruited to and stored in the channel through Beaver activity. Prior to 1864, Beaver are known to have been abundant in the shrub-steppe region of central Oregon, and the eradication of Beaver from central Oregon is thought to have caused a cascade of effects: gradual disintegration of Beaver dams led to incision of streambeds, lowering of water

Table 3.4. Distributions of large wood per 100 m of stream channel by forest regions in Washington State and by bankfull width (BFW) class (Fox and Bolton 2007). Large wood was defined as pieces exceeding 10 cm (4 in) in diameter and 2 m (≈6 ft) in length. Key piece sizes are defined in Table 3.1. One meter is approximately 3.3 feet.

Forest zones	BFW Class (m)	75th Percentile	Median	25th Percentile
		Number of pieces per 100 m		
Sitka Spruce *Picea sitchensis*, Western Hemlock *Tsuga heterophylla*, Silver Fir *Abies alba*, and Mountain Hemlock *T. mertensiana*	0-6	> 38	29	< 26
	> 6-30	> 63	52	< 29
	> 30-100	> 208	106	< 57
Subalpine Fir *Abies lasiocarpa* and Grand Fir *A. grandis*	0-3	> 28	22	< 15
	> 3-30	> 56	35	< 25
	> 30-50	> 63	34	< 22
Douglas-fir *Pseudotsuga menziesii* and Ponderosa Pine *Pinus ponderosa*	0-6	> 29	15	< 5
	> 6-30	> 35	17	< 5
		Number of key pieces per 100 m		
Sitka Spruce, Western Hemlock, Silver Fir, and Mountain Hemlock	0-30	> 11	6	< 4
	> 30-100	> 4	1.3	< 1
Subalpine Fir and Grand Fir	0-15	> 4	2	< 0.5
	>15-50	> 1	0.3	< 0.5
Douglas-fir and Ponderosa Pine	0-30	> 2	0.4	< 0.5
		Volume (m^3) per 100 m		
Sitka Spruce, Western Hemlock, Silver Fir, and Mountain Hemlock	0-30	> 99	51	< 28
	> 30-100	> 317	93	< 44
Subalpine Fir and Grand Fir	0-3	> 10	8	< 3
	> 3-50	> 30	18	< 11
Douglas-fir and Ponderosa Pine	0-30	> 15	7	< 2



Wood jams are habitat features and are less common now than they were historically/Ned Pittman, WDFW

tables, loss of riparian vegetation, and subsequently deeper incision of channels (Buckley 1993). According to Pollock et al. (2007), the exact mechanism that caused widespread incision of streambeds remains uncertain, however, incision almost invariably coincided with widespread trapping of Beaver and the onset of intensive livestock grazing.

For the semi-arid grassland and shrub-steppe regions of Washington, we currently lack data with which to describe reference conditions for instream wood and for riparian plant communities. Historical reconstruction using General Land Office survey notes and historical photos is one way to develop qualitative descriptions of riparian plant communities (McAllister 2008); however, more quantitative descriptions would benefit development of management objectives. Much remains unknown about historical conditions of riparian areas in non-forested regions.

3.5. Fish, Wildlife, and Instream Wood

Authoritative reviews of the scientific literature regarding relationships between instream wood and fish or wildlife species have been written by Bisson et al. (1987), Benke and Wallace (2003), Dolloff and Warren (2003), Zalewski et al. (2003), Steel et al. (2003), and Wondzell and Bisson (2003). Certain small mammal and bird species are known to be associated with wood in stream channels (Steel et al. 2003). However, we discuss only fish, amphibians, reptiles, and invertebrates; taxonomic groups known to have strong associations with instream wood.

3.5.1. Fish

For salmonids, especially juvenile Coho Salmon, there is no more important structural component than instream wood (Bisson et al. 1987). In Puget Sound lowland streams, measures of salmonid rearing habitat were strongly linked to instream large wood abundance (May et al. 1997). In headwater streams, step pools formed by large wood were important for Dolly Varden *Salvelinus malma,* juvenile Coho Salmon, steelhead, and Cutthroat Trout *Oncorhynchus clarkii* in reaches with gradients less than 4% to greater than 10% (Bryant et al. 2007). Adult spawning Sockeye Salmon *Oncorhynchus nerka* densities were positively correlated with cover provided by large wood and undercut banks, pool area, and large wood (Braun and Reynolds 2011). The instream abundance of juvenile salmonids often is directly related to the amount of large wood (Murphy et al. 1986; Bisson et al. 1987). Stream reaches where large wood was artificially added were used by higher densities of juvenile Coho Salmon in summer and winter, and Cutthroat Trout and steelhead in winter in 30 western Oregon and Washington streams when compared to reaches where large wood was not enhanced (Roni and Quinn 2001). Spawning Coho Salmon abundance increased after instream wood structures were restored (Crispin et al. 1993). A study in British Columbia found that the biomass of yearling and older salmonids was positively correlated with stream pool volume (R^2 = 0.92) and that over 70% of pool volume was formed by large wood (Fausch and Northcote 1992).

Large wood provides both direct and indirect benefits to fish (Bisson et al. 1987). Indirect benefits are related to wood's role as a roughness element, and this role is especially obvious in smaller streams where wood

can bridge much of a channel (Zalewski et al. 2003). Large wood within a small channel dissipates flow velocity, which reduces the energy fish expend as they move upstream (Zalewski et al. 2003). Bisson et al. (1987) state that sediment storage by large wood benefits fish primarily by buffering the stream network against rapid changes in sediment load that would degrade habitats, such as rapid sediment increases due to landslides. Wood also benefits fish by increasing habitat diversity. In seeking a path around large wood obstructions, water creates complex hydraulic patterns that carve pools and side channels, form falls, and enhance channel sinuosity, imposing numerous variations in a stream's hydrology and geomorphology. Another indirect benefit of instream large wood is its influences on the availability of prey for fish in the form of macroinvertebrates. Large wood provides habitat for invertebrates, which then supplies fish with a source of food (Bisson et al. 1987).

The direct benefits of instream large wood to fish are also important. Large pieces of instream wood provide fish with refuge from high velocity flows during floods and provide hiding cover from predators (Sedell et al. 1985; Bisson et al. 1987; Braun and Reynolds 2011). Upturned tree roots and logs were the most common type of cover used by juvenile Coho Salmon and steelhead in an unlogged, west coast Vancouver Island stream (Bustard and Narver 1975). The deep pools often formed around these features made for good cover, particularly for older juveniles (Bustard and Narver 1975). After logging, almost all Coho Salmon that remained in channels over the winter sheltered in stream segments jammed with logs, with undercut banks, and in pools filled with upturned tree roots and other forest debris (Tschaplinski and Harman 1983). Hartman (1965) also found overwintering Coho Salmon fry preferring cover near logs, roots, and banks in streams in coastal British Columbia. Large wood increases fish density by visually isolating individual fish, which reduces inter- and intra-species competition (Dolloff and Reeves 1990; Crook and Robertson 1999).

3.5.2. Amphibians and Reptiles

Amphibians can be a dominant biotic component in Pacific Northwest streams (Olson et al. 2007), but in contrast to fishes and invertebrates, studies that characterize the importance of instream large wood for amphibians are sparse (Wondzell and Bisson 2003). However, diverse sources of data on stream-associated amphibian species life histories indicate that instream wood contributes to the creation and maintenance of breeding, rearing, and foraging habitats, and likely overwintering habitats as well. In particular, large wood can serve as the instream substrate for amphibian oviposition (Henry and Twitty 1940; Jones et al. 1990). Wood also forms steps in streams that promote sediment wedges (May and Gresswell 2003) that serve as variable but often extensive habitat matrices for oviposition and rearing (Nussbaum 1969; Wilkins and Peterson 2000). Moreover, wood-formed steps often create dam and plunge pools that are important for amphibian foraging or refuge (Wilkins and Peterson 2000; Welsh and Lind 2002). The basis of the former is that many aquatic invertebrates eaten by stream-associated amphibians occur in the habitat matrices created by wood-formed steps (Parker 1994; Steele and Brammer 2006; see next section). In coastal Washington headwater streams, the density of stream-associated amphibians



Van Dyke's Salamander Plethodon vandykei *use large wood for cover/ Eric Lund, WDFW*

was positively correlated with the amount of functional large wood (R^2 = 0.50), and torrent salamander (family Rhyacotritonidae) densities were positively correlated with the percentage of pools, indicating the importance of habitat complexity that large wood creates (Jackson et al. 2007). In Olympic National Park, large wood was a significant variable in explaining the densities of all three stream-associated amphibian species that were present, but its relative importance varied between species and was less important than one or more of aspect, gradient, and substrate in habitat use models for tailed frogs (family Ascaphidae) and torrent salamanders (Adams and Bury 2002).

Instream large wood is especially important for one Pacific Northwest reptile order: turtles. In the Northwest, water temperatures, even in the lowland stillwater habitats in which our two native turtle species occur, is often limiting (Holland 1994). Hence, the ability to bask securely (i.e., in a relatively predator-free environment) at temperatures that exceed those of water is critical to the normal processes of digestion and for female turtles, successfully yolking up eggs. Large floating or anchored-downed logs with enough area extending above the water surface are the key structures on which basking can occur (Holland 1994). Such structures are especially important in stillwater side- and off-channel habitats of large streams.

3.5.3. Aquatic Invertebrates

The distribution and abundance of aquatic invertebrates are influenced by instream wood and certain taxa are dependent on instream wood. In streams of all sizes, areas of wood accumulation are often also invertebrate biodiversity hot spots (Benke and Wallace 2003; Wondzell and Bisson 2003). Many aquatic invertebrates use the numerous grooves, splits, and fissures in large wood as refuges from predators and harsh environments. Other invertebrate uses of wood include



Large wood in Deschutes River/Noll Steinweg, WDFW

oviposition, case making, and emergence, especially when submerged pieces are decayed rather than firm (Harmon et al. 1986). Several families of caddisfly use wood for case construction. Of ninety-two case-making caddisfly genera reviewed by Wiggins (1977), roughly a quarter exploit bark or wood to varying degrees for case construction. Instream wood also is used as sites for oviposition above and below the water line. Many caddisflies in the family Limnephilidae deposit their egg masses on moist wood. In the Coast Range of Oregon, Wisseman and Anderson (1984) found oviposition by a number of caddisfly taxa on overhanging logs. The surfaces of instream wood also are used as nursery areas for early instars, and for resting, molting, and pupation (Anderson et al. 1978).

Large wood is especially important as substrate for invertebrates to attach to in rivers with limited sources of stable substrate (Benke and Wallace 2003). Trees that have fallen into the main channels of low-gradient rivers frequently are the only stable habitat (Benke and Wallace 2003). In these streams, wood can be especially important for periphyton and macroinvertebrate taxa to attach themselves (Benke and Wallace 2003). In contrast to smaller rivers, instream large wood shifts to channel margins and floodplains of larger rivers (Bisson et al. 1987), and hence, in these main-stem locations invertebrate densities peak (Ward et al. 1982). In headwater streams, large wood and gravel habitats supported higher densities and biomass of benthic invertebrates than cobble habitats (Hernandez et al. 2005). Coe et al. (2009) saw significantly higher densities of invertebrates in Pacific Northwest streams where engineered logjams were added. They attributed this to increased overall habitat surface area, and thereby the potential for increased productivity relative to reaches with low levels of wood. Instream large wood also supported a richer and more diverse invertebrate fauna than either cobble or gravel substrates.

Wood provides invertebrates with access to a wide variety of food sources. Large wood traps and stores



Large wood on Cedar River/Hal Beecher, WDFW

organic matter, and wood can be directly consumed by some invertebrates (Benke and Wallace 2003). Trapped organic materials are food sources for bacteria, fungi, mollusks, insects, and crustaceans. Although only a small fraction of aquatic insect taxa exploit woody debris as a source of food (Harmon et al. 1986), direct wood consumption by aquatic invertebrates in the Pacific Northwest has been observed in some species of caddisfly, mayfly, beetles, and snails (Anderson et al. 1978; Dudley and Anderson 1982; Pereira and Anderson 1982; Pereira et al. 1982). Submerged large wood may also support surface films of micro-organisms (e.g., diatoms, bacteria, fungi) that efficiently take up instream nitrogen and form a food web base for aquatic invertebrates (Dudley and Anderson 1982; Johnson et al. 2003), that in turn support vertebrate species (Ashkenas et al. 2004). By moderating pulses of fine sediment (Entrekin et al. 2009), instream large wood also acts to reduce the accumulation of sediment on algae (Richardson 2008), which is an important food to many macroinvertebrate taxa.

3.5.4. Fish and Wildlife Summary

The vital ecological role of instream wood has been known for at least 40 years (Swanson et al. 1976). Relationships between high quality salmonid habitats and instream large wood are well established (Bisson et al. 1987; Dollof and Warren 2003). Invertebrate taxa,

such as aquatic insects, are also known to rely on large wood as a habitat substrate and food source. Juvenile salmonids prey on aquatic insects. Amphibians and turtles also depend on the channel morphology and wood structure created by instream large wood.

3.6. Land Use Effects

The major human land uses in Washington–urban/suburban, agriculture, and forestry–have altered or removed extensive areas of riparian forest and have adversely impacted instream wood size, abundance, and distribution, and left many streams with a chronic deficiency of instream large wood compared to historical conditions (Maser et al. 1988; Bilby and Ward 1991; Stouder et al. 1997; May et al. 1997).

In general, the three major land uses impact instream large wood in similar ways–they diminish the amount of instream wood by reducing the number and size of trees in riparian areas. Furthermore, large wood is often purposefully removed from rivers and streams because it can block culverts or damage other human-made structures such as bridges, dams, or levees; cause streambank erosion that destroys private property; and present hazards to navigation or recreation. Culverts and dams also disrupt the transport of wood through a stream network and reduce the amount of wood in higher order streams and rivers.



Juvenile fish use large wood for shelter/WDFW

Most research on instream wood and riparian forests has occurred in unmanaged and managed forests, but much of the knowledge gained in forests–such as the functions of instream wood, natural amounts of instream wood, and recruitment mechanisms–is applicable to riparian areas in urban/suburban and agricultural settings as well, especially in forested ecoregions.

3.6.1. Forestry

Because mature conifer trees in the Pacific Northwest have large-diameter, decay-resistant boles, streams in this region have naturally high volumes of large wood compared to other parts of North America (Harmon et al. 1986). Nevertheless, harvest in and around riparian areas can result in immediate and long-term changes to the volume of instream wood. Czarnomski et al. (2008) found that instream wood volume and abundance varied significantly relative to timber harvest and adjacent tree stand age. They found instream wood volume and abundance were significantly higher in streams adjacent to unmanaged, mature and old-growth stands compared to streams along 30- to 50-year-old plantations, and significantly less in streams adjacent to 30- to 50-year-old plantations compared to those adjacent to 20- to 30-year-old plantations or mature and old-growth forest. Beechie et al. (2000) estimated that if a riparian buffer was established today in a 50-year-old stand of Douglas-fir, recovery of pool-forming large wood might take less than 100 years in small channels (e.g., ≤ 66 ft [20 m] wide), but could take as much as 200 years in larger channels.

The impacts of logging on instream large wood and aquatic habitats may not be realized for many decades after logging. In interior British Columbia, Chen et al. (2005) found that in the short term, instream large wood volume and biomass increased after logging. However, they concluded that in the long term, abundance of instream large wood may be greatly reduced as a

result of increased rates of decay, transport, and reduced recruitment from the adjacent riparian forest. With instream wood residence times averaging about 30 years, Hyatt and Naiman (2001) estimated that harvesting large riparian conifers would adversely impact aquatic habitats of large streams in about three to five decades. Murphy and Koski (1989) showed a 70% reduction of instream large wood 90 years after clearcutting without a riparian buffer. They also estimated a 250-year recovery time to pre-harvest levels.



Harvest near riparian areas can impact aquatic habitats/Marc Hayes, WDFW

The loss of riparian trees can come with long-term repercussions to functional aquatic habitat. Where riparian trees are absent, Beechie et al. (2000) predicted a lag of 7-49 and 15-91 years before pool-forming large wood could be recruited from Red Alder and Douglas-fir forests, respectively. The lag time for a given stream depends on multiple factors including channel width and the minimum size of pool-forming wood. In Alberta, instream large wood generated from stand-replacing fires was depleted within 100 years of the event but once the forests reestablished, new large wood recruitment was delayed by roughly 40 years (Powell et al. 2009).

A riparian management zone (RMZ) adjacent to logging differs in its ability to supply instream wood compared to riparian areas adjacent to unlogged uplands. On average, tree mortality was 50% greater in RMZs compared to riparian areas in unlogged landscapes, 3 to 15 years post-harvest (Martin and Grotefendt 2007). Differences in stand mortality between logged and unlogged tracts were primarily due to greater windthrow at a small proportion of RMZs in logged tracts. Additionally, downed tree recruitment from RMZ outer zones was more than double that of trees recruited in unlogged tracts. Consequently, wood recruitment increased by an average of 2 trees per 330 ft (100 m) in the buffered versus unlogged forested tracts (Martin and Grotefendt 2007).

Trees in RMZs with adjacent clear-cuts may be more susceptible to windthrow. Windthrow in RMZs (85 ft [26 m] wide on both side of streams) increased instream large wood by 34% within one to three years after logging in small streams (Grizzel and Wolff 1998). The authors of that study suggested that the RMZs adjacent to clearcuts served as a long-term source of large wood. They added that over a 10-year period, windthrow could add an average of 1.9 trees per 984 ft (300 m) of stream. Along second to fifth order streams, windthrow in RMZs was 26 times greater up to three years post-harvest compared to estimated mortality rates of trees in riparian stands in unlogged tracts (Liquori 2006). Post-harvest windthrow may reduce tree density in RMZs enough to significantly reduce competition-induced tree mortality, which in turn may lead to substantially different wood recruitment dynamics in buffers compared to unlogged forests (Liquori 2006).

3.6.2. Urban/Suburban

Very few studies have examined the impacts of development on instream large wood dynamics. In their analysis of the effects of urbanization, May et al. (1997) noted that as a basin's urbanization increased the quantity of large wood declined, as did related measures of habitat quality, namely loss of riparian forest area, reduced pool area, and decreased habitat complexity. Urban streams greater than 2% gradient and lacking large wood were found to be more susceptible to scour than less developed counterparts. Other than restoration sites where instream large wood had been replaced, high quantities of instream large wood were only found in undeveloped watersheds.

An analysis of relationships of channel characteristics, land ownership, land use, and land cover to instream large wood abundance in western Oregon showed that the most important predictor for large wood volume was land ownership, followed by stream gradient (Wing and Skaugset 2002). They also observed fewer large wood pieces in streams near rural residential areas compared to managed forests. In a study outside the Pacific Northwest, researchers in the Piedmont region of Georgia found that the absence of forest cover in catchments in suburban Atlanta corresponded to a decrease of instream large wood biomass (Roy et al. 2005).



Agricultural area in western Washington/Marlin Greene, One Earth Images

3.6.3. Agriculture

Many types of agriculture remove riparian forest, and consequently, reduce the recruitment of large wood to fish-bearing rivers and streams. Within the Nooksack River basin of northwest Washington, riparian forest along reaches accessible to anadromous fish were evaluated based on their ability to contribute instream wood large enough to form pools (Hyatt et al. 2004). Seventy-four percent of this basin's riparian forests that failed to meet this criterion were found in lowland rural-agricultural areas. In contrast, only 20% of the stands that failed to meet this threshold were in federal and commercial forestlands. This contrast is notable given that agricultural and rural areas comprised only about 22% of Nooksack basin (Hyatt et al. 2004). Similar results were observed in an analysis relating land use and land cover to instream wood abundance in western Oregon (Wing and Skaugset 2002). In this study, they found fewer pieces of large wood in streams near agricultural land uses compared to that of managed forestlands.

In shrub-steppe and grassland ecoregions of eastern Washington, livestock grazing in riparian areas significantly reduces the amount of woody vegetation. Significant reductions in woody vegetation lead to numerous adverse impacts to aquatic habitats: increased streambank erosion, increased overland flow and erosion within riparian areas, increased turbidity, reduced shade, higher water temperatures, loss of cover for fish due to reductions in overhanging vegetation and undercut banks, reduction in the amount of instream small wood, changes to channel morphology such as fewer pools, fewer meanders, and channel incision, lowering the water table, and reduction in essential nutrients derived from detritus (Belsky et al. 1999).

3.6.4. Land Use Effects Summary

Land uses that affect riparian forest also affect instream large wood. Of the three major land uses, contemporary forestry has the least effect on instream large wood. However, for all three land uses, the severity of effects depends largely on how riparian areas are managed.

3.7. Conclusions

Many effects of wood on aquatic ecosystems are well understood and not subtle, and therefore, ecologists are very confident about the critical role of wood in fish habitats. Ecologists are also confident about the role of riparian forests in supplying large wood to aquatic systems. Successful conservation of fish habitats and fish species in the forested regions of Washington depends on riparian forest management that delivers adequate wood to aquatic ecosystems. From a management perspective, the main scientific uncertainties are: 1) the shape of the wood recruitment function (e.g., Figure 3.5), especially the shape under different watershed and site-level conditions; and 2) the potential contributions from recruitment mechanisms outside the riparian forest, such as landslides, debris flows, or extreme channel migration. Addressing these uncertainties through research could lead to more ecologically effective and economically efficient management of riparian areas.

To maintain or restore 100% of a site's large wood recruitment potential, the site's composition and structure should be similar to that of an unmanaged riparian forest. Given current uncertainties, re-establishing riparian forest similar to unmanaged, mature or old-growth forests should be the most reliable way to provide instream large wood sizes and abundance that are similar to historical levels.

An important management question is: what are source distances for large wood recruitment from riparian areas to aquatic ecosystems? We know that source distances for wood in riparian areas are a function of tree height—source distances are longer for riparian forests with taller trees. We also know that tree heights for old-growth conifer forests can exceed 200 ft (60 m). In Washington State, Fox (2003) found that mean heights of canopy trees in old-growth riparian areas (i.e., stand age > 200 years old) ranged from 100 to 240 ft (30 to 73 m). Height variation among riparian areas was largely explained by forest zone and site productivity class. If large wood has a minimum diameter of 4 in (10 cm), then only that portion of a tree's stem greater than 4 in (10 cm) in diameter is large wood. From tree taper equations for Douglas-fir (Biging 1984), we know that for trees between 100 to 240 ft (30 and 73 m) tall about 15 to 3 percent of the stem is not large wood, respectively.[3] In other words, for the purpose of large wood recruitment, the "effective" tree height (*sensu* Robison and Beschta. 1990; Van Sickle and Gregory 1990) ranges from 85 to 230 ft (26 to 70 m), depending on site productivity class. Therefore, in forested ecoregions, 100% of a site's large wood recruitment potential, is located about 85 to 230 ft (26 to 70 m) from the stream channel, depending on site productivity class. These source distances only account for trees recruited via bank erosion, windthrow, or tree mortality. It does not account for large wood recruited to the stream channel through landslides or debris flows, nor does it account for recruitment through extreme channel migration in large river floodplains. In addition, this does not account for source distances of small wood. Source distances for small wood equal a full tree height from the stream channel.

Ecologists are confident about the critical role of wood in creating fish habitat and the role of riparian forests in supplying large wood to aquatic systems.

[3] Effective tree height calculations were done in Microsoft Excel with equations from Robison and Beschta (1990) and Biging (1984).

3.8. Literature Cited[4]

Abbe, T.B., and D.R. Montgomery. 1996. Large woody debris jams, channel hydraulics and habitat formation in large rivers. Regulated Rivers: Research & Management 12:201-221. (i)

Acker, S.A., S.V. Gregory, G. Lienkaemper, W.A. McKee, F.J. Swanson, and S.D. Miler. 2003. Composition, complexity, and tree mortality in riparian forests in the central western Cascades of Oregon. Forest Ecology and Management 173:293-308. (i)

Adams, M. J., and R. B. Bury. 2002. The endemic headwater stream amphibians of the American Northwest: associations with environmental gradients in a large forested preserve. Global Ecology & Biogeography 11:169-178. (i)

Anderson, N.H., J.R. Sedell, L.M. Roberts, and F.J. Triska. 1978. The role of aquatic invertebrates in processing of wood debris in coniferous forest streams. The American Midland Naturalist 100:64–82. (i)

Barnes, D.M., and A.U. Mallik. 1996. Use of woody plants in construction of Beaver dams in northern Ontario. Canadian Journal of Zoology 74:1781-1786. (i)

Beechie, T.J., G. Pess; P. Kennard, R.E. Bilby, and S. Bolton. 2000. Modeling recovery rates and pathways for woody debris recruitment in northwestern Washington streams. North American Journal of Fisheries Management 20:436-452. (i)

Belsky, A.J., A. Matzke, and S. Uselman. 1999. Survey of livestock influences on stream and riparian ecosystems in the western United States. Journal of Soil and Water Conservation 54:419-431. (i)

Benda, L., and P. Bigelow. 2014. On the patterns and processes of wood in northern California streams. Geomorphology 209:79-97. (i)

Benda, L.E., P. Bigelow, and T.M. Worsley. 2002. Recruitment of wood to streams in old-growth and second-growth redwood forests, northern California, U.S.A. Canadian Journal of Forest Research 32:1460-1477. (i)

Benda, L., D. Miller, J. Sias, D. Martin, R. Bilby, C. Veldhuisen, and T. Dunne. 2003. Wood recruitment processes and wood budgeting. Pages 49-74 *in* S.V. Gregory, K.L. Boyer, and A.M. Gurnell, editors. The ecology and management of wood in world rivers. American Fisheries Society, Symposium 37, Bethesda, Maryland. (i)

Benke, A.C., and J.B. Wallace. 2003. Influence of wood on invertebrate communities in streams and rivers. Pages 149-178 *in* S.V. Gregory, K.L. Boyer, and A.M. Gurnell, editors. The ecology and management of wood in world rivers. American Fisheries Society, Symposium 37, Bethesda, Maryland. (i)

Beschta, R.L. 1979. Debris removal and its effects on sedimentation in an Oregon Coast Range stream. Northwest Science 53:71-77. (i)

Biging, G.S. 1984. Taper equations for second-growth mixed conifers of northern California. Forest Science 30:1103-1117. (i)

Bilby, R.E. 1981. Role of organic debris dams in regulating the export of dissolved and particulate matter from a forested watershed. Ecology 62:1234-1243. (i)

Bilby, R.E. 1984. Removal of woody debris may affect stream channel stability. Journal of Forestry 82:609-613. (i)

Bilby, R.E. 2003. Decomposition and nutrient dynamics of wood in streams and rivers. Pages 135-148 *in* S.V. Gregory, K.L. Boyer, and A.M. Gurnell, editors. The ecology and management of wood in world rivers. American Fisheries Society, Symposium 37, Bethesda, Maryland. (i)

Bilby, R.E., and P.A. Bisson. 1998. Function and distribution of large woody debris. Pages 324-346 *in* R.J. Naiman and R.E. Bilby, editors. River ecology and management: lessons from the Pacific Coastal Ecoregion. Springer-Verlag, New York. (i)

Bilby, R.E., and G.E. Likens. 1980. Importance of organic debris dams in the structure and function of stream ecosystems. Ecology 61:1107-1113. (i)

4 References are classified according to RCW 34.05.271 (see Appendix 1) denoted by a lower case roman numeral (i – viii) in parentheses at the end of the citation.

Bilby, R.E., and J.W. Ward. 1989. Changes in characteristics and function of woody debris with increasing size of streams in western Washington. Transactions of the American Fisheries Society 118:368-378. (i)

Bilby, R.E., and J.W. Ward. 1991. Characteristics and function of large woody debris in streams draining old-growth, clear-cut, and second-growth forests in southwestern Washington. Canadian Journal of Fisheries and Aquatic Sciences 48:2499-2508. (i)

Bisson, P.A., R.E. Bilby, M.D. Bryant, C.A. Dollof, G.B. Grette, R.A. House, M.L. Murphy, K.V. Koski, and J.R. Sedell. 1987. Large woody debris in forested streams in the Pacific Northwest: past, present, and future. Pages 143-190 *in* E.O. Salo, and T.W. Cundy, editors. Streamside management: forestry and fishery interactions. Contribution No. 57. Institute of Forest Resources, University of Washington, Seattle. (viii)

Bisson, P.A., S.M. Wondzell, G.H. Reeves, and S.V. Gregory. 2003. Trends in using wood to restore aquatic habitats and fish communities in western North America. Pages 391-406 *in* S.V. Gregory, K.L. Boyer, and A.M. Gurnell, editors. The ecology and management of wood in world rivers. American Fisheries Society, Symposium 37, Bethesda, Maryland. (i)

Blersch, D.M., and P.C. Kangas. 2014. Signatures of self-assembly in size distributions of wood members in dam structures of *Castor canadensis.* Global Ecology and Conservation 2:204-213. (i)

Boyer, K.L., D.R. Berg and S.V. Gregory. 2003. Riparian management for wood in rivers. Pages 407-420 *in* S.V. Gregory, K.L. Boyer, and A.M. Gurnell, editors. The ecology and management of wood in world rivers. American Fisheries Society, Symposium 37, Bethesda, Maryland. (i)

Brookshire, E.N.J., and K.A. Dwire. 2003. Controls on patterns of coarse organic particle retention in headwater streams. Journal of the North American Benthological Society 22:17-34. (i)

Braun, D.C., and J.D. Reynolds. 2011. Relationships between habitat characteristics and breeding population densities in Sockeye Salmon. Canadian Journal of Fisheries and Aquatic Sciences 68:758-767. (i)

Bryant, M.D., T. Gomi, and J.J. Piccolo. 2007. Structures linking physical and biological processes in headwater streams of the Maybeso Watershed, southeast Alaska. Forest Science 53:371-383. (i)

Buckley, G.L. 1993. Desertification of the Camp Creek Drainage in central Oregon. Yearbook of the Association of Pacific Coast Geographers 55:91-126. (i)

Bustard, D.R., and D.W. Narver. 1975. Aspects of the winter ecology of juvenile Coho Salmon (*Oncorhynchus kisutch*) and steelhead trout (*Salmo gairdneri*). Journal of the Fisheries Research Board of Canada 32:667-680. (i)

Carah, J.K., C.C. Blencowe, D.W. Wright, and L.A. Bolton. 2014. Low-cost restoration techniques for rapidly increasing wood cover in coastal Coho Salmon streams. North American Journal of Fisheries Management 34(5):1003-1013. (i)

Case, T.L., and J.B. Kauffman. 1997. Wild ungulate influence on the recovery of willows, Black Cottonwood, and Thin-leaf Alder following cessation of cattle grazing in northeastern Oregon. Northwest Science 71:115-126. (i)

Cederholm, C.J., D.B. Houston, D.L. Cole, and W.J. Scarlett. 1989. Fate of Coho Salmon (*Oncorhynchus kisutch*) carcasses in spawning streams. Canadian Journal of Fisheries and Aquatic Sciences 46:1347-1355. (i)

Cederholm, C.J., and N.P. Peterson. 1985. The retention of Coho Salmon (*Oncorhynchus kisutch*) carcasses by organic debris in small streams. Canadian Journal of Fisheries and Aquatic Sciences 42:1222-1225. (i)

Chen, X., X. Wei, and R. Scherer. 2005. Influence of wildfire and harvest on biomass, carbon pool, and decomposition of large woody debris in forested streams of southern interior British Columbia. Forest Ecology and Management 208:101-114. (i)

Coe, H.J., P.M. Kiffney, G.R. Pess, K.K. Kloehn, and M.L. McHenry. 2009. Periphyton and invertebrate response to wood placement in large Pacific coastal rivers. River Research and Applications 25:1025-1035. (i)

Collen, P., and R.J. Gibson. 2001. The general ecology of Beavers (*Castor* spp.), as related to their influence in stream ecosystems and riparian habitats, and the subsequent effects on fish—a review. Reviews in Fish Biology and Fisheries 10:439-461. (i)

Collins, B.D., D.R. Montgomery, and A.D. Haas 2002. Historical changes in the distribution and functions of large wood in Puget lowland rivers. Canadian Journal of Fisheries and Aquatic Sciences 59:66-76. (i)

Crawford, R.C. 2003. Riparian vegetation classification of the Columbia Basin, Washington. Natural Heritage Program Report 2003-03. Washington Department Natural Resources. Olympia, Washington. (viii)

Crispin, V., R. House, and D. Roberts. 1993. Changes in instream habitat, large woody debris, and salmon habitat after the restructuring of a coastal Oregon stream. North American Journal of Fisheries Management 13:96-102. (i)

Crook, D A., and A.I. Robertson. 1999. Relationship between riverine fish and woody debris: implications for lowland rivers. Marine and Freshwater Research 50:941-953. (i)

Czarnomski, N.M., D.M. David, K.U. Snyder, J.A. Jones, and F.J. Swanson. 2008. Dynamics of wood in stream networks of the western Cascades Range, Oregon. Canadian Journal of Forest Research 38:2236-2248. (i)

Dolloff, C.A., and C.H. Reeves. 1990. Microhabitat partitioning among stream-dwelling juvenile Coho Salmon, *Oncorhynchus kisutch,* and Dolly Varden, *Salvelinus malma.* Canadian Journal of Fisheries and Aquatic Sciences 47:2297-2306. (i)

Dolloff, C.A., and M.L. Warren. 2003. Fish relationships with large wood in small streams. Pages 179-194 *in* S.V. Gregory, K.L. Boyer, and A.M. Gurnell, editors. The ecology and management of wood in world rivers. American Fisheries Society, Symposium 37, Bethesda, Maryland. (i)

Dominguez, L.G., and C.J. Cederholm. 2000. Rehabilitating stream channels using large woody debris with considerations for salmonid life history and fluvial geomorphic processes. Pages 545-563 *in* E.E. Knudsen, C.R. Steward, D.D. MacDonald, J.E. Williams, and D.W. Reiser, editors. Sustainable fisheries management: Pacific salmon. Lewis Publishers, New York. (i)

Dudley T., and N.H. Anderson. 1982. A survey of invertebrates associated with wood debris in aquatic habitats. Melanderia 39:1-21. (i)

Entrekin, S.A., J.L. Tank, E.J. Rso-Marshall, T.J. Hoellein, and G.A. Lamberti. 2009. Response of secondary production by macroinvertebrates to large wood addition in three Michigan streams. Freshwater Biology 54:1741-1758. (i)

Ehrman, T.P., and G.A. Lamberti. 1992. Hydraulic and particulate matter retention in a 3rd-order Indiana stream. Journal of the North American Benthological Society 11:341-349. (i)

Fausch, K.D., and T. G. Northcote. 1992. Large woody debris and salmonid habitat in a small coastal British Columbia stream. Canadian Journal of Fisheries and Aquatic Sciences 49:682-693. (i)

Fetherston, K.L., R.J. Naiman, and R.E. Bilby. 1995. Large woody debris, physical process, and riparian forest development in montane river networks of the Pacific Northwest. Geomorphology 13:133-144. (i)

Fox, M.J. 2001. A new look at the quantities and volumes of instream wood in forested basins within Washington State. Master's thesis. University of Washington, Seattle. (i)

Fox, M.J. 2003. Spatial organization, position, and source characteristics of large woody debris in natural systems. Doctoral dissertation. University of Washington, Seattle. (i)

Fox, M., and S. Bolton. 2007. A regional and geomorphic reference for quantities and volumes of instream wood in unmanaged forested basins of Washington State. North American Journal of Fisheries Management 27:342-359. (i)

Franklin, J.F., and C.T. Dyrness. 1988. Natural vegetation of Oregon and Washington. Oregon State University press, Corvallis, Oregon. (i)

Gregory, K.J. 2003. The limits of wood in world rivers: present, past, and future. Pages 1-19 *in* S.V. Gregory, K.L. Boyer, and A.M. Gurnell, editors. The ecology and management of wood in world rivers. American Fisheries Society, Symposium 37, Bethesda, Maryland. (i)

Gregory, S.V., K.L. Boyer, and A.M. Gurnell, editors. 2003. The ecology and management of wood in world rivers. American Fisheries Society, Symposium 37, Bethesda, Maryland. (i)

Gregory, S.V., F.J. Swanson, W.A. McKee, and K.W. Cummins. 1991. An ecosystem perspective of riparian zones: focus on links between land and water. Bioscience 41:540-551. (i)

Grizzel, J.D., and N. Wolff. 1998. Occurrence of windthrow in forest buffer strips and its effect on small streams in northwest Washington. Northwest Science 72: 214-223. (i)

Gurnell, A.M. 2003. Wood storage and mobility. Pages 75-92 *in* S.V. Gregory, K.L. Boyer, and A.M. Gurnell, editors. The ecology and management of wood in world rivers. American Fisheries Society, Symposium 37, Bethesda, Maryland. (i)

Gurnell, A.M., K.J. Gregory, and G.E. Petts. 1995. The role of coarse woody debris in forest aquatic habitats: implications for management. Aquatic Conservation: Marine and Freshwater Ecosystems 5:143-166. (i)

Gurnell, A.M., H. Piégay, F.J. Swanson, and S.V. Gregory. 2002. Large wood and fluvial processes. Freshwater Biology 47:601-619. (i)

Harmon, M.E., J.F. Franklin, F.J. Swanson, P. Sollins, S.V. Gregory, J.D. Lattin, N.H. Anderson, S.P. Cline, N.G. Aumen, J.R. Sedell, G.W. Lienkaemper, K. Cromack, and K.W. Cummins. 1986. Ecology of coarse woody debris in temperate ecosystems. Advances in Ecological Research 15:133–302. (i)

Hartman, G.F. 1965. The role of behavior in the ecology and interaction of underyearling Coho Salmon (*Oncorhynchus kisutch*) and steelhead trout (*Salmo gairdneri*). Journal of the Fisheries Board of Canada 22:1035-1081. (i)

Hassan, M.A., D.L. Hogan, S.A. Bird, C.L. May, T. Gomi, and D. Campbell. 2005. Spatial and temporal dynamics of wood in headwater streams of the Pacific Northwest. Journal of the American Water Resources Association 41:899-919. (i)

Henry, W.V., and V.C. Twitty. 1940. Contributions to the life histories of *Dicamptodon ensatus* and *Ambystoma gracile*. Copeia 1940:247-250. (i)

Heede, B.H. 1972. Influences of a forest on the hydraulic geometry of two mountain streams. Water Resources Bulletin 8:523-530. (i)

Hernandez, O., R.W. Merritt, and M.S. Wipfli. 2005. Benthic invertebrate community structure is influenced by forest succession after clearcut logging in southeastern Alaska. Hydrobiologia 533:45-59. (i)

Holland D.C. 1994. The Western Pond Turtle: habitat and history. Bonneville Power Administration, Wildlife Diversity Program, BP-62137-1, unpublished report, Portland, Oregon. (viii)

Hyatt, T.L., and R.J. Naiman. 2001. The residence time of large woody debris in the Queets River, Washington, USA. Ecological Applications 11:191-202. (i)

Hyatt, T.L., T.Z. Waldo, and T.J. Beechie. 2004. A watershed scale assessment of riparian forests, with implications for restoration. Restoration Ecology 12:175-175. (i)

Jackson, C.R., D.P. Batzer, S.S. Cross, S.M. Haggerty, and C.A. Sturm. 2007. Headwater streams and timber harvest: channel, macroinvertebrate, and amphibian response and recovery. Forest Science 53:356-370. (i)

Jamieson, B., and J. Braatne. 2001. Riparian cottonwood ecosystems and regulated flows in Kootenai and Yakima subbasins: impacts of flow regulation on riparian cottonwood forests of the Yakima River. BPA Report DOE/BP-00000005-3. Bonneville Power Administration, Portland, Oregon. (viii)

Johnson, L. B., D.H. Breneman, and C. Richards. 2003. Macroinvertebrate community structure and function associated with large wood in low gradient streams. River Research and Applications 19:199-218. (i)

Johnston, N.T., S.A. Bird, D.L. Hogan, and E.A. MacIsaac. 2011. Mechanisms and source distances for the input of large woody debris to forested streams in British Columbia, Canada. Canadian Journal of Forest Research 41:2231-2246. (i)

Jones, L.L.C., R.B. Bury, and P.S. Corn. 1990. Field observation on the development of a clutch of Pacific Giant Salamander (*Dicamptodon tenebrosus*) eggs. Northwestern Naturalist 71:93-94. (i)

Kauffman, J.B., R.L. Beschta, N. Otting, and D. Lytjen. 1997. An ecological perspective of riparian and stream restoration in the western United States. Fisheries 22:12-24. (i)

Keller, E.A., and F.J. Swanson. 1979. Effects of large organic material on channel form and fluvial processes. Earth Surface Processes 4:361-380. (i)

Latterell, J.J., and R.J. Naiman. 2007. Sources and dynamics of large logs in a temperate floodplain river. Ecological Applications 17:1127-1141. (i)

Liquori, M.K. 2006. Post-harvest riparian buffer response: implications for wood recruitment modeling and buffer design. Journal of the American Water Resources Association 42:177-189. (i)

Mack, R.N., and J.N. Thompson 1982. Evolution in steppe with few large, hooved mammals. American Naturalist 119:757-773. (i)

Martin, D.J., and L.E. Benda. 2001. Patterns of instream wood recruitment and transport at the watershed scale. Transactions of the American Fisheries Society 130:940-958. (i)

Martin, D.J., and R.A. Grotefendt. 2007. Stand mortality in buffer strips and the supply of woody debris to streams in Southeast Alaska. Canadian Journal of Forest Research 37:36-49. (i)

Maser, C.M., R.F. Tarrant, J.M. Trappe, and J.F. Franklin, editors. 1988. From the forest to the sea: a story of fallen trees. PNW-GTR-229. U.S. Forest Service, Pacific Northwest Research Station, Portland, Oregon. (viii)

May, C.L., and R.E. Gresswell. 2003. Large wood recruitment and redistribution in headwater streams in the southern Oregon Coast Range, USA. Canadian Journal of Forest Research 33:1352-1362. (i)

May, C.W., R.R. Horner, J.R. Karr, B.W. Mar, and E.B. Welch. 1997. Effects of urbanization on small streams in the Puget Sound Lowland Ecoregion. Watershed Protection Techniques 2(4):485-494. (i)

McAllister, L.S. 2008. Reconstructing historical riparian conditions for two river basins in eastern Oregon, USA. Environmental Management 42:412-425. (i)

McDade, M.H., F.J. Swanson, W.A. McKee, J.F. Franklin, and J.V. Sickle. 1990. Source distances for coarse woody debris entering small streams in western Oregon and Washington. Canadian Journal of Forest Research 20:326-330. (i)

Minckley, W.L., and J.N. Rune. 1985. Large woody debris in hot-desert streams: an historical overview. Desert Plants 7(3):142-153. (i)

Montgomery, D.R., and J.M. Buffington. 1997. Channel-reach morphology in mountain drainage basins. Geological Society of America Bulletin 109:596–611. (i)

Montgomery, D.R., J.M. Buffington, R.D. Smith, K.M. Schmidt, and G. Pess. 1995. Pool spacing in forest channels. Water Resources Research 31:1097-1105. (i)

Murphy, M.L., J. Heifetz, S.W. Johnson, K.V. Koski, and J.F. Thedinga. 1986. Effects of clear-cut logging with and without buffer strips on juvenile salmonids in Alaskan streams. Canadian Journal of Fisheries and Aquatic Sciences 43:1521-1533. (i)

Murphy, M.L., and K.V. Koski. 1989. Input and depletion of woody debris in Alaska streams and implications for streamside management. North American Journal of Fisheries Management 9:427-436. (i)

Naiman, R.J., E.V. Balian, K.K. Bartz, R.E. Bilby, and J.J. Latterell. 2002a. Dead wood dynamics in stream ecosystems. Pages 23-47 *in* W.F. Laudenslayer, P.J. Shea, B.E. Valentine, C.P Weatherspoon, and T.E. Lisle, technical coordinators. Proceedings of the symposium on the ecology and management of dead wood in western forests. PSW-GTR-181. U.S. Forest Service, Pacific Southwest Research Station, Portland, Oregon. (viii)

Naiman, R.J., R.E. Bilby, and P.A. Bisson. 2000. Riparian ecology and management in the Pacific coastal rain forest. BioScience 50:996-1011. (i)

Naiman, R.J., R.E. Bilby, D.E. Schindler, and J.M. Helfield. 2002b. Pacific salmon, nutrients, and the dynamics of freshwater and riparian ecosystems. Ecosystems 5:399–417. (i)

Naiman, R.J., C.A. Johnston, and J.C. Kelley. 1988. Alteration of North American streams by Beaver. BioScience 38:753-762. (i)

Naiman, R.J., and J.R. Sedell. 1979. Characterization of particulate organic matter transported by some Cascade Mountain streams. Journal of the Fisheries Research Board of Canada 36:17-31. (i)

Nakamura, F., and F.J. Swanson. 1993. Effects of coarse woody debris on morphology and sediment storage of a mountain stream system in western Oregon. Earth Surface Processes and Landforms 18:43-61. (i)

Nussbaum, R.A. 1969. Nests and eggs of the Pacific Giant Salamander, *Dicamptodon ensatus* (Eschsacholtz). Herpetologica 25:257–262. (i)

Olson, D.H., P.D. Anderson, C.A. Frissell, H.H. Welsh Jr., and D.F. Bradford. 2007. Biodiversity management approaches for stream–riparian areas: perspectives for Pacific Northwest headwater forests, microclimates, and amphibians. Forest Ecology and Management 246: 81-107. (i)

Parker, M.S. 1994. Feeding ecology of stream-dwelling Pacific Giant Salamander larvae (*Dicamptodon tenebrosus*). Copeia 1994:705-718. (i)

Pereira, C.R.D., and N.H. Anderson. 1982. Observations on the life history and feeding of *Cinygma integrum* (Eaton) and *Ironodes nitidus* (Eaton) (*Ephemeroptera: Heptageniidae*). Melanderia 39:35-45. (i)

Pereira, C.R.D., N.H. Anderson, and T. Dudley. 1982. Gut content analysis of aquatic insects from wood substrates. Melanderia 39:23-33. (i)

Piégay, H. 2003. Dynamics of wood in large rivers. Pages 109-134 *in* S.V. Gregory, K.L. Boyer, and A.M. Gurnell, editors. The ecology and management of wood in world rivers. American Fisheries Society, Symposium 37, Bethesda, Maryland. (i)

Pollock, M.M., T.J. Beechie, and C.E. Jordan. 2007. Geomorphic changes upstream of Beaver dams in Bridge Creek, an incised stream channel in the interior Columbia River basin, eastern Oregon. Earth Surface Processes and Landforms 32:1174-1185. (i)

Pollock, M.M., M. Heim, and D. Werner. 2003. Hydrological and geomorphic effects of Beaver dams and their influence on fishes. Pages 213-233 *in* S.V. Gregory, K.L. Boyer, and A.M. Gurnell, editors. The ecology and management of wood in world rivers. American Fisheries Society, Symposium 37, Bethesda, Maryland. (i)

Pollock, M.M., G. Lewallen, K. Woodruff, C.E. Jordan, and J.M. Castro, editors. 2015. The Beaver restoration guidebook: working with Beaver to restore streams, wetlands, and floodplains. Version 1.02. U.S. Fish and Wildlife Service, Portland, Oregon. (viii)

Powell, S.R., L.D. Daniels, and T.A. Jones. 2009. Temporal dynamics of large woody debris in small streams of the Alberta foothills, Canada. Canadian Journal of Forest Research 39:1159-1170. (i)

Ralph, S.C., G.C. Poole, L.L. Conquest, and R.J. Naiman. 1994. Stream channel morphology and woody debris in logged and unlogged basins of western Washington. Canadian Journal of Fisheries and Aquatic Sciences 51:37-51. (i)

Reeves, G.H., K.M. Burnett, and E.V. McGarry. 2003. Sources of large wood in the main stem of a fourth-order watershed in coastal Oregon. Canadian Journal of Forest Research 33:1363-1370. (i)

Reich, M., J.L. Kershner, and R.C. Wildman. 2003. Restoring streams with large wood: a synthesis. Pages 355-366 *in* S.V. Gregory, K.L. Boyer, and A.M. Gurnell, editors. The ecology and management of wood in world rivers. American Fisheries Society, Symposium 37, Bethesda, Maryland. (i)

Reimchen T.E., D. Mathewson, M.D. Hocking, J. Moran, and D. Harris. 2003. Isotopic evidence for enrichment of salmon-derived nutrients in vegetation, soil, and insects in riparian zones in coastal British Columbia. Pages 59-69 *in* J. Stockner, editor. Nutrients in salmonid ecosystems: sustaining production and

biodiversity. American Fisheries Society, Symposium 34, Bethesda, Maryland. (i)

Rhoads, B.L. 1988. Mutual adjustments between process and form in a desert mountain fluvial system. Annals of the Association of American Geographers 78:271-287. (i)

Richardson, J.S. 2008. Aquatic arthropods and forestry: effects of large-scale land use on aquatic systems in Nearctic temperate regions. The Canadian Entomologist 140:495-509. (i)

Robison, E.G., and R.L. Beschta. 1990. Identifying trees in riparian areas that can provide coarse woody debris. Forest Science 36:790-801. (i)

Roni, P., T.J. Beechie, G.R. Pess, and K.M. Hanson. 2014. Wood placement in river restoration: fact, fiction and future direction. Canadian Journal of Fisheries and Aquatic Sciences 72(3):466-478. (i)

Roni, P., and T.P. Quinn. 2001. Density and size of juvenile salmonids in response to placement of large woody debris in western Oregon and Washington streams. Canadian Journal of Fisheries and Aquatic Sciences 58:282–292. (i)

Roy, A.H., C.L. Faust, M.C. Freeman, and J.L. Meyer. 2005. Reach-scale effects of riparian forest cover on urban stream ecosystems. Canadian Journal of Fisheries and Aquatic Sciences 62:2312-2329. (i)

Schuett-Hames, D., A.E. Pleus, J. Ward, M. Fox, and J. Light. 1999. Method manual for the large woody debris survey. TFW-AM9-99-004. Forest Practices Division, Washington Department of Natural Resources, Olympia, Washington. (viii)

Sedell, J.R., P.A. Bisson, F.J. Swanson, and S.V. Gregory. 1988. What we know about large trees that fall into stream and rivers. Pages 47-80 *in* C.M. Maser, R.F. Tarrant, J.M. Trappe, and J.F. Franklin, editors. From the forest to the sea: a story of fallen trees. PNW-GTR-229. U.S. Forest Service, Pacific Northwest Research Station, Portland, Oregon. (viii)

Sedell, J.R., and K.J. Luchessa. 1981. Using the historical record as an aid to salmonid habitat enhancement. Pages 210-233 *in* N.B. Arementrout, editor. Acquisition and utilization of aquatic habitat inventory information. American Fisheries Society, Bethesda, Maryland. (i)

Sedell, J.R., F.J. Swanson, and S.V. Gregory. 1985. Evaluating fish response to woody debris. Pages 222-245 *in* T.J. Hassler, editor. Pacific Northwest stream habitat management workshop. Humboldt State University, Arcata, California. (viii)

Spence, B.C., G.A., Lomnicky, R.M. Hughes, and R.P Novitzki. 1996. An ecosystem approach to salmonid conservation. TR-4501-96-6057. ManTech Environmental Research Services Corporation, Corvallis, Oregon. (viii)

Spies, T., M. Pollock, G. Reeves, and T. Beechie. 2013. Effects of riparian thinning on wood recruitment: a scientific synthesis. Science Review Team Wood Recruitment Subgroup, Forest Science Laboratory, Corvallis, Oregon. (viii)

Steel, E.A., W.H. Richards, and K.A. Kelsay. 2003. Wood and wildlife: benefits of river wood to terrestrial and aquatic vertebrates. Pages 235-248 *in* S.V. Gregory, K.L. Boyer, and A.M. Gurnell, editors. The ecology and management of wood in world rivers. American Fisheries Society, Symposium 37, Bethesda, Maryland. (i)

Steele, C.A., and C. Brammer. 2006. Dietary overlap in giant salamanders (*Dicamptodon*): applying null models to resource partitioning. Western North American Naturalist 66:115-120. (i)

Stouder, D.J., P.A. Bisson, and R.J. Naiman, editors. 1997. Pacific salmon and their ecosystems: status and future options. Chapman & Hall, New York. (i)

Sullivan, K, T.E. Lisle, C.A. Dolloff, G.E. Grant, and L.M. Reid. 1987. Stream channels: the link between forests and fishes. Pages 30-97 *in* E.O. Salo and T.W. Cundy, editors. Streamside management: forestry and fishery interactions. Contribution No. 57. Institute of Forest Resources, University of Washington, Seattle. (viii)

Swanson, F.J., G.W. Lienkaemper, and J.R. Sedell. 1976. History, physical effects, and management implications of large organic debris in western Oregon streams. PNW-GTR-56. U.S. Forest Service, Pacific Northwest Research Station, Portland, Oregon. (viii)

Tschaplinski, P.J., and G.F. Hartman. 1983. Winter distribution of juvenile Coho Salmon (*Oncorhynchus kisutch*) before and after logging in Carnation Creek, British Columbia, and some implications for overwinter survival. Canadian Journal of Fisheries and Aquatic Sciences 40:452-461. (i)

Van Sickle, J., and S.V. Gregory. 1990. Modeling inputs of large woody debris from falling trees. Canadian Journal Forest Research 20:1593-1601. (i)

Ward, G.H., K.W. Cummins, R.W. Speaker, A.K. Ward, S.V. Gregory, and T.L. Dudley. 1982. Habitat and food resources for invertebrate communities in South Fork Hoh River, Olympic National Park. Pages 9-14 *in* E.E. Starkey, J.F. Franklin, and J.W. Matthews, editors. Ecological research in national parks of the Pacific Northwest. Forest Research Laboratory, Oregon State University, Corvallis, Oregon. (viii)

WDNR (Washington Department of Natural Resources). 2005. Forest practices habitat conservation plan. Forest Practices Division, Washington Department of Natural Resources, Olympia, Washington. (v)

Welsh, H.H., Jr., and A.J. Lind. 2002. Multiscale habitat relationships of stream amphibians in the Klamath-Siskiyou Region of California and Oregon. Journal of Wildlife Management 66:581-602. (i)

WFPB (Washington Forest Practices Board). 1987. Proposed forest practices rule and regulations: final environmental impact statement. Washington Forest Practices Board, Washington Department of Natural Resources, Olympia, Washington. (v)

WFPB (Washington Forest Practices Board). 2011. Board manual: standard methodology for conducting watershed analysis. Version 5.0. Appendix F: Fish habitat module. Washington Forest Practices Board, Washington Department of Natural Resources, Olympia, Washington. (v)

Wiggins, G.B. 1977. Larvae of North American Caddisfly Genera (Trichoptera). 1st Edition. University of Toronto Press, Ontario, Canada. (i)

Wilkins, R.P., and N.P. Peterson. 2000. Factors related to amphibian occurrence and abundance in headwater streams draining second-growth Douglas-fir forests in southwestern Washington. Forest Ecology and Management 139:79-79. (i)

Wing, M.G., and A. Skaugset. 2002. Relationships of channel characteristics, land ownership, and land use patterns to large woody debris in western Oregon streams. Canadian Journal of Fisheries and Aquatic Sciences 59:796-807. (i)

Wisseman, R.W., and N.H. Anderson. 1984. Mortality factors affecting trichoptera eggs and pupae in an Oregon coast range watershed. Pages 455-460 *in* J.C. Morse, editor. Proceedings of the 4th International Symposium on Trichoptera. Dr W. Junk Publishers, The Hague, Netherlands. (viii)

Wissmar, R.C. 2004. Riparian corridors of eastern Oregon and Washington: functions and sustainability along lowland-arid to mountain gradients. Aquatic Sciences 66:373-387. (i)

Wissmar, R.C., J.E. Smith, B.A. McIntosh, H.W. Li, and G.H. Reeves. 1994. A history of resource use and disturbance in riverine basins of eastern Oregon and Washington (early 1800s-1990s). Northwest Science 68 (special issue):1-35. (i)

Wondzell, S.M., and P.A. Bisson. 2003. Influence of wood on aquatic biodiversity. Pages 249-264 *in* S.V. Gregory, K.L. Boyer, and A.M. Gurnell, editors. The ecology and management of wood in world rivers. American Fisheries Society, Symposium 37, Bethesda, Maryland. (i)

Zalewski, M., M. Lapinska, and P.B. Bayley. 2003. Fish relationships with wood in large rivers. Pages 194-212 *in* S.V. Gregory, K.L. Boyer, and A.M. Gurnell, editors. The ecology and management of wood in world rivers. American Fisheries Society, Symposium 37, Bethesda, Maryland. (i)

Chapter 4. Stream Temperature

By: Kirk L. Krueger, Daniel J. Isaak, and Marc P. Hayes

4.1. Introduction

The great diversity of Washington's landscapes creates equally diverse stream thermal conditions (Figure 4.1). Broad ranges in elevation (0 -14,000 ft, 0 - 4,300 m), precipitation, stream size, topography, and other factors contribute to some streams having average summer temperatures as low as 39°F (4°C); whereas others only a few miles away may exceed 68°F (20°C). Much of that thermal heterogeneity is dictated by effectively immutable geomorphic attributes of landscapes (e.g., elevation, aspect, topographic slope), which affect the potential amount of solar radiation available at a given location (Boyd and Kasper 2003). However, the types of riparian vegetation and their condition also play important roles in determining the amount of solar radiation that reaches a stream's surface. Through management of riparian ecosystem conditions, especially vegetation, the spatiotemporal distribution of stream temperatures (i.e., thermal regime) (Boyd and Kasper 2003; Caissie 2006) can be affected, which in turn, directly and indirectly affect the survival and productivity of aquatic species (Beschta et al. 1987; McCullough 1999) including salmon.

Shade can substantially reduce the amount of direct (shortwave) solar radiation, usually the main cause of heating, that reaches a stream (Poole and Berman 2001). Indirect effects of riparian vegetation include, but are not limited to, maintenance of channel form and



Pink Salmon Oncorhynchus gorbuscha *moving upstream to spawn/Ned Pittman, WDFW*

hyporheic connectivity (Gregory et al. 1991; Stanford 1998; Poole and Berman 2001) that also affect stream temperatures (Boyd and Kasper 2003; Webb et al. 2008). Maintaining and restoring riparian ecosystem functions and the thermal regimes of aquatic systems is increasingly important in light of climate change and as land use intensifies. Land use can strongly influence the intensity, timing, duration, and geographic distributions (i.e., structure) of stream temperatures (NRC 2002).

In this chapter we briefly summarize the results of our literature review, and present a simple conceptual model that identifies components (environmental factors) and structures (relations of components) that affect stream temperatures, to facilitate understanding of potential effects of different management alternatives. We also briefly discuss considerations of the effects of riparian management on stream thermal regime within a watershed or stream network context, the sensitivity of some priority species to changes in stream thermal regime, and applications of current scientific information to riparian management for suitable thermal regimes for aquatic species. Much of the literature describing the effects of human activity on stream temperature has focused on summer maximum water temperatures. Increasingly, scientists are focusing on better understanding stream thermal regimes, which describe how the temperature of streams varies through time and throughout stream networks. This shift recognizes two important ideas: 1) fish and other aquatic organism use different stream habitats, defined in part by specific water temperature ranges, to complete their life cycle, and 2) heat energy inputs into streams are variable in space and time and heat energy is often carried downstream of the reach from which it was gained.

Our review of the scientific literature on the effects of riparian conditions on stream temperatures was extensive; including more than 6,000 articles relevant to riparian ecosystem research, of which more than 700 referenced stream temperatures and over 100 that referred to or reported measured effects of riparian ecosystem conditions on stream temperatures. Our work also identifies research to inform management recommendations that are applicable across a wide range of environmental conditions (e.g., various latitudes, topographies, and land uses). Further, we wanted to address the broad range of thermal conditions that are important to aquatic species (e.g., frequency, duration, intensity, and predictability of summer high temperatures and temperatures during incubation (Lytle and Poff 2004); and the geographic distribution of stream temperatures (Torgersen et al. 1999; Poole et al. 2001; Ebersole et al. 2003a). Therefore, we reference additional scientific information to provide the context that allows for better understanding and application of riparian ecosystem-specific information. Several reviews were particularly valuable in directing our efforts (e.g., Elmore and Kauffman 1994; May 2003; Moore et al. 2005; Sather and May 2007; Bowler et al. 2012; Czarnomski and Hale 2013).

Scientists are focusing on better understanding stream thermal regimes, which describe how the temperature of streams varies through time and throughout stream networks.

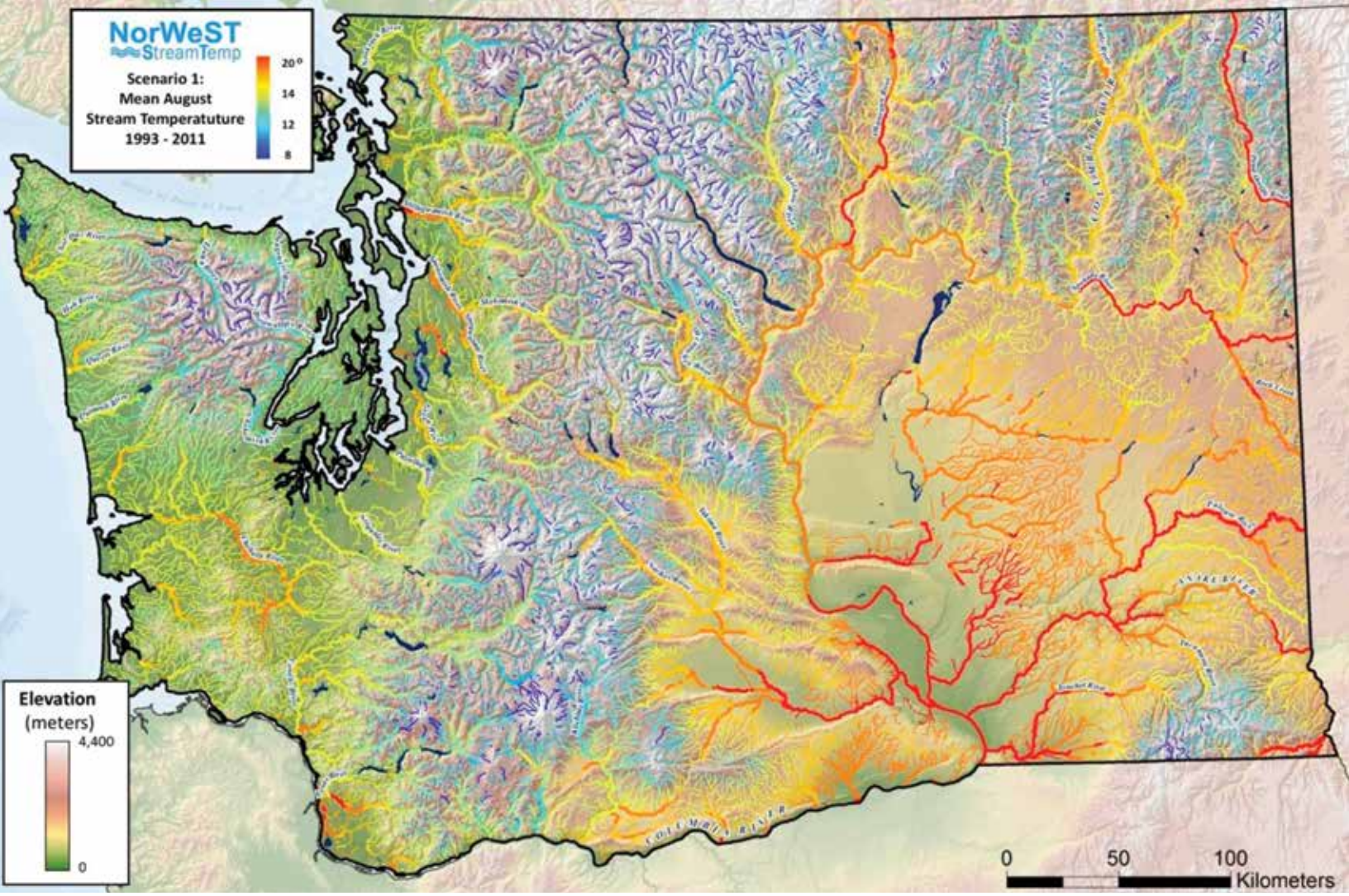


Figure 4.1. Stream thermalscape showing mean August temperatures for 66,236 kilometers (41,157 miles) of streams across Washington that was developed in the NorWeST project (poster available here: http://www.fs.fed .us/rm/boise/AWAE/projects/stream_temp/downloads/14NorWeST_WashingtonStreamTemperatureMap.pdf). Topographic and geomorphic complexity across the state creates significant thermal heterogeneity that is moderated locally by riparian conditions.

4.1.1. State of the Science

The scientific literature establishes a clear expectation that reduction of stream shade, especially due to vegetation removal, will result in warmer summer stream temperatures (e.g., Sridhar et al. 2004; Allen et al. 2007). The literature, derived primarily from descriptive (e.g., case study) and occasionally statistically predictive (e.g., generalization across many case studies) studies, demonstrates that riparian management can affect shade and in turn stream temperatures (Johnson 2004; Moore et al. 2005). The vast majority of those studies document an increase in a temperature statistic, often mean daily maximum temperature during summer, associated with a loss of shade (Johnson 2004; Moore et al. 2005; Bowler et al. 2012), but a few studies have shown mixed results (Johnson 2004; Moore et al. 2005; Janisch et al. 2012; Kibler et al. 2013).

Variability in stream temperatures among locations (Figure 4.1) and among some study results is due to both temporally constant attributes of landscapes (e.g., elevation, topographic slope, drainage area) and temporally variable attributes (e.g., stream wetted width, stream flow) that affect the potential amount of solar radiation available at a given location (Boyd and Kasper 2003) and the thermal sensitivity of the stream, respectively. The amount of solar radiation available is often referred to as thermal loading potential or

potential solar load. At a given thermal input or load, the temperature change responsiveness of a stream is often referred to as "thermal sensitivity" (Beschta et al. 1987; Moore et al. 2005). Thermal sensitivity is influenced by many physical factors. Streams with higher flows of surface and groundwater, and hyporheic exchange rates (Cristea and Burges 2010; Arismendi et al. 2012) tend to be relatively thermally insensitive. Wood loading, channel complexity and depth can also affect thermal load and sensitivity. The potential solar load in combination with thermal sensitivity (discussed in detail below) of locations across a stream network and through time largely determine a stream thermal regime.

In addition to solar radiation, other microclimate variables - such as air temperature, wind speed, and humidity - may affect instream water temperatures. Microclimate conditions interact with energy exchanges at the air-water interface (Figure 4.2) and can thereby affect stream thermal regimes (Moore et al. 2005; Benyahya et al. 2010), especially in small streams (Caissie 2016). However, we believe the effects of microclimate on the thermal regime of streams with fully functioning riparian ecosystems are minor for two reasons: 1) microclimate effects (e.g., changes in air temperature and humidity) at forest edges rarely extend farther than one tree height into mature riparian forest (Moore et al. 2005; Rykken et al. 2007; Reeves at al. 2018), and 2) sensible heat exchanges comprise only a small portion of total heat flux in streams (Johnson 2004; Moore et al. 2005). In fact, net solar radiation effects on stream temperatures are generally about an order of magnitude greater than sensible and latent heat exchanges at the air-water interface (Moore et al. 2005; D. Caissie, Fisheries and Oceans Canada, personal communication). However, we also agree with Reeves et al. (2018), who note that the range of effects measured in different studies suggests substantial uncertainties regarding riparian ecosystem management with respect to microclimate.

Riparian ecosystem-stream temperature research appears to be transitioning from largely local, descriptive (e.g., case study and generalizations of case studies) to predictive, mechanistic, and deterministic modeling across larger areas (e.g., Boyd and Kasper 2003; Allen et al. 2007). Mechanistic models attempt to include most of the factors that affect stream temperatures (Figure 4.2) in a given area and thus do not rely on statistical extrapolation from other locations. These types of models can provide relatively accurate and precise temperature predictions at various spatial and temporal scales (Leinenbach et al. 2013). Further, they can provide useful information on systems and processes that are not readily estimated through statistical approaches used in case studies. However, collecting the environmental data necessary for accurate prediction of the effects of riparian management actions on stream thermal regimes via mechanistic models is difficult and often prohibitively expensive (Allen et al. 2007). For example, studies on the effects of riparian ecosystem or land cover management on stream temperatures at large spatial extents (e.g., watersheds of large streams or rivers) and cumulative effects are very rare. Watershed-scale studies (e.g., Janisch et al. 2012; Kibler et al. 2013) are often limited to relatively small watersheds (e.g., 2 to 1,000 ha) and second order streams.

New types of statistical models for stream network data (Ver Hoef et al. 2006; Isaak et al. 2014) have been applied to large stream temperature databases (Isaak et al. 2017a) and these have enabled relatively accurate predictions (R^2 = 0.90; RMSE = 1.8°F or 1.0°C) and mapping of summer thermal conditions across all Washington streams (Figure 4.1). Those statistical approaches use predictor variables derived from broad geospatial and remotely sensed datasets (e.g., elevation, stream slope, riparian density from the National Land Cover Database) so they do not provide insights to local temperature anomalies that could be associated with alterations of riparian or channel conditions. However,

these statistical models do provide accurate thermal status maps that could be used with mechanistic models or field measurements to better ascertain the influence of riparian conditions on stream temperatures.

Scientific knowledge of the importance of stream temperatures on aquatic species has also advanced since the publication of Knutson and Naef in 1997; especially by better describing the importance of thermal regimes (rather than only extreme high temperatures) on fish survival, growth, and productivity (Ward and Stanford 1982; McCullough 1999; Caissie 2006; McCullough et al. 2009; Hinch et al. 2012). For example, the collapse of the Fraser River Sockeye Salmon *Oncorhynchus nerka* spawning run in 2009 was largely attributed to thermal exposure due to early migration, which resulted in indirect, but often fatal, effects (Hinch et al. 2012). Following Olden and Naiman (2010), we suggest that thermal regimes can be described by their rates of change, magnitude, frequency, timing, and duration, and also their spatial distribution in a stream. The timing and duration of thermal exposure, in addition to exposure to extreme temperatures, affects the survival and productivity of many aquatic species (Caissie 2006).

Importantly, studies such as those of Murphy and Hall (1981), Murphy et al. (1981), Hawkins et al. (1983), and Bilby and Bisson (1987) that demonstrated apparent beneficial effects of reduced riparian shade on an aquatic species, such as increased salmonid growth or abundance, can now be considered in a broader ecological context. It should be noted that in these studies observed temperature increases were small and apparent beneficial effects were attributed to increased solar radiation, primary production, and consequent bottom-up stimulation of the food web. These findings are consistent with the idea that oftentimes the biological effects of altered temperatures differ among locations (Li et al. 1994; Farrell et al. 2008), and that such differences in effects may be attributed to the difference between local temperature and the thermal niche of a species. For example, in reaches where temperatures are near a species' thermal maxima, additional warming will cause the habitat to become unsuitable. However, in streams that are too cold for a species, warmer temperatures may increase habitat suitability (Isaak and Hubert 2004; Isaak et al. 2017b). In addition to direct stream temperature changes on a single species, changes may affect ecological trade-offs between species. Rezende et al. (2014) showed that faster growth might also be associated with increased competition with non-native species (Lawrence et al. 2014).

Widespread alterations of upland and riparian conditions and subsequent changes in stream composition and structure have likely already impacted thermal conditions in many streams (Poole and Berman 2001) and such impacts will be further exacerbated by the ongoing effects of climate change (Isaak et al. 2012; Holsinger et al. 2014). Streams with degraded riparian conditions, however, also offer opportunities where restoration actions could mitigate future warming and improve ecological resilience by enhancing the survival and productivity of the populations and assemblages that use those systems.

4.2. Conceptual Model

We provide a conceptual model to help describe the important components, structures, and processes that affect stream temperatures and that can result in different effects of riparian management actions on stream temperatures among locations (Figure 4.2). Our conceptual model is largely a simplification of the model "Heat Source" in Boyd (1996) and Boyd and Kasper (2003) and developed based on the preponderance of scientific evidence. Heat Source is a deterministic, mechanistic model developed to predict dynamic open channel heat and mass transfer. As such, it includes parameters for all variables that are known

to significantly affect stream temperatures. Our simplified conceptual model describes components and parameters that can have a large effect on stream temperatures or that are affected by riparian ecosystem management. We provide this model in an attempt to improve basic understanding of stream thermal processes and to identify important composition, structure, and functions that are subject to management and that affect stream temperatures. Additional information based on the models of Poole and Berman (2001), Moore et al. (2005), and Leinenbach et al. (2013) are included to more clearly identify factors that affect thermal loading potential and stream thermal sensitivity via riparian management.

Scientific understanding of the environmental factors and their relations that affect stream thermal regimes is well developed, as demonstrated by the development of deterministic, mechanistic models (e.g., Boyd and Kasper 2003) that can provide accurate temperature predictions when sufficient data are available to run the model and when the stream system remains relatively stable. Such models have been applied successfully at the spatial extent of individual stream reaches (Cristea and Janisch 2007; Cole and Newton 2013) and watersheds (Coffin et al. 2011; Bisson et al. 2013; Booth et al. 2014), suggesting that our understanding of the composition, structure, and functions that affect stream temperatures are well understood and can be

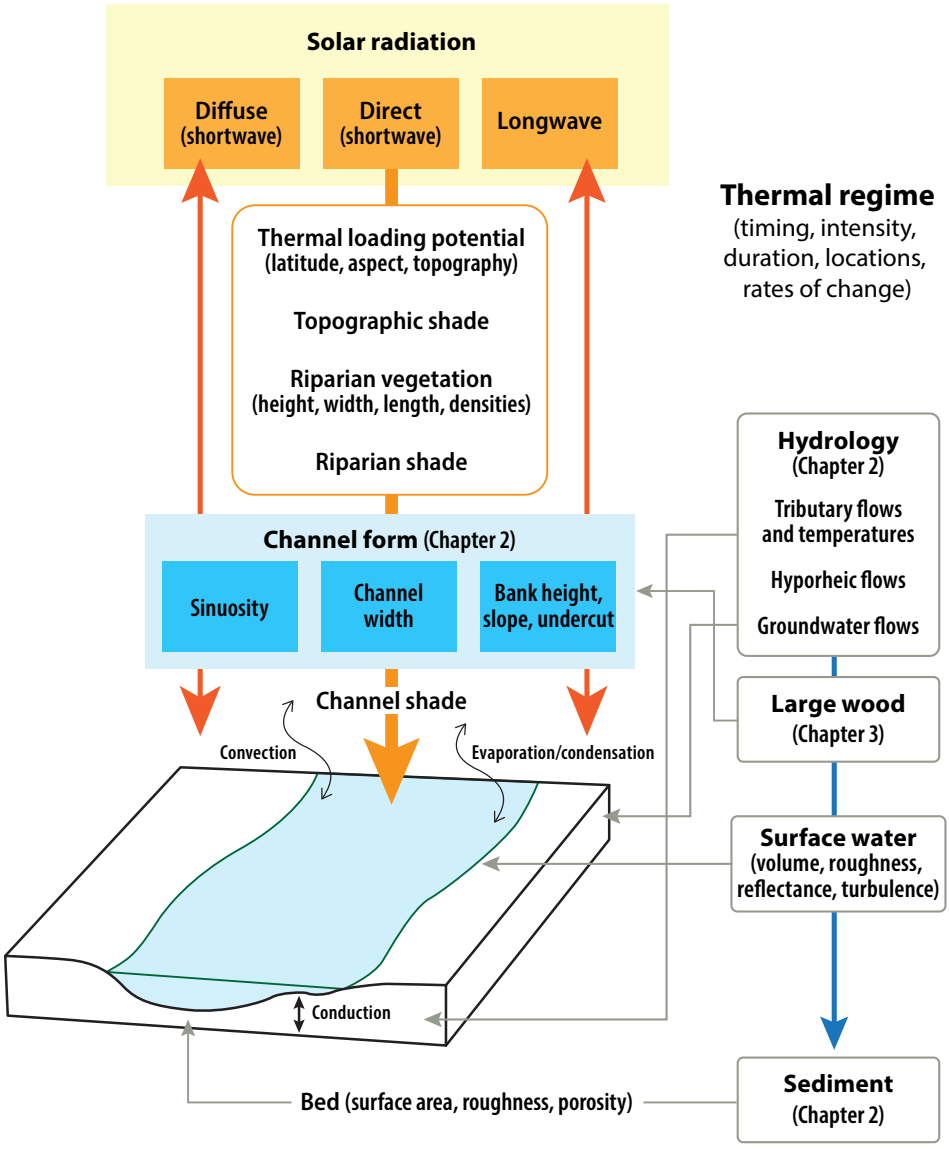


Figure 4.2. Conceptual model that identifies some factors that affect the thermal regime of stream networks. Relative importance is noted by line weight and arrows indicate directions of flows. Note that most of the elements in the model are influenced by human activities and that many components and structures are not presented here. See Boyd and Kasper (2003) for a more thorough review.



Dense tree canopies rarely provide 100% shade/Ned Pittman, WDFW

reliably applied to management problems. Rates of direct (shortwave) solar radiation reaching the stream surface and the volumes and temperatures of water are consistently identified as the dominant processes affecting the thermal regime of streams (Sinokrot and Stefan 1993; Johnson 2004). At many locations these two dominant processes are subject to management: direct solar radiation reaching a stream via vegetation management and water flows via water diversion, storage, and return (Olden and Naiman 2010).

The thermal loading potential of a stream reach is controlled in part by temporally constant and largely independent factors such as latitude, aspect, elevation, and topographic shading (Figure 4.2, Boyd and Kasper 2003; Janisch et al. 2012). Streams at high latitudes are less exposed to solar radiation, the ultimate source of heat energy to streams, than streams at low latitudes. Stream aspect affects stream temperatures because a stream's orientation relative to the path of the sun (which differs seasonally) determines the amount of direct solar radiation that a stream receives (Johnson 1971). Elevation affects the ambient air temperatures that streams are exposed to, as well as the dominant form and amount of precipitation (i.e., snow or rain). For these reasons, higher elevation streams are usually colder and commonly, although not always, less thermally sensitive than lower elevation streams (Luce et al. 2014). Topography can shade a stream from direct solar radiation and the effects of topography and aspect can interact. The effects of these four geographic factors can be difficult to detect (Isaak and Hubert 2001) and are likely responsible for some of the variability of the results of case studies that measured the effects of riparian management on stream temperatures. Note that some of these attributes (e.g., elevation) also affect the composition and structure of riparian vegetation. Stream thermal loading is not only controlled by independent factors such as latitude, aspect, elevation, and topographic shading. The scientific literature clearly identifies shade from riparian vegetation as important to stream temperatures, especially for small (narrow) streams (e.g., Beschta 1987; Poole and Berman 2001; Johnson 2004; Sridhar et al. 2004; Moore et al. 2005; Caissie 2006; Allen et al. 2007; Bowler et al. 2012; Garner et al. 2014). The effects of altered stream shading on temperatures is complex because thermal loading potential and thermal sensitivity of streams differ among locations. Some attributes, such as water volume, wetted width, and width-depth ratio can affect both thermal loading potential and thermal sensitivity (Cristea and Janisch 2007; DeWalle 2010). For a given volume of water, wider channels of the same length have a greater surface area that can intercept more direct solar radiation (Boyd and Kasper 2003) and also exchange more heat through atmospheric conduction. The width of a stream also affects the amount of shade that can be provided by topography and riparian vegetation (Cristea and Janisch 2007; DeWalle 2010). That is, riparian vegetation of given height, density, and width might shade a larger proportion of a narrow channel for a longer period than for a wide channel. Stream widths, especially wetted channel widths, are often much less temporally stable than the other factors that control thermal loading potential. Management actions that result in changes in stream width (e.g., over-grazing [Belsky et al. 1999; Chapter 2] and maintenance of wide forested riparian areas that can result in wide channels [Sweeney and Newbold 2014]) can increase thermal loading potential and thermal sensitivity.

While shortwave radiation input and water volume and temperature largely control temperature regime, longitudinal channel form (stream reach and cross section) can also affect stream temperature, for example, via high sinuosity and the presence of undercut banks (Frissell et al. 1986; Bisson et al. 2006). Channel form and features that increase stream roughness can store gravel (Buffington et al. 2004) and increase hyporheic exchange (Wondzell and Gooseff 2013) that, in turn, can affect stream temperatures by storing and releasing heat (Burkholder et al. 2008). Large wood can also store large amounts of gravel in some streams (Buffington et al. 2004) and affect channel form (Chapter 3; Keller and Swanson 1979; Abbe and Montgomery 1996; Konrad et al. 2005) which might subsequently affect stream temperatures. For example, sediment deposition due to instream large wood might increase hyporheic flow and stream width, which can subsequently effect stream temperatures. Steep or undercut banks can also provide shade (Boyd and Kasper 2003) which, in some locations (Ebersole et al. 2003b), can lower water temperatures at small spatial extents (e.g., individual pools; Ebersole et al. 2003a), even in large streams and rivers. Unfortunately, relatively few studies quantify the effects of channel form on thermal sensitivity and stream temperatures, which likely adds variability among stream temperature case studies and limits our ability to predict their relative importance at specific locations. Groundwater and tributary flows also affect stream temperatures (Malard et al. 2002) in two ways, 1) by adding volume and increasing flow velocity that can make streams less sensitive to thermal change (i.e., increasing thermal capacity), and 2) by adding water that is at a different temperature than receiving waters (Boyd and Kasper 2003; Story et al. 2003). However, the effects of groundwater flows can be difficult to detect due to spatiotemporal lags (Alvarez et al. 2004; Arrigoni et al. 2008) and difficult to apply to management due to the paucity of information describing groundwater flows. Additionally, side channels and wetlands can provide large volumes of water at different temperatures to receiving stream water (Bobba et al. 2010). Streambed attributes, such as porosity and surface area, are largely controlled by the flows of water and available sediment (see Chapter 2). Streambed attributes can affect the thermal regime of a reach by affecting heat conduction (Sinokrot and Stefan 1993), by regulating the amount and velocity of water flow through the streambed, and by controlling the rates and locations of groundwater flows (Malcolm et al. 2002). The effects of these processes on stream temperatures can be spatially and temporally discontinuous and dynamic, especially in systems where stream form is heterogeneous and dynamic (Wright et al. 2005; Wondzell 2012). Hyporheic flows often have little effect on average stream surface water temperatures except for small streams at low flows but can create discrete locations of cool water (Wondzell 2012) that may serve as important refugia for salmon. Hyporheic flows can be influenced by flow regulation (e.g., dams), which can reduce variation in both flows and temperatures that reduces the potential for hyporheic exchange to act as a thermal buffer (Ward and Stanford 1995; Poole and Berman 2001; Nyberg et al. 2008).



Juvenile salmon/Portia Leigh, WDFW

The interaction of complex in- and near-stream riparian ecosystem processes can lead to a cascade of events (i.e., a series of related events triggered by single event) and new system states (Pringle and Triska 2000; Allan 2004). These cascading events are almost impossible to predict. For example, the removal of riparian trees typically reduces shading and increases solar radiation to the stream. Even when reductions in shade have a small direct effect on stream temperatures, the loss of trees can increase bank susceptibility to erosion (Chapters 2 and 3; Micheli and Kirchner 2002; Gomi et al. 2004) resulting in a wider stream that increases thermal loading and thermally sensitivity of the stream. Similarly, channel incision resulting from riparian management, may increase local topographic shading to the stream, but lower streambed and water elevations that can shift the riparian vegetation composition and structure. This shift in riparian vegetation can result in less stable streambanks and less riparian shade that ultimately offsets any benefits of topographical shading on water temperature (Toledo and Kauffman 2001). The results of such interactions are difficult to predict because they rely on accurate predictions of changes to stream morphology, vegetation composition and structure (which interact and have non-linear responses), and water and sediment flows (which can be stochastic).

The processes that affect the timing, duration, and geographic distribution of stream temperatures are complex due to the variability of the environment in which these processes occur (Figure 4.2). The relative importance of these ecological processes differs among locations and through time (Poole and Berman 2001; Webb et al. 2008). Scientific literature is clear about the expected effect of reducing stream shading, especially during summer; water gets warmer, particularly peak temperatures. Science is less able to provide accurate and precise predictions of the effects of specific riparian management measures. For example, the studies presented in Figure 4.3 represent statistical models relating changes in riparian buffer width to changes in stream temperature. Data in Figure 4.3 are collected by measuring stream temperature before and after a reduction in the width of a forested riparian buffer which in turn decreases shade to the stream. Model output (prediction) is change in temperature related to specific buffer widths. The models tell us that reducing shade usually increases stream temperatures (following the shape of the dotted line connecting points), but they cannot predict exactly how much shade reduction will result in a specific temperature increase. A manager attempting to use the statistical model in Figure 4.3 to predict how a reduction from a fully forested site to a 30-foot wide buffer might affect summer stream temperatures is confronted with a range of possible answers. Those answers fall within the 90% credible intervals for one study representing a change between 1.25 and 2.25°C (2.25 and 4.05°F), and for another study between -0.5 to nearly 5.0°C (-0.9 to nearly 9.0°F). Uncertainty in this case describes our inability to accurately predict exact outcomes. While rarely applied due to their expense, mechanistic models and attendant data (e.g., hyporheic flows and temperatures) provide the best approach for predicting accurate site-specific outcomes from management.

Fortunately, the literature is very clear that solar radiation is often the dominant factor affecting stream heat budgets during all seasons except winter (Webb et al. 2008). Results of case studies can prove very useful by clearly describing the expected direction and shape of the relations between attributes of riparian ecosystems (e.g., width of vegetation) and stream shade and temperature. Importantly, riparian shade is often directly amenable to management and in many locations riparian vegetation height and density may be more closely associated with shade than width of riparian vegetation per se (DeWalle 2010). In any case, the literature is very clear about the importance of riparian vegetation for providing shade to streams (Figure 4.3a).

4.3. Species Sensitivity

4.3.1. Fish

The scientific literature describing the importance of temperature, especially high temperatures, to fish is extensive (e.g., Brett 1952, 1971; Brett et al. 1969; Richter and Kolmes 2005). As aquatic ectotherms, the physiology of fish are strongly affected by water temperatures (McCullough et al. 2001; Welsh et al. 2001). Studies have frequently found associations between temperature and the geographic distribution (Welsh et al. 2001), spawn timing (Hodgson and Quinn 2002), growth rates, egg development and survival, competitive interactions, life stage survival, and behavior of fish (McCullough 1999; McCullough et al. 2009). Salmonids have frequently been studied because of their cultural and economic importance and their relative sensitivity to high temperatures, narrow thermal tolerance, and narrow aerobic scope (Farrell et al. 2008; Eliason et al. 2011; Ayllon et al. 2013). Summer temperature information is useful for identifying acute problems, but may be insufficient for ensuring population resilience because indirect effects and exposure to altered thermal regimes, not just extreme summer temperatures, can affect fish survival and productivity (McCullough 1999).

Recent research has increasingly focused on the effects of water temperatures and thermal regimes for fishes that have narrow thermal tolerance (i.e., range of suitable temperatures) or aerobic scope (Farrell et al. 2008; Eliason et al. 2011; Ayllon et al. 2013). This work is particularly relevant to salmonids in the Pacific Northwest that have life histories adapted to historical, location-specific thermal regimes (Brannon et al. 2004; Farrell et al. 2008; Eliason et al. 2011). Much of this research is related to the increasing threats posed by climate change, and some studies have already found evidence of existing, detrimental effects of increased stream temperatures on fish. For example, Isaak et al.



Juvenile anadromous salmon can spend up to 3 years in streams depending on the species/Ned Pittman, WDFW

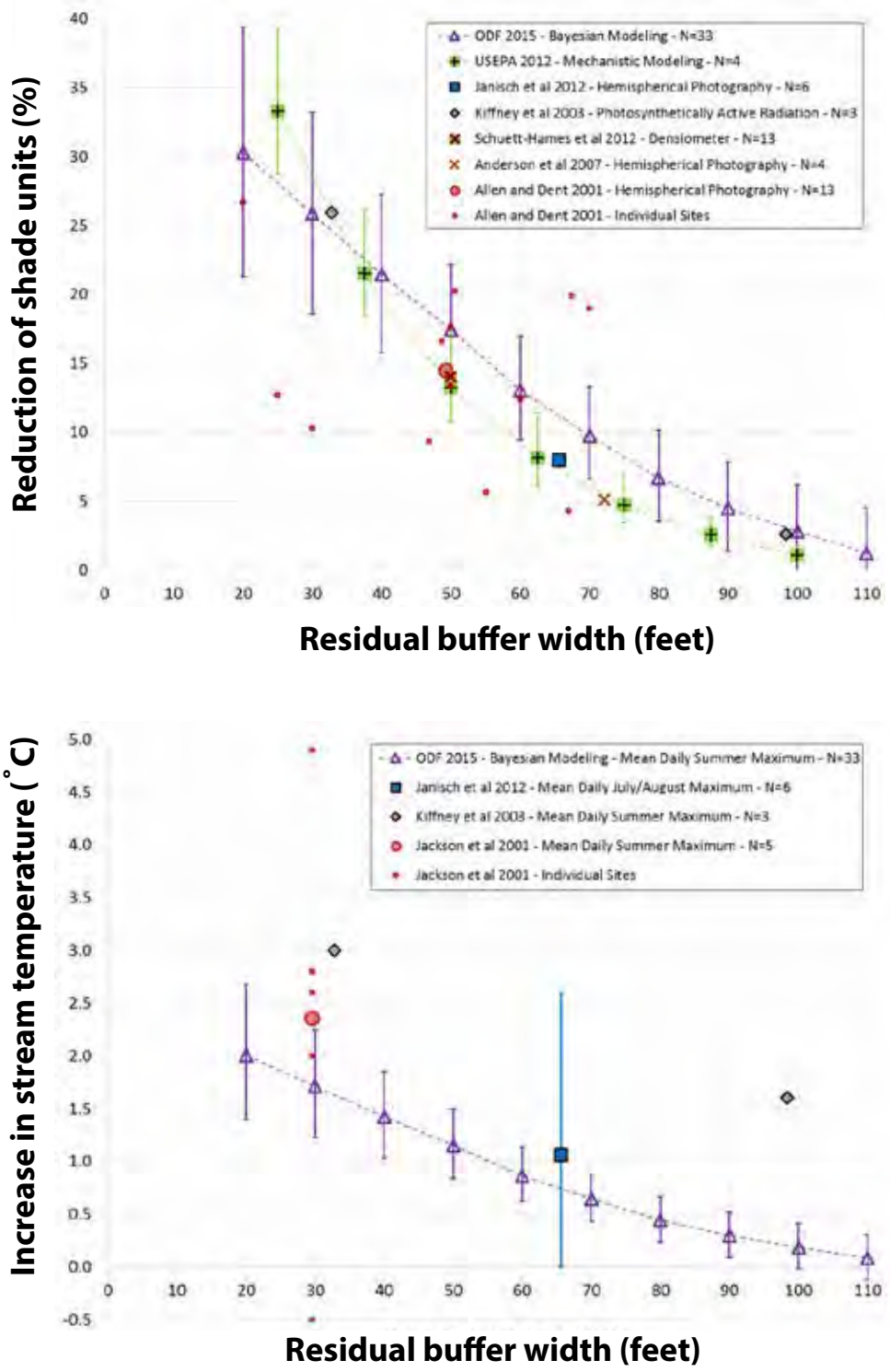


Figure 4.3. Observed shade (a: top panel) and temperature response (b: bottom panel) associated with "no-cut" riparian buffers with adjacent clearcut harvest. Only studies that employed a Before-After-Control-Impact design and conducted in Pacific Northwest forests are included. Shade unit is percent from completely shaded. Bayesian modeling results (and 90% credible intervals) were derived from data collected as part of Groom et al. (2011). Analyses provided by P. Leinenbach, USEPA Region 10.



Chum Salmon Oncorhynchus keta *in spawning colors/Ned Pittman, WDFW*

(2010, 2015) found increases in stream temperatures would result in losses of Bull Trout *Salvelinus confluentus* and Cutthroat Trout *Oncorhynchus clarkii* habitats, but also that especially cold streams could serve as climate refugia during the 21st century. Additionally, a number of recent studies have described some complex effects of altered thermal regimes to the productivity and survival of fish at different life stages and dramatic differences in thermal tolerance and aerobic scope among populations and species. For example, Hinch et al. (2012) describe complex links between the physiology, behavior, environment, disease exposure, and the effect of thermal exposure, on the population-specific survival of migrating Sockeye Salmon. Hodgson and Quinn (2002), Keefer et al. (2007), Strange (2010) and others have documented that high temperatures and previous thermal exposure can inhibit fish migration, and Marsh (1985) and Kappenman et al. (2013) have documented that high and low temperatures can impede spawning and embryo development and that optimal temperatures for embryo survival and development differ among species. Steel et al. (2012) found that thermal variability (without changing mean temperature) can affect the emergence timing and development of Chinook Salmon *Oncorhynchus tshawytscha*.

The literature is conclusive about the importance of stream thermal regimes to fish survival and productivity and also demonstrates wide variability in sensitivity to altered thermal regimes among species and among populations within species (Steel et al. 2012). More research would help us fill the sizeable gap in our understanding of the risk posed by altered thermal regimes on the survival and productivity of populations of salmonids or non-salmonid fishes, and on the ecological interactions that affect survival, productivity and population viability. For example, the time of hatching (i.e., duration of incubation) of salmonid eggs is largely determined by their thermal exposure during incubation. Relatively small changes in temperature can advance or delay maturation and subsequently hatching date (Groot and Margolis 2010) and effects of temperature can differ among closely related populations of the same species that spawn in different habitats (Hendry et al. 1998). Regardless of the ultimate cause, changes in thermal regimes can, for example, uncouple trophic interactions due to temporal mismatches, such as fry emerging when their preferred food is not available to them (Winder and Schindler 2004; Post et al. 2008). Altered thermal regimes can also affect other life stages by altering the timing of parr-smolt transformation (Zaugg and Wagner 1973), the duration of freshwater rearing (Sauter et al. 2001) which can affect ocean survival (Weitkamp et al. 2015), and the timing and success of spawning migration (Crossin et al. 2008). Altered thermal regimes can also affect ecological interactions. For example,

Wise management of riparian and aquatic systems would ideally consider the distribution and dynamics of stream temperatures in space and time and at scales that are relevant to the species in the region.

Lawrence et al. (2014) demonstrated that higher stream temperatures can expand the geographic distribution of non-native Smallmouth Bass *Micropterus dolomieu* and increase their predation on salmon. These results are complicated by the fact that effects of altered thermal regimes often differ among populations and life stages of a species, and among species (Brett 1971; Zaugg and Wagner 1973) which makes prediction of the exact effects of any riparian shade reduction and subsequent effects on stream thermal regime on fish survival and productivity uncertain. This uncertainty is compounded by fish behavioral responses, such as daily and seasonal movement among locations where thermal conditions differ (Torgersen et al. 2001).

Our understanding of the importance of altered thermal regimes on fish has improved substantially since the publication of Knutson and Naef (1997). Discussion of stream temperature by Knutson and Naef (1997) focused mostly on summer high temperatures and their effects on fish, but did not identify many components and structures of ecosystems that can affect stream temperatures or the importance of thermal regimes to fish. In particular, more recent studies are able to measure thermal exposure of fish through time, occasionally in field conditions, and estimate physiological attributes such as growth rate (Sauter and Connolly 2010).

Most studies calculate a single statistic that describes an important attribute of a stream's thermal regime (e.g., mean maximum daily summer temperature) and identify species, population, or life stage attributes that are correlated with that statistic, such as a critical thermal limit. These studies have been useful for demonstrating the importance of temperature and for setting some management objectives. However, they are insufficient for effective, long-term management of perturbed systems because changes in temperature means (i.e., chronic exposure) or extremes (i.e., acute exposure) can result in different selective pressures and evolutionary responses (Rezende et al. 2014) and because life stages, populations, and species differ widely in their sensitivity to altered thermal regimes (Farrell et al. 2008; Hinch et al. 2012). Further, we now better understand that many individual fish and especially populations use (and perhaps are dependent on) a dynamic mosaic of habitats (Fausch et al. 2002; Ward et al. 2002; Wiens 2002); that is, they move between discrete locations with different temperatures (Torgersen et al. 1999). Such movement among "patches" can be important to individual survival and population persistence because thermal conditions at discrete locations can be highly temporally variable (Dugdale et al. 2013) and spatially complex (Fullerton et al. 2015). Management of stream thermal regimes should carefully consider the spatiotemporal distribution and dynamics of thermal conditions at scales that are relevant to the species in the region (Fausch et al. 2002) at durations that are relevant to the rates of system change and recovery from disturbance.

4.3.2. Amphibians and Reptiles

Few studies address the effects of altered thermal regimes on stream-associated amphibians and reptiles, which currently limits the level of specificity to which reliable management recommendations can be made. However, some important insights are possible and these are best discussed in the context of breeding habitat: 1) amphibians that breed in the flowing portions of stream networks, and 2) amphibians and reptiles that breed in or use off-channel stillwater habitats associated with stream networks.

Instream-breeding amphibians (giant salamanders, *Dicamptodon* spp.; tailed frogs, *Ascaphus* spp.; and torrent salamanders, *Rhyacotriton* spp.) are generally described as having low thermal requirements (Bury 2008). However, those requirements are often characterized solely in terms of critical thermal maxima (Brattstrom 1963; Claussen 1973; Brown 1975; Bury



*Giant salamanders (*Dicamptodon *spp.) can be found in small western Washington streams/Eric Lund, WDFW*

2008), while stream temperatures in which these species are found are considerably lower than those maxima (invariably ≤61°F [16°C]; e.g., Brattstrom 1963; Welsh 1990; Welsh and Lind 1996; Pollett et al. 2010). Moreover, water temperatures at which these species first become stressed are entirely unknown. Several studies demonstrate higher density or relative abundances (Stoddard and Hayes 2005; Pollett et al. 2010) of amphibians at the margin of their temperature maxima although the mechanism responsible for this effect is unclear. Similar to fish, identifying critical effects of temperatures on amphibians is complicated by a host of potential variables, e.g., younger life stages frequently have cooler temperature requirements (de Vlaming and Bury 1970; Brown 1975) than older life stages. Importantly, very little research has been conducted on the effects of altered thermal regimes on the timing of life history events, such as the time of hatching, and indirect effects, such as possible ecological temporal mismatches, altered predator-prey relations, and disease frequency and effect (e.g., Hari et al. 2006), that would be useful for identifying important conservation and management actions.

Amphibians and reptiles that breed or utilize riverine off-channel stillwater habitats (e.g., oxbow lakes and permanent and seasonally flooded riverine wetlands) associated with stream networks generally have warmer thermal requirements than instream breeding amphibians. For stillwater-breeding amphibians, thermal requirements vary as a function of the thermal tolerance limits of a specific life stage (often eggs and embryos), which determine the seasonal interval in which they lay eggs. For example, Northern Red-legged Frog *Rana aurora* embryos have the lowest critical thermal maximum of any North American frog (about 68°F or 20°C) (Licht 1971), and they oviposit in late winter, at which time surface water temperatures of stillwater habitats rarely if ever put its embryos at risk. Except for our two turtle species (Western Pond Turtle *Actinemys marmorata* and Western Painted Turtle *Chryemys picta*) and selected garter snake species *Thamnophis*, especially the Common Garter Snake *T. sirtalis* and the Western Terrestrial Garter Snake *T. elegans,* few reptiles utilize aquatic habitats in the Pacific Northwest. These reptiles have



Riparian corridor/Ned Pittman, WDFW

thermal requirements that are more elevated than the temperatures generally found in stillwater habitats except during the warmest part of summer. For this reason, aerial basking (basking out of water) at daytime temperatures that are warmer than water temperature can be critical for these species for effective digestion of food or production of eggs. This pattern is especially important for turtles that need aquatic aerial basking sites isolated from predators, which in most stillwater habitats are provided by large downed wood with relatively level accessible surfaces above the water line (Holland 1994).

4.3.3. Invertebrates

Few studies have examined the effects of altered thermal regimes on stream-associated invertebrates in the Pacific Northwest. However, broad relationships between the geographic distributions of invertebrates and their thermal tolerance have been reported (Beschta et al. 1987; Moulton et al. 1993) as have changes in emergence timing and asynchronous emergence among sexes due to small increases in summer temperatures (Li et al. 2011), demonstrating the importance of temperature to invertebrates. Stream temperature can affect invertebrate density, growth, size at maturation, and sex ratios and the effects often differ among species (Hogg and Williams 1996). Altered stream thermal regimes appear to have important effects on many invertebrates and, subsequently, on stream food webs. Indirect effects such as altered predator-prey relations and disease frequency may also be important but have not been well studied. Riparian ecosystem management for aquatic invertebrates is also constrained by a general lack of information on their geographic distribution.

4.3.4. Species Sensitivity Summary

Management of vegetation in riparian ecosystems can affect stream temperatures and, subsequently, fish, amphibian, and invertebrate abundance and survival. Stream temperature influences important food web and energetic interactions between fish, amphibians, and invertebrates in multiple direct ways and likely in more subtle but relatively unstudied indirect ways (Baxter et al. 2005). The effects of thermal regime has received little study for amphibians and invertebrates. Fortunately, our understanding of the mechanisms that affect stream thermal regime can provide useful guidance in the absence of better information.

4.4. Land Use Effects

4.4.1. Urbanization

There have been very few studies specifically relating urbanization to riparian ecosystem function and subsequent effects on stream thermal regimes (Paul and Meyer 2001). Clearly, urbanization related changes to riparian areas can be similar to riparian changes associated with agriculture and forestry as far as stream temperature is concerned, e.g., removal of shade, reduction in large wood inputs. Urban areas have additional issues that can affect stream temperatures including heat island

effects, and inputs of wastewater and runoff from impervious surfaces (Kinouchi et al. 2006; Hester and Doyle 2011). Some of these complicating factors may contribute to the absence of detectable effects on stream temperatures studies in some comparative studies (Wahl et al. 2013). Nonetheless, urbanization is considered to have adverse effects on stream temperatures (LeBlanc et al. 1997; Finkenbine 1998), especially when riparian functions are affected (Booth et al. 2001). To protect stream thermal regimes in urban settings, conservation efforts should focus on maintaining riparian functions, mitigating anthropogenic changes to hydrology, and preserving watershed connectivity (e.g., movement of water, sediment, wood, nutrients, and species).

4.4.2. Agriculture

In comparison to urbanization studies, studies of the effects of agricultural practices on riparian ecosystems or subsequent effects on stream thermal regimes are fairly abundant, especially for grazing lands (e.g., Li et al. 1994; Tait et al. 1994; Maloney et al. 1999; Zoellick 2004) and crop lands (e.g., Waite and Carpenter 2000). Studies examining the effects of agriculture, particularly livestock grazing, generally find stream temperature increases associated with disturbance of the riparian ecosystem (Zoellick 2004; Webb et al. 2008). Livestock use of streamside areas can increase a stream's exposure to direct sunlight by reducing shade from streamside vegetation (Li et al. 1994). Livestock can also reduce the amount of undercut banks and increase stream channel width through trampling and vegetation removal (Belsky et al. 1999; Chapter 2). Channel widening can also result in reduced depth, which can exacerbate warming (Poole and Berman 2001). However, results of observational studies are mixed, with occasional absences of predicted detectable increases in stream temperature due to changes in riparian ecosystems as a result of agriculture (e.g., Tait et al. 1994) and wide variation in effect on riparian vegetation among locations and types of agriculture (see Maloney et al. 1999). Importantly, Zoellick (2004) found that riparian vegetation can recover after removal of the disturbance agent (e.g., livestock). For crop lands, the importance of riparian ecosystem attributes, e.g., vegetation width, height and density, on stream temperatures have been documented (Waite and Carpenter 2000) and, similar to grazed lands, effects differ widely among locations (Benedict and Shaw 2012).

Studies of the effects of land management on riparian functions and stream temperatures confirm the importance of riparian ecosystems to stream thermal regimes.

4.4.3. Forestry

Relative to urbanization and agriculture, many studies in the Pacific Northwest have examined the effects of forest management on stream temperatures. Decades of research have frequently documented increased stream temperature due to forestry practices (Olson and Rugger 2007), and our understanding of the mechanisms by which forest practices affect stream temperatures is well developed (Beschta et al. 1987; Groom et al. 2011). Most studies find that forestry, especially when riparian vegetation is disturbed, results in higher stream temperatures than in less disturbed locations (Li et al. 1994), however, exceptions to this pattern are not uncommon. For example, Liquori and Jackson (2001) found stream temperatures 3 to 7°F (1.5 to 4°C) greater in stream reaches surrounded by dense riparian forests compared to downstream reaches

adjacent to scrub-shrub riparian communities. Many of the studies of the effects of forestry on stream temperatures include consideration of some of the components and structures that affect stream thermal regimes identified by Boyd and Kasper (2003) and Poole and Berman (2001). For example, Liquori and Jackson (2001) suggest that their results are due to lower width-to-depth ratio, higher rates of hyporheic or groundwater exchange, and greater amounts of shade in shrub-scrub associated reaches. Maloney et al. (1999) found that much of the variation in their results (in mostly agricultural settings) was explained by reach length, shade, elevation, aspect, and especially by stream gradient and air temperature. Similarly, Kiffney et al. (2003) and Janisch et al. (2012) described the influence of groundwater and hyporheic exchange on their results.

4.4.4. Land Use Summary

Studies of the effects of land management, especially the many studies of forestry, on riparian functions and stream temperatures confirm the importance of riparian ecosystems to stream thermal regimes. Additionally, they emphasize the high degree of variability among locations of the functions that affect stream thermal regimes, even among adjacent stream reaches, that so often produce variable results. Unfortunately, studies that examined the effects of land management on the complete thermal regime of a stream are lacking. Such studies could be especially valuable because the cumulative effects of riparian ecosystem or upland management on stream temperatures can dominate local effects (Chapter 8). Further, most studies use only a few statistics that describe peak or average temperatures, usually during summer. Such statistics are useful, but have limited ability to address dynamic, water quality parameters including temperature (Poole et al. 2004) related to species needs. Thus, predicting the effects of land management on other thermal attributes (e.g., duration or frequency of stressful temperatures) or during other seasons when thermal exposure can significantly affect some species (e.g., overwinter incubation) is difficult. Similarly, even cumulatively, the relatively small number of studies and their skewed geographic distribution (i.e., most are on low-order streams in maritime regions) constrain our ability to provide broad and precise generalizations or make accurate predictions to other locations. Conservation efforts for maintaining stream thermal regimes must be based on our understanding of direct and indirect mechanisms of stream heating affected by human activities, wise use of statistical models relating shade and stream temperature across the watershed until mechanistic models become available, and preserving watershed connectivity (e.g., movement of water, sediment, wood, nutrients, and species).



Light through alder tree canopy/Ned Pittman, WDFW

4.5. Conclusions

Scientific understanding of the structure and function of streams and the importance of thermal regimes has improved substantially since the publication of Knutson and Naef (1997). This understanding underscores the need to consider temperature statistics other than the daily maximum temperature during summer. We now have mechanistic,



Giant salamander (Dicamptodon *spp.*) *egg cluster/Jack Armstrong, WDFW*

deterministic models that can accurately predict changes in stream temperatures for specific locations due to specific management actions in the riparian ecosystem. We are also better able to set directional or qualitative expectations for cumulative effects on temperatures at the spatial extent of watersheds. However, quantitative information needed to run mechanistic, deterministic models to make site-scale predictions (e.g., surface water and groundwater flows and temperatures) is expensive to collect and thus are rarely used in management settings. Further, even the most capable stream temperature predictive models are limited by the assumption that the channel structure remains relatively stable (e.g., cross-section shape will not change) even though there is strong evidence that riparian and some types of upslope management affects channel stability (Chapters 2 and 3) at least in some reach types.

Scientific models and most observational studies find that shade from riparian vegetation can affect stream thermal regimes, particularly by lowering peak temperatures during summer. Recent monitoring studies have found substantial variation in the thermal sensitivity of apparently similar stream reaches. The use of improved monitoring tools (e.g., digital temperature loggers), more robust study designs e.g., Before-After-Control-Impact designs (Eberhardt 1976; Stewart-Oaten et al. 1986), more powerful statistical analyses (Gomi et al. 2006; Isaak et al. 2014), and longer study durations have improved our ability to detect effects of riparian management actions on stream temperatures. Importantly, better understanding of the structure and function of streams, especially the importance of surface, ground, and hyporheic water flows on stream temperatures, has allowed scientists to identify likely causes for failures to detect effects of riparian shade reductions on stream temperatures.

Scientific understanding of the importance of stream temperatures on aquatic species has improved substantially over the past two decades, especially for salmonids. Most studies provide useful descriptions of some direct effects of exposure to high temperatures on specific life stages. Laboratory and field studies demonstrated the importance of temperature on fish survival and allowed for comparisons among species, populations, and life stages, and thus the identification of those that are likely most sensitive to heat stress. They have also demonstrated substantial differences in sensitivity among species, populations, and life stages which make developing simple thermal standards challenging and likely inadequate for management. Several recent studies have described effects of prolonged exposure to elevated, but non-lethal, temperatures and altered thermal regimes. These studies demonstrate some of the complexity of this management challenge. Even when altered thermal regimes do not have immediate lethal effects on species, there are costs or trade-offs, such as changes in growth, survival, productivity, and energetic requirements. Detecting such effects is beyond the scope of most studies and will often require long-term, comprehensive monitoring of populations through several life cycles. Such studies will likely need to be conducted at spatial



Salmon eggs in Morse Creek/Steve Boessow, WDFW

extents and durations that account for fish behavior, such as daily and seasonal movement among locations where temperature regimes differ.

Relatively few studies that describe the effects of temperatures or thermal regimes on reptiles, amphibians or invertebrates have been completed. Most studies of these taxonomic groups have simply identified seasonal thermal preferences in the field or the effects of acute temperature in laboratory settings. Such studies are valuable for identifying thermally sensitive species, but are insufficient for management. Further, we found no study that addressed ecological interactions that might be mediated by riparian condition on a stream's thermal regime.

Studies generally show that the effects of urbanization, agriculture, and forestry on watershed and riparian ecosystems result in warmer summer stream temperatures, an expectation consistent with the conceptual model. Importantly, these land uses often include surface water routing to streams (e.g., roads and ditches) that can change the timing, intensity, duration, and temperatures of stream flows. The changes in temperature detected differed among regions, land uses, and studies. The relatively low number of studies and high variability among study results limits our ability to accurately predict outcomes in unstudied locations and precludes us from reliably calculating a mean (i.e., expected) resulting temperature change, even for a specific temperature statistic. Of the studies we reviewed, most were designed to detect an effect using a specific stream temperature statistic (e.g., mean daily maximum summer temperature) rather than changes in the stream's thermal regime. This limits the inferences that can be made, especially from studies in which anticipated temperature changes were not detected, and to make reliable, precise generalizations from study results.

Although we have sound understanding of the composition, structure, and functions that affect stream thermal regimes, substantial uncertainty remains regarding the effects of any specific riparian management action on stream thermal regimes in most locations. That uncertainty is amplified by our relative lack of understanding at large spatial and long temporal extents for which few studies have been

completed. Recovery of stream temperatures due to shade from vegetation regrowth can occur in less than a decade following disturbance (D'Souza et al. 2011), but recovery rates differ widely among locations due to differences in stream size and components that control rates of vegetation re-establishment and growth (Gecy and Wilson 1990; D'Souza et al. 2011). Although scientists are very certain that temperatures and thermal regimes are important to many aquatic species, relatively little is known about ecological interactions (e.g., predator-prey relations), behaviors (e.g., movement among locations of different temperature), and indirect effects (e.g., effects on the rates and severity of disease). These interactions may be very important. For example, Lawrence et al. (2014) suggest that riparian restoration in some locations might prevent extirpation of Chinook Salmon and restrict the expansion of non-native fish in some locations by maintaining relatively cool stream temperatures. Such uncertainties often compound and should be addressed explicitly when making management decisions, especially when the decisions can have important, lasting effects (Harwood and Stokes 2003). Management of riparian ecosystem composition (e.g., vegetation species, side channels) and structure (e.g., longitudinal and lateral connectivity) can importantly benefit aquatic species. Management for such beneficial effects might prove especially important as our climate continues to change.

The state of the science regarding stream thermal regimes is uneven. On the one hand, we have a very good understanding of the physics of stream heating and cooling. We understand the relative magnitudes of direct and indirect effects of ecosystem changes on stream thermal regimes and have the ability to quantify these effects given enough time and resources. Shade provided by riparian vegetation is generally considered the single most important, albeit not the only, process of the system that humans can directly effect. These findings are undisputed. On the other hand, because thermal regimes are affected by a variety of factors and their interactions, stream temperatures are difficult to precisely predict on the basis on any single factor alone (e.g., shade). Thus, predicting stream temperature based solely on shade removal or buffer width will likely always suffer from imprecision. In addition to this prediction challenge, and despite the fact that we know suitable water temperatures are critical to the persistence of aquatic species, we are only now beginning to understand how aquatic organisms interact with and are impacted by changes in the stream thermal regime. The combination of what we know and do not know about how changes to stream thermal regimes affect aquatic species and how human activities can affect those regimes makes conservation in the face of a changing climate particularly challenging.

4.6. Literature Cited[1]

Abbe, T.B., and D.R. Montgomery. 1996. Large woody debris jams, channel hydraulics and habitat formation in large rivers. Regulated Rivers Research & Management 12:201-221. (i)

Allan, J.D. 2004. Landscapes and riverscapes: the influence of land use on stream ecosystems. Annual Review of Ecology and Systematics 35:257-284. (i)

Allen, M., and L. Dent. 2001. Shade conditions over forested streams in the Blue Mountain and Coast Range georegions of Oregon. ODF Technical Report #13. Oregon Department of Forestry.

Allen, D., W.E. Dietrich, P.F. Baker, F. Ligon, and B. Orr. 2007. Development of a mechanistically-based, basin-scale stream temperature model: applications to cumulative effects modeling. Pages 11-24 *in* R.B. Standiford, G.A. Giusti, Y. Valachovic, W.J. Zielinski, M.J. Furniss, technical editors. Proceedings of the Redwood Region forest science symposium: what does the future hold? PSW-GTR-194. U.S. Forest Service, Pacific Southwest Research Station, Albany, California. (viii)

Alvarez, S.M., J.K. Johnson, and R. Spafford. 2004. Reclamation project allows new phase for Moon

Creek. Land and Water 48:10-15. (i)
Anderson, P.D., D.J. Larson, and S.S. Chan. 2007. Riparian buffer and density management influences on microclimate of young headwater forests of western Oregon. Forest Science 53(2): 254-269.
Arismendi, I., S.L. Johnson, J.B. Dunham, R. Haggerty, and D. Hockman-Wert. 2012. The paradox of cooling streams in a warming world: regional climate trends do not parallel variable local trends in stream temperature in the Pacific Continental United States. Geophysical Research Letters 39:L10401. (i)
Arrigoni, A.S., G.C. Poole, L.A.K. Mertes, S.J. O'Daniel, W.W. Woessner, and S.A. Thomas. 2008. Buffered, lagged, or cooled? Disentangling hyporheic influences on temperature cycles in stream channels. Water Resources Research 44:W09418.
Ayllón D., G.G. Nicola, B. Elvira, I. Parra, and A. Almodóvar. 2013. Thermal carrying capacity for a thermally-sensitive species at the warmest edge of its range. PLoS One 8:e81354. (i)
Baxter, C.V., K.D. Fausch, and W.C. Saunders. 2005. Tangled webs: reciprocal flows of invertebrate prey link streams and riparian zones. Freshwater biology 50:201-220. (i)
Belsky, A. J., A. Matzke, and S. Uselman. 1999. Survey of livestock influences on stream and riparian ecosystems in the western United States. Journal of Soil and Water Conservation 54:419–431. (i)
Benedict, C., and J. Shaw. 2012. Agricultural waterway buffer study. Washington State University Extension, Bellingham, Washington. (viii)
Benyahya L., D. Caissie, N. El-Jabi, and M.G. Satish. 2010. Comparison of microclimate vs. remote meteorological data and results applied to a water temperature model (Miramichi River, Canada). Journal of Hydrology 380:247–259. (i)
Beschta, R.L., R.E. Bilby, G.W. Brown, L.B. Holtby, and T.D. Hofstra. 1987. Stream temperature and aquatic habitat: fisheries and forestry interactions. Pages 191-232 *in* E.O. Salo and T.W. Cundy, editors. Streamside management: forestry and fishery interactions. Contribution No. 57. Institute of Forest Resources, University of Washington, Seattle. (viii)
Bilby, R.E., and P.A. Bisson. 1987. Emigration and production of hatchery Coho Salmon (*Oncorhynchus kisutch*) stocked in streams draining an old-growth and clear-cut watershed. Canadian Journal of Fisheries and Aquatic Sciences 44:1397-1407. (i)
Bisson, P.A., J.M. Buffington, and D.R. Montgomery. 2006. Valley segments, stream reaches, and channel units. Pages 23-49 *in* F.R. Hauer and G.A. Lamberti, editors. Methods in stream ecology. Elsevier, Burlington, Massachusetts. (i)
Bisson, P.A., S.M. Claeson, S.M. Wondzell, A.D. Foster, and A. Steel. 2013. Evaluating headwater stream buffers: lessons learned from watershed-scale experiments in southwest Washington. Pages 165-184 *in* P.D. Anderson and K.L. Ronnenberg, editors. Density management in the 21st Century: west side story. PNW-GTR-880. U.S. Forest Service, Pacific Northwest Research Station, Portland, Oregon. (viii)
Bobba, A.G., P.A. Chambers, and J. Spoelstra. 2010. Environmental impacts in arid and semiarid floodplains. Journal of Environmental Hydrology 18:1-15. (i)
Booth, D.B., J.R. Karr, S. Schauman, C.P. Konrad, S.A. Morley, M.G. Larson, P.C. Henshaw, E.J. Nelson, and S.J. Burges. 2001. Urban stream rehabilitation in the Pacific Northwest. Final report of EPA Grant Number R82-5284-010. University of Washington, Seattle (viii)
Booth, D.B., K.A. Kraseski, and C.R. Jackson. 2014. Local-scale and watershed-scale determinants of summertime urban stream temperatures. Hydrological Processes 28:2427-2438. (i)
Bowler, D.E., R. Mant, H. Orr, D.M. Hannah, and A.S. Pullin. 2012. What are the effects of wooded riparian zones on stream temperature? Environmental Evidence 2012:3-9. (i)
Boyd, M. 1996. Heat source: stream temperature prediction. Master's thesis. Oregon State University, Corvallis, Oregon. (i)
Boyd, M., and B. Kasper. 2003. Analytical methods for dynamic open channel heat and mass transfer:

[1] References are classified according to RCW 34.05.271 (see Appendix 1) denoted by a lower case roman numeral (i – viii) in parentheses at the end of the citation.

methodology for heat source model Version 7.0. Available: https://www.oregon.gov/deq/FilterDocs/heatsourcemanual.pdf. (January 2019). (viii)

Brannon, E.L., M.S. Powell, T.P. Quinn, and A. Talbot 2004. Population structure of Columbia River basin Chinook Salmon and steelhead trout. Reviews in Fisheries Science 12:99–232. (i)

Brattstrom, B.H. 1963. A preliminary review of the thermal requirements of amphibians. Ecology 44:238-255. (i)

Brett, J.R. 1952. Temperature tolerance in young Pacific salmon, genus *Oncorhynchus*. Journal of the Fisheries Research Board of Canada 9:265-323. (i)

Brett, J.R. 1971. Energetic responses of salmon to temperature. A study of some thermal relations in the physiology and freshwater ecology of Sockeye Salmon (*Oncorhynchus nerka*). American Zoologist 11:99–113. (i)

Brett, J.R., J.E. Shelbourn, and C.T. Shoop. 1969. Growth rate and body composition of fingerling Sockeye Salmon, *Oncorhynchus nerka,* in relation to temperature and ration size. Journal of the Fisheries Research Board of Canada 26:2363–2394. (i)

Brown, H.A. 1975. Temperature and the development of the Tailed Frog, *Ascaphus truei.* Comparative Biochemistry and Physiology 50A(2):397-405. (i)

Buffington, J.M., D.R. Montgomery, and H.M. Greenberg. 2004. Basin-scale availability of salmonid spawning gravel as influenced by channel type and hydraulic roughness in mountain catchments. Canadian Journal of Fisheries and Aquatic Sciences 61:2085-2096. (i)

Burkholder, B.K., G.E. Grant, R. Haggerty, T. Khangaonkar, and P.J. Wampler. 2008. Influence of hyporheic flow and geomorphology on temperature of a large, gravel-bed river, Clackamas River, Oregon, USA. Hydrological Processes 22:941-953. (i)

Bury, R.B. 2008. Low thermal tolerances of stream amphibians in the Pacific Northwest: implications for riparian and forest management. Applied Herpetology 5:63-74. (i)

Caissie, D. 2006. The thermal regime of rivers: a review. Freshwater Biology 51:1389–1406. (i)

Caissie, D. 2016. River evaporation, condensation and heat fluxes within a first order tributary of Catamaran Brook (New Brunswick, Canada). Hydrological Processes 30:1872–1883. (i)

Claussen, D.L. 1973. The thermal relations of the Tailed Frog, *Ascaphus truei,* and the Pacific Treefrog, *Hyla regilla*. Comparative Biochemistry and Physiology 44A(1):137-153. (i)

Coffin, C., S. Lee, and D. Garland. 2011. Bear-Evans Watershed temperature, dissolved oxygen and fecal coliform bacteria total maximum daily load: water quality implementation plan. Publication No.11-10-024. Washington Department of Ecology, Bellevue, Washington. (viii)

Cole, E., and M. Newton. 2013. Influence of streamside buffers on stream temperature response following clear-cut harvesting in western Oregon. Canadian Journal of Forest Research 43:993-1005. (i)

Cristea, N.C., and S.J. Burges. 2010. An assessment of the current and future thermal regimes of three streams located in the Wenatchee River basin, Washington State: some implications for regional river basin systems. Climatic Change 2010:493-520. (i)

Cristea, N., and J. Janisch. 2007. Modeling the effects of riparian buffer width on effective shade and stream temperature. Washington Department of Ecology, Olympia. (viii)

Crossin, G.T., S.G. Hinch, S.J. Cooke, D.W. Welch, D.A. Patterson, S.R.M. Jones, A.G. Lotto, R.A. Leggatt, M.T. Mathes, J.M. Shrimpton, G. Van Der Kraak, and A.P. Farrell. 2008. Exposure to high temperatures influences the behavior, physiology, and survival of Sockeye Salmon during spawning migration. Canadian Journal of Zoology 86:127-140. (i)

Czarnomski, N., C. Hale, W.T. Frueh, M. Allen, and J. Groom. 2013. Effectiveness of riparian buffers at protecting stream temperature and shade in Pacific Northwest forests: a systematic review. Final Report to the Forest Practices Monitoring Program. Oregon

Department of Forestry, Salem. (viii)
de Vlaming, V.L., and R.B. Bury. 1970. Thermal selection in tadpoles of the Tailed-Frog, *Ascaphus truei.* Journal of Herpetology 4:179-189. (i)
DeWalle, D.R. 2010. Modeling stream shade: riparian buffer height and density as important as buffer width. Journal of the American Water Resources Association 46:323-333. (i)
D'Souza, L.E., M. Reiter, L.J. Six, and R.E. Bilby. 2011. Response of vegetation, shade and stream temperature to debris torrents in two western Oregon watersheds. Forest Ecology and Management 261:2157-2167. (i)
Dugdale, S.J., N.E. Bergeron, and A. St-Hilaire. 2013. Temporal variability of thermal refuges and water temperature patterns in an Atlantic Salmon river. Remote Sensing of Environment 136:358-373. (i)
Eberhardt, L.L. 1976. Quantitative ecology and impact assessment. Journal of Environmental Management 4:27–70. (i)
Ebersole, J.L., W.J. Liss, and C.A. Frissell. 2003a. Thermal heterogeneity, stream channel morphology, and salmonid abundance in northeastern Oregon streams. Canadian Journal of Fisheries and Aquatic Sciences 60:1266-1280. (i)
Ebersole, J.L., W.J. Liss, and C.A. Frissell. 2003b. Cold water patches in warm streams: physicochemical characteristics and the influence of shading. Journal of the American Water Resources Association 39:355-368. (i)
Eliason, E.J., T.D. Clark, M.J. Hague, L.M. Hanson, Z.S. Gallagher, K.M. Jeffries, M.K. Gale, D.A. Patterson, S.G. Hinch, and A.P. Farrell. 2011. Differences in thermal tolerance among Sockeye Salmon populations. Science 332:109-112. (i)
Elmore, W., and J.B. Kauffman. 1994. Riparian and watershed systems: degradation and restoration. Pages 211-232 *in* M. Vavra, W.A. Laycock, and R.D. Piper, editors. Ecological implications of livestock herbivory in the West. Society of Range Management, Denver, Colorado. (viii)
Farrell, A.P., S.G. Hinch, S.J. Cooke, D.A. Patterson, G.T. Crossin, M. Lapointe, and M.T. Mathes. 2008. Pacific salmon in hot water: applying aerobic scope models and biotelemetry to predict the success of spawning migrations. Physiological and Biochemical Zoology 81:697-709. (i)
Fausch, K.D., C.E. Torgersen, C.V. Baxter, and H.W. Li. 2002. Landscapes to riverscapes: bridging the gap between research and conservation of stream fishes. BioScience 52:1-16. (i)
Finkenbine, J.K., J.W. Atwater, and D.S. Mavinic. 2000. Stream health after urbanization. Journal of the American Water Resources Association 36:1149-1160. (i)
Frissell, C.A., W.J. Liss, C.E. Warren, and M.D. Hurley. 1986. A hierarchical framework for stream habitat classification: viewing streams in a watershed context. Environmental Management 10:199-214. (i)
Fullerton, A.H., C. Torgersen, J.J. Lawler, R.N. Faux, E.A. Steel, T.J. Beechie, J.L. Ebersole, and S.J. Leibowitz. 2015. Rethinking the longitudinal stream temperature paradigm—region-wide comparison of thermal infrared imagery reveals unexpected complexity of river temperatures. Hydrological Processes 29:4719-4737. (i)
Garner, G., I.A. Malcolm, J.P. Sadler, and D.M. Hannah. 2014. What causes cooling water temperature gradients in a forested stream reach? Hydrology and Earth System Sciences 18:5361-5376. (i)
Gecy, J.L., and M.V. Wilson. 1990. Initial establishment of riparian vegetation after disturbance by debris flows in Oregon. American Midland Naturalist 123:282-291. (i)
Gomi, T., R.D. Moore, and A.S. Dhakal. 2006. Headwater stream temperature response to clear-cut harvesting with different riparian treatments, coastal British Columbia, Canada. Water Resources Research

42: W08437.
Gomi, T., R.C. Sidle, and D.N. Swanston. 2004. Hydrogeomorphic linkages of sediment transport in headwater streams, Maybeso Experimental Forest, southeast Alaska. Hydrological Processes 18:667-667. (i)
Gregory, S.V., F.J. Swanson, W.A. McKee, and K.W. Cummins. 1991. An ecosystem perspective of riparian zones. BioScience 41:540-551. (i)
Groom, J.D., L. Dent, and J. Madsen. 2011. Stream temperature change detection for state and private forests in the Oregon Coast Range. Water Resources Research 47:1-12. (i)
Groot, C., and L. Margolis. 2010. Pacific salmon life histories. University of Washington Press, Seattle. (i)
Hari, R.E., D.M. Livingston, R. Siber, P. Burkhardt-Holm, and H. Guttinger. 2006. Consequences of climate change for water temperature and brown trout populations in alpine rivers and streams. Global Change Biology 12:10-26. (i)
Harwood, J., and K. Stokes. 2003. Coping with uncertainty in ecological advice: lessons from fisheries. Trends in Ecology and Evolution 18:617–622. (i)
Hawkins, C.P., M.L. Murphy, N.H. Anderson, and M.A. Wilzbach. 1983. Density of fish and salamanders in relation to riparian canopy and physical habitat in streams of the northwestern United States. Canadian Journal of Fisheries and Aquatic Sciences 40:1173-1185. (i)
Hendry, A.P., J.E. Hensleigh, and R.R. Reisenbichler. 1998. Incubation temperature, developmental biology, and the divergence of Sockeye Salmon (*Oncorhynchus nerka*) within Lake Washington. Canadian Journal of Fisheries and Aquatic Sciences 55:1387–1394. (i)
Hester, E.T., and M.W. Doyle. 2011. Human impacts to river temperature and their effects on biological processes: a quantitative synthesis. Journal of the American Water Resources Association 47:571–587. (i)
Hinch, S.G., S.J. Cooke, A.P. Farrell, K.M. Miller, M. LaPointe, and D.A. Patterson. 2012. Dead fish swimming: a review of research on the early migration and high premature mortality in adult Fraser River Sockeye Salmon (*Oncorhynchus nerka*). Journal of Fish Biology 81:576-599. (i)
Hodgson, S., and T.P. Quinn. 2002. The timing of adult Sockeye Salmon migration into fresh water: adaptations by populations to prevailing thermal regimes. Canadian Journal of Zoology 80:542-555. (i)
Hogg, I.D., and D.D. Williams. 1996. Response of stream invertebrates to a global-warming thermal regime: an ecosystem-level manipulation. Ecology 77:395-407. (i)
Holland, D.C. 1994. The Western Pond Turtle: habitat and history. Unpublished final report, U. S. Dept. of Energy, Portland, Oregon. (viii)
Holsinger, L., R.E. Keane, D.J. Isaak, L. Eby, and M.K. Young. 2014. Relative effects of climate change and wildfires on stream temperatures: a simulation modeling approach in a Rocky Mountain watershed. Climate Change 124:191-206. (i)
Isaak, D.J., and W.A. Hubert. 2001. A hypothesis about factors that affect maximum summer stream temperatures across montane landscapes. Journal of the American Water Resources Association 37:351-366. (i)
Isaak, D.J., and W.A. Hubert. 2004. Nonlinear response of trout abundance to summer stream temperatures across a thermally diverse montane landscape. Transactions of the American Fisheries Society 133:1254-1259. (i)
Isaak, D.J., C.H. Luce, B.B. Rieman, D.E. Nagel, E.E. Peterson, D.L. Horan, S. Parkes, and G.L. Chandler. 2010. Effects of climate change and wildfire on stream temperatures and salmonid thermal habitat in a mountain river network. Ecological

Applications 20:1350-1371. (i)
Isaak, D.J., E.E. Peterson, J.M. Ver Hoef, S.J. Wenger, J.A. Falke, C. Torgersen, C. Sowder, E.A. Steel, M. Fortin, C.E. Jordan, A.S. Ruesch, N. Som, and P. Monestiez. 2014. Applications of spatial statistical network models to stream data. Wiley Interdisciplinary Reviews–Water 1:277-294. (i)
Isaak, D., S. Wenger, E. Peterson, J. Ver Hoef, D. Nagel, C. Luce, S. Hostetler, J. Dunham, B. Roper, S. Wollrab, G. Chandler, D. Horan, and S. Parkes-Payne. 2017a. The NorWeST summer stream temperature model and scenarios for the western U.S.: a crowd-sourced database and new geospatial tools foster a user community and predict broad climate warming of rivers and streams. Water Resources Research 53:9181-9205. (i)
Isaak, D.J., S.J. Wenger, and M.K. Young. 2017b. Big biology meets microclimatology: defining thermal niches of ectotherms at landscape scales for conservation planning. Ecological Applications 27:977–990. (i)
Isaak, D.J., S. Wollrab, D. Horan, and G. Chandler. 2012. Climate change effects on stream and river temperatures across the Northwest U.S. from 1980–2009 and implications for salmonid fishes. Climatic Change 113:499-524. (i)
Isaak, D.J., M.K. Young, D. Nagel, D. Horan, and M. Groce. 2015. The coldwater climate shield: delineating refugia to preserve salmonid fishes through the 21st Century. Global Change Biology 21:2540-2553. (i)
Jackson, C.R., C.A. Sturm, and J.M. Ward. 2001. Timber harvest impacts on small headwater stream channels in the coast ranges of Washington. Journal of the American Water Resources Association 37:1533–1549.
Janisch, J.E., S.M. Wondzell, and W. J. Ehinger. 2012. Headwater stream temperature: interpreting response after logging, with and without riparian buffers, Washington, USA. Forest Ecology and Management 270:302-313. (i)
Johnson, F.A. 1971. Stream temperatures in an alpine area. Journal of Hydrology 14:322-336. (i)
Johnson, S.L. 2004. Factors influencing stream temperatures in small streams: substrate effects and a shading experiment. Canadian Journal of Fisheries and Aquatic Sciences 61:913-923. (i)
Kappenman, K.M., M.A.H. Webb, and M. Greenwood. 2013. The effect of temperature on embryo survival and development in Pallid Sturgeon *Scaphirhynchus albus* (Forbes & Richardson 1905) and Shovelnose Sturgeon *S. platorynchus* (Rafinesque, 1820). Journal of Applied Ichthyology 29:1193-1203. (i)
Keefer, M.L., C.A. Peery, and M.J. Heinrich. 2008. Temperature-mediated en route migration mortality and travel rates of endangered Snake River Sockeye Salmon. Ecology of Freshwater Fish 17:136–145. (i)
Keller, E.A., and F.J. Swanson. 1979. Effects of large organic material on channel form and fluvial processes. Earth Surface Processes 4:361-380. (i)
Kibler, K.M., A. Skaugset, L.M. Ganio, and M.M. Huso. 2013. Effects of contemporary forest harvesting practices on headwater stream temperatures: initial response of the Hinkle Creek catchment, Pacific Northwest, USA. Forest Ecology and Management 310:680-691. (i)
Kiffney, P.M., J.S. Richardson, and J.P. Bull. 2003. Responses of periphyton and insect consumers to experimental manipulation of riparian buffer width along headwater streams. Journal of the American Water Resources Association 40:1060-1076. (i)
Kinouchi, T., H. Yagi, and M. Miyamoto. 2006. Increase in stream temperature related to anthropogenic heat input from urban wastewater. Journal of Hydrology 335:78–88. (i)
Knutson, K.L., and V.L. Naef. 1997. Management recommendations for Washington's priority habitats: riparian. Washington Department of Fish and Wildlife,

Olympia, Washington. (iii)
Konrad, C.P., D.B. Booth, and S.J. Burges. 2005. Effects of urban development in the Puget Lowland, Washington, on interannual streamflow patterns: consequences for channel form and streambed disturbance. Water Resources Research 41:W07009. (i)
Lawrence, D.J., B. Stewart-Koster, J.D. Olden, A.S. Ruesch, C.E. Torgersen, J.J. Lawler, D.P. Butcher, and J.K. Crown. 2014. The interactive effects of climate change, riparian management, and a nonnative predator on stream-rearing salmon. Ecological Applications 24:895-912. (i)
LeBlanc, R.T., R.D. Brown, and J.E. FitzGibbon. 1997. Modeling the effects of land use change on the water temperature in unregulated urban streams. Journal of Environmental Management 49:445–469. (i)
Leinenbach, P., G. McFadden, and C. Torgersen. 2013. Effects of riparian management strategies on stream temperature, Part II. Summary report of the Science Review Team submitted to the Interagency Coordinating Subcommittee. Bureau of Land Management, Portland, Oregon. (viii)
Li, H.W., G.A. Lamberti, T.N. Pearsons, C.K. Tait, and J.C. Buckhouse. 1994. Cumulative effects of riparian disturbances along high desert trout streams of the John Day Basin, Oregon. Transactions of the American Fisheries Society 123:627–640. (i)
Li, J.L., S.L. Johnson, and J.B. Sobota. 2011. Three responses to small changes in stream temperature by autumn-emerging aquatic insects. Journal of the North American Benthological Society 30:474-484. (i)
Licht, L.E. 1971. Breeding habits and embryonic thermal requirements of the frogs, *Rana aurora aurora* and *Rana pretiosa pretiosa*, in the Pacific Northwest. Ecology 52:116–124. (i)
Liquori, M., and C.R. Jackson. 2001. Channel response from shrub dominated riparian communities and associated effects on salmonid habitat. Journal of the American Water Resources Association 37:1639–1651. (i)
Luce, C.H., B.P. Staab, M.G. Kramer, S.J., D.J. Isaak, and C. McConnell. 2014. Sensitivity of summer stream temperatures to climate variability in the Pacific Northwest. Water Resources Research 50:1-16. (i)
Lytle, D.A., and N.L. Poff. 2004. Adaptation to natural flow regimes. Trends in Ecology and Evolution 19:94-100. (i)
Malard, F., K. Tockner, M. Dole-Olivier, and J.V. Ward. 2002. A landscape perspective of surface-subsurface hydrological exchanges in river corridors. Freshwater Biology 47:621-640. (i)
Malcolm, I.A., C. Soulsby, and A.F. Youngson. 2002. Thermal regime in the hyporheic zone of two contrasting salmonid spawning streams: ecological and hydrological implications. Fisheries Management and Ecology 9:1-10. (i)
Maloney, S.B., A.R. Tiedemann, D.A. Higgins, T.M. Quigley, and D.B. Marx. 1999. Influence of stream characteristics and grazing intensity on stream temperatures in eastern Oregon. PNW-GTR-459. U.S. Forest Service, Pacific Northwest Research Station, Portland, Oregon. (viii)
Marsh, P.C. 1985. Effect of incubation temperature on survival of embryos of native Colorado River fishes. The Southwestern Naturalist 30:129-140. (i)
May, C.W. 2003. Stream-riparian ecosystems in the Puget Sound lowland ecoregions: a review of best available science. Watershed Ecology, LLC, Poulsbo, Washington. (i)
McCullough, D.A. 1999. A review and synthesis of effects of alterations to the water temperature regime of freshwater life stages of salmonids, with special reference to Chinook Salmon. U.S. Environmental Protection Agency, Region 10, Seattle,

Washington. (viii)
McCullough, D.A., J.M. Bartholow, H.I. Jager, R.L. Beschta, E.F. Cheslak, M.L. Deas, J.L. Ebersole, J.S. Foote, S.L. Johnson, K.R. Marine, M.G. Mesa, J.H. Petersen, Y. Souchon, K.F. Tiffan, and D.A. Wurtsbaugh. 2009. Research in thermal biology: burning questions for coldwater stream fishes. Reviews in Fisheries Science 17:90-115. (i)
McCullough, D., S. Spalding, D. Sturdevant, and M. Hicks. 2001. Issue Paper 5. Summary of technical literature examining the physiological effects of temperature on salmonids. EPA-910-D-01-005. U.S. Environmental Protection Agency, Region 10, Seattle, Washington. (viii)
Micheli, E.R., and J.W. Kirchner. 2002. Effects of wet meadow riparian vegetation on streambank erosion. 2. Measurements of vegetated bank strength and consequences for failure mechanics. Earth Surface Processes and Landforms 27:687-697. (i)
Moore, R.D., D.L. Spittlehouse, and A. Story. 2005. Riparian microclimate and stream temperature response to forest harvesting: a review. Journal of the American Water Resources Association 41:813-834. (i)
Moulton, S.R., T.L. Beitinger, K.W. Stewart, and R.J. Currie. 1993. Upper temperature tolerance of four species of caddisflies (Insecta: Trichoptera). Journal of Freshwater Ecology 8:193–198. (i)
Murphy, M.L., and J.D. Hall. 1981. Varied effects of clear-cut logging on predators and their habitat in small streams in the Cascade Mountains, Oregon. Canadian Journal of Fisheries and Aquatic Sciences 38:137-145. (i)
Murphy, M.L., C.P. Hawkins, and N.H. Anderson. 1981. Effects of canopy modification and accumulated sediment on stream communities. Transactions of the American Fisheries Society 110:469-478. (i)
NRC (National Research Council). 2002. Riparian areas: functions and strategies for management. National Academy Press, Washington, D.C. (i)
Nyberg, L., O. Calles, and L. Greenberg. 2008. Impact of short-term regulation on hyporheic water quality in a boreal river. River Research and Applications 24:407-419. (i)
Olden, J.D., and R.J. Naiman. 2010. Incorporating thermal regimes into environmental flows assessments: modifying dam operations to restore freshwater ecosystem integrity. Freshwater Biology 55:86-107. (i)
Olson, D.H., and C. Rugger. 2007. Preliminary study of the effects of headwater riparian reserves with upslope thinning on stream habitats and amphibians in western Oregon. Forest Science 53:331-342. (i)
Paul, M.J., and J.L. Meyer. 2001. Streams in the urban landscape. Annual Review of Ecology and Systematics 32:333–365. (i)
Pollett, K.L., J.G. MacCracken, and J.A. MacMahon. 2010. Stream buffers ameliorate the effects of timber harvest on amphibians in the Cascade Range of southern Washington, USA. Forest Ecology and Management 260:1083-1087. (i)
Poole, G.C., and C.H. Berman. 2001. An ecological perspective on in-stream temperature: natural heat dynamics and mechanisms of human-caused thermal degradation. Environmental Management 27:787-802. (i)
Poole, G.C., J.B. Dunham, D.M. Keenan, S.T. Sauter, D.A. McCullough, C. Mebane, J.C. Lockwood, D.A. Essig, M.P. Hicks, D.J. Sturdevant, E.J. Materna, S.A. Spalding, J. Risley, and M. Deppman. 2004. The case for regime-based water quality standards. BioScience 54:155-161. (i)
Poole, G., J. Risley, and M. Hicks. 2001. Issue paper 3: spatial and temporal patterns of stream temperature (revised). EPA-910-D-01-003. U.S. Environmental Protection Agency, Region 10, Seattle, Washington. (viii)
Post, D.M., E.P. Palkovacs, E.G. Schielke, and S.I. Dodson. 2008. Interspecific variation in a predator affects community structure and cascading trophic interactions. Ecology 98:2019–2032. (i)
Pringle, C.M., and F.J. Triska. 2000. Emergent biological patterns in streams resulting from surface-subsurface water interactions at landscape scales. Pages 167-193 *in* J.B. Jones and P.J. Mulholland, editors. Streams and groundwaters. Elsevier, Burlington, Massachusetts. (i)

Reeves, G.H., D.H. Olson, S.M. Wondzell, P.A. Bisson, S. Gordon, S.A. Miller, J.W. Long, and M.J. Furniss. 2018. Chapter 7: The Aquatic Conservation Strategy of the Northwest Forest Plan–a review of the relevant science after 23 years. Pages 461-642 *in* T.A. Spies, P.A. Stine, R. Gravenmier, J.W. Long, and M.J. Reilly, technical coordinators. Synthesis of science to inform land management within the Northwest Forest Plan area. PNW-GTR-966. U.S. Forest Service, Pacific Northwest Research Station, Portland, Oregon. (viii)

Rezende E.L., L.E. Castañeda, and M. Santos. 2014. Tolerance landscapes in thermal ecology. Functional Ecology 28:799–809. (i)

Richter, A., and S.A. Kolmes. 2005. Maximum temperature limits for Chinook, Coho, and Chum Salmon, and steelhead trout in the Pacific Northwest. Reviews in Fisheries Science 13:23–49. (i)

Rykken, J.J., S.C. Chan, and A.R. Moldenke. 2007. Headwater riparian microclimate patterns under alternative forest management treatments. Forest Science 53:270-280. (i)

Sather, N.K., and C.W. May. 2007. Riparian buffer zones in the interior Columbia River Basin: a review of best available science. Battelle Memorial Institute, Marine Sciences Laboratory, Sequim, Washington. (viii)

Sauter, S.T., L.I. Cershaw, and A.G. Maule. 2001. Behavioral thermoregulation by juvenile spring and fall Chinook Salmon, *Oncorhynchus tshawytscha*, during smoltification. Environmental Biology of Fishes 61:295–304. (i)

Sauter, S.T., and P.J. Connolly. 2010. Growth, condition factor, and bioenergetics modeling link warmer stream temperatures below a small dam to reduced performance of juvenile steelhead. Northwest Science 84:369-377. (i)

Schuett-Hames, D., A. Roorbach, and R. Conrad. 2012. Results of the westside type N buffer characterization, integrity and function study final report. Cooperative Monitoring Evaluation and Research Report, CMER 12-1201. Washington Department of Natural Resources, Olympia.

Sinokrot, B.A., and H.G. Stefan. 1993. Stream temperature dynamics: measurements and modeling. Water Resources Research 29:2299-2312. (i)

Sridhar,V., A.L. Sansone, J. Lamarche, T. Dubin, and D.P. Lettenmaier. 2004. Prediction of stream temperature in forested watersheds. Journal of the American Water Resources Association 40:197-213. (i)

Stanford, J.A. 1998. Rivers in the landscape: introduction to the special issues on riparian and groundwater ecology. Freshwater Biology 40:402-406. (i)

Steel, E.A., A. Tillotson, D.A. Larsen, A. Fullerton, K.P. Denton, and B.R. Beckman. 2012. Beyond the mean: the role of variability in predicting ecological effects of stream temperatures on salmon. Ecosphere 3:104 (i)

Stewart-Oaten, A., W.W. Murdoch, and K.R. Parker. 1986. Environmental impact assessment: pseudoreplication in time? Ecology 67:929–940. (i)

Stoddard, M.A., and J.P. Hayes. 2005. The influence of forest management on headwater stream amphibians at multiple spatial scales. Ecological Applications 15:811-823. (i)

Story, A., R.D. Moore, and J.S. Macdonald. 2003. Stream temperatures in two shaded reaches below cutblocks and logging roads: downstream cooling linked to subsurface hydrology. Canadian Journal of Forest Research 33:1383-1396. (i)

Strange, J.S. 2010. Upper thermal limits to migration in adult Chinook Salmon: evidence from the Klamath River basin. Transactions of the American Fisheries Society 139:1091-1108. (i)

Sweeney, B.W., and J.D. Newbold. 2014. Streamside forest buffer width needed to protect stream water quality, habitat, and organisms: a literature review. Journal of the American Water Resources Association 50:560-584. (i)

Tait, C.K., J.L. Li, G.A. Lamberti, T.N. Pearsons, and H.W. Li. 1994. Relationships between riparian cover and the community structure of high desert streams. Journal of the North American Benthological Society 13:45–56. (i)

Toledo, Z.O., and J.B. Kauffman. 2001. Root biomass in relation to channel morphology of headwater streams. Journal of the American Water Resources Association 37:1653-1663. (i)

Torgersen, C.E., R. Faux, B.A. McIntosh, N. Poage, and D.J. Norton. 2001. Airborne thermal remote sensing for water temperature assessment in rivers and streams. Remote Sensing of Environment 76:386-398. (i)

Torgersen, C.E., D.M. Price, H.W. Li, and B.A. McIntosh. 1999. Multiscale thermal refugia and stream habitat associations of Chinook Salmon in northwestern Oregon. Ecological Applications 9:301-319. (i)

USEPA 2012. Technical memorandum to the Idaho Department of (state) Lands (IDL) Private Lands Forest Practices Act (FPA) Shade Subcommittee. Available: ftp://ftp.epa.gov/ reg10ftp/forestry/. (June 2015). (viii)

Ver Hoef, J.M., E.E. Peterson, and D. Theobald. 2006. Spatial statistical models that use flow and stream distance. Environmental and Ecological Statistics 13:449–464. (i)

Wahl, C.M., A. Neils, and D. Hooper. 2013. Impacts of land use at the catchment scale constrain the habitat benefits of stream riparian buffers. Freshwater Biology 58:2310–2324. (i)

Waite, I.R., and K.D. Carpenter. 2000. Associations among fish assemblage structure and environmental variables in Willamette Basin streams, Oregon. Transactions of the American Fisheries Society 129:754–770. (i)

Ward, J.V., F. Malard, and K. Tockner. 2002. Landscape ecology: a framework for integrating pattern and process in river corridors. Landscape Ecology 17(Supplement 1):35–45. (i)

Ward, J.V., and J.A. Stanford. 1982. Thermal responses in the evolutionary ecology of aquatic insects. Annual Review of Entomology 27:97-117. (i)

Ward, J.V., and J.A. Stanford. 1995. Ecological connectivity in alluvial river ecosystems and its disruption by flow regulation. Regulated Rivers: Research & Management 11:105-119. (i)

Webb, B.W., D.M. Hannah, R.D. Moore, L.E. Brown, and F. Nobilis. 2008. Recent advances in stream and river temperature research. Hydrological Processes 22:902–918. (i)

Weitkamp, L.A., D.J. Teel, M. Liermann, S.A. Hinton, D.M. Van Doornik, and P.J. Bentley. 2015. Stock-specific size and timing at ocean entry of Columbia River juvenile Chinook Salmon and steelhead: implications for early ocean growth. Marine and Coastal Fisheries: Dynamics, Management, and Ecosystem Science 7:370-392. (i)

Welsh, H.H. 1990. Relictual amphibians and old-growth forests. Conservation Biology 4:309-319. (i)

Welsh, H.H., Jr., G R. Hodgson, B.C. Harvey, and M.E. Roche. 2001. Distribution of juvenile Coho Salmon in relation to water temperatures in tributaries of the Mattole River, California. North American Journal of Fisheries Management 21:464-470. (i)

Welsh, H.H., Jr., and A.J. Lind. 1996. Habitat correlates of the Southern Torrent Salamander, *Rhyacotriton variegatus* (Caudata: Rhyacotritonidae), in northwestern California. Journal of Herpetology 30:385-398. (i)

Wiens, J.A. 2002. Riverine landscapes: taking landscape ecology into the water. Freshwater Biology 47:501–515. (i)

Winder, M., and D.E. Schindler. 2004. Climate change uncouples trophic interactions in an aquatic ecosystem. Ecology 85:2100–2106. (i)

Wondzell, S.M. 2012. Hyporheic zones in mountain streams: physical processes and ecosystem functions. Stream Notes (Jan. - Apr.):1-10. Stream Systems Technology Center, Rocky Mountain Research Station, Fort Collins, Colorado. (i)

Wondzell, S.M., and M.N. Gooseff. 2013. Geomorphic controls on hyporheic exchange across scales: watersheds to particles. Pages 203-218 *in* J. Shroder, editor-in-chief, and E. Wolh, editor. Treatise on Geomorphology. Academic Press, San Diego, California.

Wright, K.K., C.V. Baxter, and J.L. Li. 2005. Restricted hyporheic exchange in an alluvial river system: implications for theory and management. Journal of the North American Benthological Society 24:447-460. (i)

Zaugg, W.S., and H.H. Wagner. 1973. Gill ATPase activity related to parr-smolt transformation and migration in steelhead trout (*Salmo gairdneri*): influence of photoperiod and temperature. Comparative Biochemistry and Physiology 45:955-965. (i)

Zoellick, B.W. 2004. Density and biomass of redband trout relative to stream shading and temperature in southwestern Idaho. Western North American Naturalist 64:18–26. (i)



Long-toed salamander Ambystoma macrodactylum/*Scott Fitkin, WDFW*

Chapter 5. Pollutant Removal

By: Jeffrey L. Ullman and George F. Wilhere

5.1. Introduction

The capability of riparian areas to remove certain pollutants from runoff has been known to scientists for over 60 years (e.g., Trimble and Sartz 1957). Understanding the complex processes and associated factors that affect the pollutant removal function of riparian areas is essential for developing management strategies that will protect aquatic ecosystems. Management of riparian areas for pollutant removal differs from the other ecological functions discussed in this document in that the primary focus is on mitigating activities occurring outside the riparian area. The pollutant removal function is unique in that it only exists in the presence of human activities that generate polluted water, and it is only necessary when runoff from upland activities threaten to degrade water quality.

This chapter summarizes key information relevant to riparian pollutant removal function. First, a general background is presented on the main processes and related site-level factors affecting the transport and fate of nonpoint source pollutants in riparian areas. Next, the biological impacts, common sources, *in situ* chemistry, transport pathways, and mitigation are reviewed for five types of pollutants—sediments, excess nutrients, metals, pesticides and other organic compounds, and pathogens. Last, a summary of what is currently known about the relationships between riparian buffer width and pollutant removal is provided. Riparian buffer is not synonymous with riparian area. Riparian area is an ecological designation that is synonymous with riparian ecosystem (see Chapter 1). Riparian buffer is a management designation, and a buffer may be narrower or wider than the riparian ecosystem.



Yellowjacket Creek/George Fornes, WDFW

This chapter only addresses nonpoint-source chemical pollutants that interact with riparian areas. Hence, it does not deal with "thermal pollution" effects on water temperature (see Chapter 4), which is another important water quality parameter. Similarly, it does not deal with pollutants routed via roads, ditches, and drains into urban and suburban stormwater runoff systems, or with polluted water routed to rivers and streams via agricultural tile drainage.

While the scientific literature reviewed here includes information collected during the 1970s and 1980s, when scientists first started to rigorously investigate the removal of pollutants by riparian areas (Correll 1997), more recent findings are highlighted. Decades of research have revealed that the ecosystem structures and processes responsible for pollutant removal functions of riparian areas are complex, spatially and temporally variable, and dependent on site-level environmental conditions. This complexity and variability are the main reasons for inconsistent results found in the published research and the lack of definitive recommendations regarding the structure and size of riparian buffers required for pollutant removal. Nevertheless, general trends in research findings can guide policy makers and resource managers to management strategies that address these uncertainties and lead to adequate protection of water quality.

5.2. The Pollutant Removal Function of Riparian Areas

Water quality refers to the physical, chemical, and biological characteristics of water that indicate a waterbody's suitability to meet human needs or habitat requirements for fish and wildlife. Riparian areas exert a significant influence on water quality due to their position between terrestrial and aquatic ecosystems. Pollutants in dissolved, chemical, or suspended solid forms are transported by water from uplands to surface waterbodies, and while passing through riparian areas contaminated water undergoes a variety of physical, chemical, and biological processes that reduce pollutant concentrations. The processes in riparian areas affecting pollutant transport and fate are complex and often interrelated. Riparian areas slow surface runoff and increase infiltration of water into the soil, thereby enhancing both deposition of solids and filtration of water-borne pollutants. Riparian areas also intercept and act on contaminants in subsurface flow through dilution, sorption[1], physical transformation, chemical degradation, or volatilization by various biogeochemical processes and through uptake and assimilation by plants, fungi, and microbes.

There is overwhelming evidence in the scientific literature that riparian buffers reduce nonpoint source water pollution for a variety of pollutants—including sediments, excess nutrients, metals, organic compounds such as pesticides, and pathogens. Management activities can enhance the physical, chemical, and biological mechanisms that reduce the flow of polluted waters to river and streams.

1 Sorption or "to sorb" is a physical and chemical process by which one substance becomes attached to another. It encompasses two processes adsorption and absorption. Adsorption is the binding of molecules or particles to a substance's surface. The reverse of adsorption is desorption. Absorption is the filling of minute pores in a substance by molecules or particles.



Riparian buffer widths for pollution removal need not be one-size-fits-all/U.S. Dept. of Agriculture, National Agriculture Imagery Program

However, the science is very clear that results vary considerably depending on local conditions, and that the configuration of a riparian buffer may effectively remove one type of pollutant while having minimal effect on another. Although riparian management can reduce significantly the quantity of pollutants entering surface waters, riparian areas are not sufficient by themselves to fully mitigate pollution from nonpoint sources. Thus, it is critical to view pollution control from a holistic, watershed perspective that also manages contaminated runoff at its source, i.e., upland areas subjected to various intensive land uses: forestry, agriculture, commercial, and urban, suburban, and rural residential. Nevertheless, maintaining functional riparian areas is essential for reducing nonpoint source pollution and must be a key component in any suite of management actions focused on water quality.

5.3. Processes Influencing the Pollutant Removal Function

Riparian areas are consistently shown to remove a variety of nonpoint source pollutants, such as those originating from agricultural lands, urban areas, construction sites, and forestry operations. However, the effectiveness of riparian buffers is highly variable (Hickey and Doran 2004; Lee et al. 2004, Anbumozhi et al. 2005; Zhang et al. 2010). Inconsistencies among research results can be explained by the multi-dimensional heterogeneity of riparian ecosystems; the complex, interconnected processes that act on contaminant transport and fate; and the variety of research methods employed. Many site-specific factors contribute to this variability,

including riparian buffer width, slope, topography, surface and subsurface hydrology, soil properties, riparian vegetation, and adjacent upland characteristics. Of all these factors hydrology, soil, and vegetation play dominant roles governing pollutant transport and fate (NRC 2002). The following sections discuss the effects of these three site-level characteristics on the pollutant removal function of riparian areas.

5.3.1. Hydrology

Hydrologic regimes at the terrestrial-aquatic interface impart a particularly significant influence on the attenuation of pollutants by riparian areas. Three principal pathways govern water movement through these systems: 1) overland flow and shallow subsurface flow from adjacent uplands, 2) groundwater flow, and 3) instream water movement that includes hyporheic exchange as well as flood conditions (NRC 2002). Each of these flow paths can act as conduits for pollutant transport to aquatic ecosystems depending on site-specific conditions and pollutant type. Furthermore, seasonal stream flows, fluctuating water tables, and intermittent flooding create a dynamic environment that subjects pollutants to a range of biogeochemical processes.

Upland sources of water often originate as precipitation. During and immediately after a precipitation event, water from upland areas follows different flow paths to the stream channel, each contributing differently to pollutant transport and fate. Overland flow can be either infiltration-excess[2] (Hortonian overland flow) or saturation-excess[3] overland flow. Water that enters the soil profile can also travel downslope in shallow subsurface flow (interflow) through the unsaturated zone[4]. Depending on site-specific conditions, water in one of these flow paths may switch to another.

Collectively these flow paths are commonly termed hillslope runoff. Under certain circumstances, such as in the presence of deep, well-drained soils that facilitate percolation, portions of the shallow subsurface flow can reach the groundwater table and resume transport in the groundwater system. These pathways extend into riparian areas before reaching a surface waterbody.

As overland flow travels through the landscape it can pick up pollutants that can be in either particulate or soluble form. When water infiltrates the soil surface, suspended particulate matter and associated contaminants are entrapped at the soil surface, almost exclusively limiting the form of pollutants that are transported through the subsurface to soluble forms that remain in solution. However, recent research highlights the significance of colloid-facilitated transport as an additional means by which contaminants can move through the subsurface (Sen and Khilar 2006; Bradford and Torkzaban 2008). Colloidal forms (particles ranging from 1 to 1,000 nm) can remain dispersed in solution and exhibit characteristics resembling solutions. This behavior can consequently mobilize substances that tend to sorb to soil particles or organic matter that would otherwise not be able to move through the subsurface. While the fundamental physics and chemistry of this mechanism is understood, the contribution of colloids to pollutant migration through the soil profile is unresolved. Essentially no literature exists on the role of colloids in riparian areas, contributing to uncertainty in predicting the ultimate fate of associated pollutants.

The fundamental variables of interest regarding groundwater are flow rate and travel time, which influence natural chemical and biological processes that remove soluble pollutants, such as sorption to soils, microbial degradation, and plant uptake (Vogt et al.

2 Infiltration-excess overland flow occurs when water enters a soil system faster than the soil can absorb or transport it, such as when precipitation exceeds the infiltration capacity of the soil.

3 Saturation-excess overland flow occurs when the soil becomes saturated, and any additional precipitation results in runoff.

4 The unsaturated zone is also known as the vadose zone. It extends from the ground surface to the water table. Beneath the water table is the zone of saturation.

2012). As groundwater approaches the stream margin biogeochemical activity increases, and this gradient contributes to temporal and spatial variability in solute fluxes (Hayashi and Rosenberry 2002). It should be noted that groundwater exhibits a different geochemical composition than shallow subsurface flow that originates from precipitation events. Groundwater samples typically have a greater specific conductance (related to salinity), higher mineral content and elevated pH (Landmeyer 2011). Differences in chemical composition and biogeochemical activity are likely to manifest differences in pollutant removal from groundwater.

The hyporheic zone is the region beneath and alongside the streambed that represents the groundwater-surface water interface. While hydrologists have a solid understanding of most other hydrologic processes occurring in riparian areas, understanding of the exchanges between groundwater and in-channel surface waters is considerably less (UKEA 2009; Gu et al. 2012). Hyporheic flow patterns are multifaceted and influenced by the pressure gradient at the stream margin, (micro)morphology of the channel, the spatial distribution of hydraulic conductivity along the streambank, and the water exchange rate between the river and the riparian area (Kalbus et al. 2009; Lewandowski 2011). The complexity of the hydrologic regime is further compounded by seasonal variations, and at times intra-seasonal oscillations, in the direction of water flow (Wroblicky et al. 1998), as well as instances where ambient movement of deeper groundwater flows near the interface. Despite the confounding nature of the hyporheic zone, it is vital to consider hyporheic exchange when discussing subsurface fluxes of pollutants, as this zone is a direct link to streams through which contaminants can be transported to lotic systems (Gordon et al. 2004).

As groundwater approaches a streambank, biogeochemical activity increases. Groundwater flow rate and travel time through the riparian area influence natural chemical and biological processes that remove soluble pollutants.

Not only does the hyporheic zone play a critical role in regulating pollutant fluxes from riparian areas to the adjacent lotic environment, the heterogeneous structure at the interface, an oscillating water table, and shifting flow regimes exert a significant influence on biogeochemical cycling. The fluctuating water table alters oxygen concentrations and oxidation-reduction (redox) potential, and the flow regime provides a continuous source of reactants. This dynamic environment allows for anaerobic and aerobic processes to occur simultaneously and in close proximity (Wang et al. 2014). The strong hydraulic and biogeochemical gradients that result from mixing of the subsurface water coming from riparian areas and the surface water of the stream channel create biogeochemical hot spots that exhibit disproportionately high reaction rates compared to the surrounding matrix (McClain et al. 2003). For instance, the convergence of shallow subsurface flow and groundwater at the stream interface can generate hot spots of denitrification. Similarly, hot moments represent brief periods of elevated reaction rates relative to longer periods (e.g., during a rainfall event). Later sections of this chapter discuss this concept in more detail.

5.3.2. Soils

Soils play a critical role in influencing the transport and fate of pollutants in riparian areas. Soil texture and structure act as primary hydrologic regulators, significantly influencing the movement and distribution of contaminants. Comprised of a complex mixture of solid, liquid, and gaseous phases, riparian soils provide a heterogeneous matrix that supports plant and microbial communities. The solid phase encompasses mineral and organic particles of differing sizes and chemical composition that can sorb metals, organic chemicals, and other pollutants, thereby preventing them from migrating to the stream channel. The multiplicity and interaction of various biogeochemical processes in riparian soils contribute greatly to pollutant removal.

Unlike upland soils that are derived from terrestrial parent material, riparian soils primarily develop through the deposition of sediments that originate from various upstream sources. These alluvial deposits establish a heterogeneous patchwork of stratified sediments of different textures, which influences the movement of waterborne contaminants. Huggenberger et al. (1998) provide a good review of the geomorphology and characterization of alluvial soils, but a brief description is warranted here to provide a background related to the movement of contaminants through riparian soils. Deposits of clay, silt, sand, and gravel, and continual disturbance by seasonal high flows and occasional extreme flood events, create a complex mosaic of soil microenvironments that can vary considerably both vertically within the soil profile and along the length of the stream channel (Malanson 1993). A general trend can be observed where coarser sediments are deposited along steep-gradient streams while finer particles are washed downstream and deposited along low-gradient reaches as stream energy dissipates and wider floodplains develop (BLM 2003). Soil particle size also tends to decrease moving away from the stream edge (Huggenberger et al. 1998). This vertical, longitudinal, and lateral spatial structure results in disparate hydrologic conditions, and corresponding differences in pollutant fate, at locations in close proximity.



Rough-skinned Newt Taricha granulosa/*Renee Kinnick, WDFW*

The soil microenvironments described above influence hydrologic conditions, which consequently affect pollutant transport. Soil texture and structure dictate water storage capacity and retention, flow paths and hydraulic conductivity. Coarse textured soils enable a greater hydraulic conductivity that shortens hydraulic residence time in the riparian area, thereby reducing the period in which attenuation mechanisms can act on soluble contaminants before they reach the stream channel. Water may percolate below the root zone and limit potential interactions between vegetation and pollutants in deep, well-drained soils, such as those commonly found in forested riparian areas in humid climatic regions (NRC 2002). However, the root zone intercepts subsurface flow to a greater degree in forested riparian areas that exhibit shallow soils overlying a confining layer (e.g., shallow aquiclude). Overland flow that predominates in arid environments often undergoes limited infiltration due to a tendency for riparian soils to exhibit low permeability in these regions, which allows much of the runoff and associated waterborne contaminants to enter the stream with minimal attenuation (NRC 2002; Buffler et al. 2005).

Altered soil structure can influence pollutant attenuation (Vervoort et al. 1999). Compaction, for instance caused by over-grazing or vehicular traffic, and accompanying structural changes and surface soil instability can lead to diminished infiltration and amplified overland flow (Bohn and Buckhouse 1985; McInnis and McIver 2001). Soils with low infiltration rates typically exhibit a diminished capacity to retain pollutants in riparian areas (Johnson and Buffler 2008). Subsurface soil structure influences water movement and distribution in the unsaturated zone, affecting pollutant transport. Subsurface soil structure also impacts soil aeration and plant root growth, which have ramifications on pollutant fate. Preferential flow in soil macropores represents another facet of soil structure that affects pollutant removal (Allaire et al. 2015). Preferential flow of water through large connected void spaces in soils, which result from fractures, animal burrows and other processes, can enhance subsurface pollutant transport to river systems (Angier et al. 2002; Fuchs et al. 2009; Menichino et al. 2014). Alluvial deposits in riparian areas can further increase the connectivity of subsurface flows with stream channels, increasing lateral contaminant transport toward the stream channel. Preferential flow paths diminish the potential for contaminant sorption by both reducing interactions with soil particles and associated sorption sites and contributing to a higher flow velocity that reduces sorption kinetics. Although preferential flow paths have been a familiar concept in the field of soil science for some time, the recognized importance of these conduits has increased in recent years. This enhanced understanding is particularly important for controlling pollutants such as phosphorus that historically were not considered to undergo much, if any, subsurface transport (Angier et al. 2002; Fox et al. 2011a).

Artificial preferential flow also can be created by tile drains that are used by agricultural operations to remove excess water from the soil profile. Tile drains have been shown to enhance the movement of nutrients and herbicides from agricultural fields to streams, bypassing the natural attenuation processes that would have otherwise reduced the movement of these agrochemicals to aquatic ecosystems (Guan et al. 2011; Vidon and Cuadra 2011; Jaynes and Isenhart 2014).

In addition to playing an integral role in influencing the hydrologic linkage between upland areas and the stream channel, riparian soils provide a dynamic framework that regulates biogeochemical processes that act on contaminants. Soluble pollutants that have entered the soil profile, either from subsurface flow from upland areas or through infiltration in the riparian area, are subject to a variety of processes. Contaminants prone to sorption can be retained within the soil profile of the riparian area, reducing their potential of migrating to the stream channel. Chemicals typically have a greater affinity for clay minerals or organic matter, and thus the attenuation due to sorption will vary depending on



Riparian area along White River/Alan Bauer

the soil composition. Microbial assemblages in riparian soils can contribute to the assimilation, transformation, and degradation of a range of chemicals. Anaerobic conditions in saturated soils found in riparian areas differ considerably from the aerobic environments of adjacent uplands, altering the redox potential. The fate of numerous contaminants is influenced strongly by the redox potential of the soil and associated microbial communities. Fluctuating water tables can alter the redox state, resulting in seasonal variations in chemical species distributed within the riparian area. Although broad generalizations can be made, the literature highlights that temporal changes in soil complexities are not well understood (NRC 2002).

Vegetative communities are also impacted by soil conditions in riparian areas. Plant species exhibit habitat preferences that follow soil moisture gradients across riparian areas. The influence of vegetation on contaminant fate and transport will be discussed in the next section. However, it is salient to note here that soil compaction and other disturbances can lead to invasive plant species that can degrade riparian ecosystem function in relation to pollutant attenuation. Disturbed soils can lose their native species diversity and develop more homogenous stands of an exotic species (e.g., Himalayan Blackberry *Rubus armeniacus*) that often do not have the same vegetative density or root structure as the native population, thereby altering riparian area efficacy in pollutant removal.

5.3.3. Vegetation

Riparian vegetation also plays a critical role in attenuating pollutant transport to surface waters. Plants physically alter the movement of water and associated contaminants, provide habitat for microbial communities that assimilate and transform contaminants, and influence soil redox conditions that govern many biogeochemical cycles. Plant root systems provide bank stabilization, which reduces the direct introduction of sediments into aquatic ecosystems via streambank erosion. Soil stabilization also limits erosion and gully formation that can result from overland flow moving through a riparian area. In addition, forested riparian



Vegetated buffers reduce nonpoint source pollution to rivers and streams/U.S. Dept. of Agriculture, National Agriculture Imagery Program

areas have been shown to enhance instream processing of contaminants, including nutrients and pesticides (Sweeney et al. 2004). This section provides a brief overview of the influence vegetation has on pollutant attenuation in riparian areas and identifies critical points to consider when developing management plans. A number of focused review articles present further details on riparian vegetation-hydrology interactions and mechanisms by which plants can attenuate contaminants in riparian areas (e.g., Tabacchi et al. 2000; Williams and Scott 2009; Dosskey et al. 2010).

The high vegetation density inherent in streamside ecosystems serves a critical function in modulating overland flow and amplifying infiltration. The stems of grass and herbaceous groundcover, trunks of woody vegetation, and downed wood create resistance to overland flow, slowing it, and causing deposition onto and infiltration into the soil profile (Fisher and Binkley 2000; Schuster and Grismer 2004). Vegetation also helps maintain soil structure by increasing soil macropore formation through root growth and decay, which further enhances soil permeability. Soluble contaminants present in overland flow enter the soil column, augmenting attenuation through the various mechanisms discussed throughout this chapter. The reduced velocity of the overland flow caused by the riparian plant community causes suspended particles to settle out of the water column, reducing the transport of sediment and sediment-borne pollutants to the stream. Similarly, lower velocity flows will limit erosion within the riparian area, reducing potential contributions to stream sediment loads and avoiding gully formation, which concentrates overland flows and short circuits pollutant attenuation. A dense overstory canopy will further reduce erosion by intercepting precipitation



that would fall directly onto bare soil, and a dense plant community also reduces erosion of riparian soils by diminishing the velocity of runoff and floodwaters (Schultz et al. 2000).

Vegetation also increases soil surface roughness by producing herbaceous litter and woody debris, and by altering micro-topography, which slows surface flow and enhances infiltration of water. In contrast, sites with exposed mineral soil tend to exhibit low surface roughness that limits infiltration, and these sites are susceptible to increased transport to streams via overland flow.

Vegetation also influences the hydrologic behavior of subsurface and groundwater flow through streamside areas. Root uptake and transpiration by both herbaceous and woody plants can modify subsurface flow and soil moisture regimes in the unsaturated zone under unsaturated conditions. These alterations not only influence pollutant transport through riparian soils, but also affect redox conditions that govern biogeochemical transformations. Deeper-rooted plants can impact groundwater levels by reducing the pressure head at the water table through direct uptake or by extracting water along a water potential gradient. Hence, trees can cause daily or seasonal changes to water table levels, a phenomenon more prevalent in drier climates (Landmeyer 2011). Correspondingly, contaminant fluxes from riparian areas to surface waterbodies may exhibit similar diurnal and seasonal patterns. Water uptake by roots can similarly form a hydraulic barrier that creates an upward water flow through the soil profile that can reduce pollutant leaching and inhibit contaminant plumes from spreading horizontally (Pilon-Smits 2005).



Chinook salmon Oncorhynchus tshawytscha/*Morgan Bond*

While vegetation modulates water flow, it is vital to recognize the interconnected nature between riparian plant communities and hydrologic regimes. Riparian plant communities are determined largely by their adaptation to high moisture environments. Groundwater often represents a primary water source for riparian plants, principally trees and deeper-rooted flora. Consequently, alterations in groundwater regimes can have a detrimental impact on species diversity, density, and distribution, especially in drier regions where vegetation is typically concentrated along a narrow band of suitable soil moisture conditions (NRC 2002). Dramatic changes to plant communities can significantly limit the pollutant removal function of a riparian area. Thus, managers should consider the interrelationships between vegetation and subsurface hydrology. Kuglerová et al. (2014) expounded on this theme in a recent review examining the effects of forest management on groundwater processes and resultant water quality. The authors concluded that logging operations in riparian areas and hydrologically connected upland forests can alter groundwater regimes and affect water quality. They recommended site-specific riparian management where wider buffers would be implemented at critical groundwater discharge locations but narrower buffers would be allowed at sites lacking groundwater flow paths.

Riparian management strategies often emphasize the effectiveness of forested riparian areas for protecting water quality. However, research over the last two decades reveals that forests are not always the most effective vegetation for removing pollutants. Results can vary between sites, but research has shown that grass buffers (also called vegetative filter strips or grass filter strips) can yield similar reductions in sediments and sediment-borne pollutants (Correll 1997; Hawes and Smith 2004; Dosskey et al. 2010). Grasses and similar plants create a dense vegetative obstacle that slows overland flow, promotes deposition of sediments and attached pollutants, and provides an opportunity for the plants and associated microbes to capture soluble contaminants that enter the soil profile (Dillaha et al. 1989). Filter strips often serve as an effective alternative for protecting water quality from pollutants generated by upland activities where it is impractical to implement forested riparian areas, such as adjacent to agricultural fields, in urban settings, or along highways.

According to Lacas et al. (2005), much of the sediment removal effected by grass filter strips occurs mainly as a result of sedimentation immediately upslope of the strip in an area of still water that builds up against the strip's outer boundary. Furthermore, they note, the deposit formed upslope can expand into the filter strip, and that sediment deposition can increase to the point of forming channels that concentrate overland flow and induce the formation of water pathways with high velocities.

The primary drawback of a vegetative filter strip is that it addresses only pollutant removal and does not provide the other functions of forested riparian areas such as shading, large wood, and bank stability. Furthermore, grasses have a relatively shallow root

structure and thus vegetative filter strips are not as effective in removing pollutants from groundwater. In contrast, trees inherently have a deeper root zone that can effectively intercept subsurface flow and often reach shallow groundwater. Therefore, forested riparian areas can be more effective at removing soluble pollutants in subsurface and groundwater flow through plant uptake and by associated microbial communities that act on the pollutants in the rhizosphere. Considering both situations, structurally diverse riparian areas that contain a combination of grasses, shrubs and trees provide a more robust system for mitigating a range of pollutants (Fischer and Fischenich 2000). A similar concept was proposed by Welsch (1991), who presented a three-zone model that considered an herbaceous filter strip between uplands and the start of the riparian area, followed by a managed forest, and culminating with an undisturbed forest immediately adjacent to the streambank.

Vegetation in riparian buffers also provides a range of phytoremediation processes, wherein plants and associated microbial populations remove, contain, degrade or eliminate pollutants. Investigations on the phytoremediation potential of riparian vegetation to attenuate nutrients have been conducted for some time and results are well documented. The management of vegetation specifically as a pollutant treatment technology for organic compounds and metals has gained acceptance in general over the last couple of decades (Pilons-Smits 2005), but studies on phytoremediation specific to riparian areas remains fairly limited. However, recent research suggests that the promotion of specific plant species to attenuate organic chemicals and metals in riparian areas can be used to treat localized areas of concern (e.g., chemical spills, industrial sites, mine tailings). Design of a phytoremediation treatment system depends largely on the three primary factors identified by Susarla et al. (2002) that govern contaminant uptake and distribution in plants and the surrounding soil system: physicochemical characteristics of the pollutant (e.g., polarity, lipophilicity), environmental conditions (e.g., soil moisture, pH), and plant characteristics (e.g., available enzymes, root structure). Specifics on the phytoremediation potential of different pollutant classes in riparian areas will be discussed later in the respective sections of this chapter, while more detailed descriptions of phytoremediation are readily found in a large number of scientific reviews (e.g., Salt et al. 1998; Pulford and Watson 2003; Pilon-Smits 2005; Sarma 2011).

5.4. Specific Pollutants

For the purposes of riparian area management, we are most interested in five types of water pollutants: sediments, excess nutrients (in particular, nitrogen and phosphorus containing compounds), metals (in particular copper), toxic organic compounds (especially pesticides), and pathogens (especially those related to agricultural animal waste). The physical, chemical, and biological processes through which riparian areas remove these pollutants from water vary tremendously. Consequently, the degree to which riparian areas can remove each of these pollutants, and thereby protect aquatic ecosystems, varies significantly. The following sections describe the complicated processes and mechanisms involved in determining removal efficacy of specific pollutants by riparian areas.

Vegetation in riparian buffers provides a range of phytoremediation processes, wherein plants and associated microbial populations remove, contain, degrade or eliminate pollutants.

5.4.1. Sediments

Sediment transport in streams is a natural process, but excessive sediment loads can significantly degrade water quality. The impact of sediments on aquatic organisms has been researched extensively for many decades, and can consist of lethal, sub-lethal and behavioral effects (Newcombe and MacDonald 1991). Sediments that settle out of the water column can smother gravel and cobble streambeds that are essential for salmonid spawning and habitat for benthic macroinvertebrates and other organisms that form critical links in stream food webs. For example, the filling of interstitial spaces in coarse sediment matrices with fine sediments are thought to reduce or eliminate refuge and foraging habitat for selected life stages of stream-dwelling amphibians (Welsh and Ollivier 1998). Increased turbidity levels, indicative of suspended particles, can elicit physiological stress in fish through gill abrasion, impaired immune function and lowered growth rates (Redding et al. 1987; Au et al. 2004). High suspended sediment loads reduce visibility, which limits fish foraging ability and influences predator avoidance reactions (Redding et al. 1987). Aquatic vegetation and periphyton can be reduced due to diminished light penetration. Sediments also impart indirect effects on aquatic organisms. Elevated turbidity decreases the water albedo (reflectiveness), which increases the fraction of radiant energy absorbed by the water and increases stream temperature, leading to corresponding reductions in dissolved oxygen concentrations. Furthermore, sediments serve as a transport mechanism for other pollutants, carrying attached contaminants from upland sources to the stream channel. Soil particles that harbor legacy contaminants perpetuate water quality problems, such as those caused by DDT in some Washington streams despite this pesticide being banned in 1972 (Ecology 2007).



Restored vegetation in riparian area to capture pollutants in runoff/U.S. Dept. of Agriculture, National Agriculture Imagery Program

While the extent of these detrimental effects is largely a function of concentration and duration, and there is little agreement on the degree of ecological risk in the literature, sediments are a ubiquitous pollutant that many scientists regard as the worst form of pollution in aquatic ecosystems (Newcombe and MacDonald 1991; Waters 1995).

Erosion rates in uplands can be significantly increased by agricultural activities, construction sites, deforestation, and other land uses. Riparian areas effectively remove soil particles carried from upland areas via overland flow by slowing overland flow velocities, promoting sediment settling, and acting as sediment sinks[5]. Mass wasting (also referred to as mass movement, mass failure, or slope movement), wherein large masses of soil and geologic material move downslope into a stream, acts as another potential sediment source in hilly or steep mountainous environments. Although limited in spatial distribution, this geomorphic process can overwhelm the sediment removal capacity of riparian areas.

Our understanding of the riparian area's sediment removal function will be enhanced with a basic understanding of sediment erosion and transport processes. Briefly, the impact of falling raindrops can loosen soil particles via splash erosion. Overland flow picks up soil particles and transports them downslope through sheet erosion. Generation of concentrated flow paths results in rill erosion, which enhances sediment delivery and increases erosion rates through flow that is on the order of a few centimeters deep. Gully erosion develops when deep, narrow channels form, leading to increased erosion and more rapid sediment delivery. It is important to prevent the formation of rill and gully erosion entering riparian areas because channel formation extending into riparian areas short-circuits sediment removal and represents a direct conduit from terrestrial to aquatic systems. Merritt et al. (2003) provide an extensive review of various erosion and sediment transport models that can be employed to determine the potential sediment loads that could enter a riparian area.

While the upland hydrologic regime acts as a principal driver governing the movement of eroded soil particles, the aforementioned erosion mechanisms can be significantly tempered by intact soil cover. This can be accomplished by vegetation overlying a dense cover of herbaceous litter and woody debris. Vegetation increases surface roughness which slows surface flow and enhances water infiltration, both of which promote the settling out of sediments (Figure 5.1). Muñoz-Carpena et al. (1999) showed that spacing between vegetation is the most important parameter in sediment attenuation in riparian buffers, although soil characteristics, sediment load, and slope also play prominent roles.

Agriculturally generated nitrogen continues to present an issue, and it is becoming increasingly apparent that smaller hobby farms and lawn fertilizers used in suburban and urban areas can lead to severely degraded water quality.

[5] Streambank erosion, channel incision, and surface erosion in riparian areas present other potential sediment sources. As this chapter focuses on the removal of pollutants generated by upland activities, these geomorphological processes are outside the scope of this chapter. However, it should be noted that riparian vegetation can increase bank stability, thereby decreasing erosion along the stream channel (see Chapter 2).

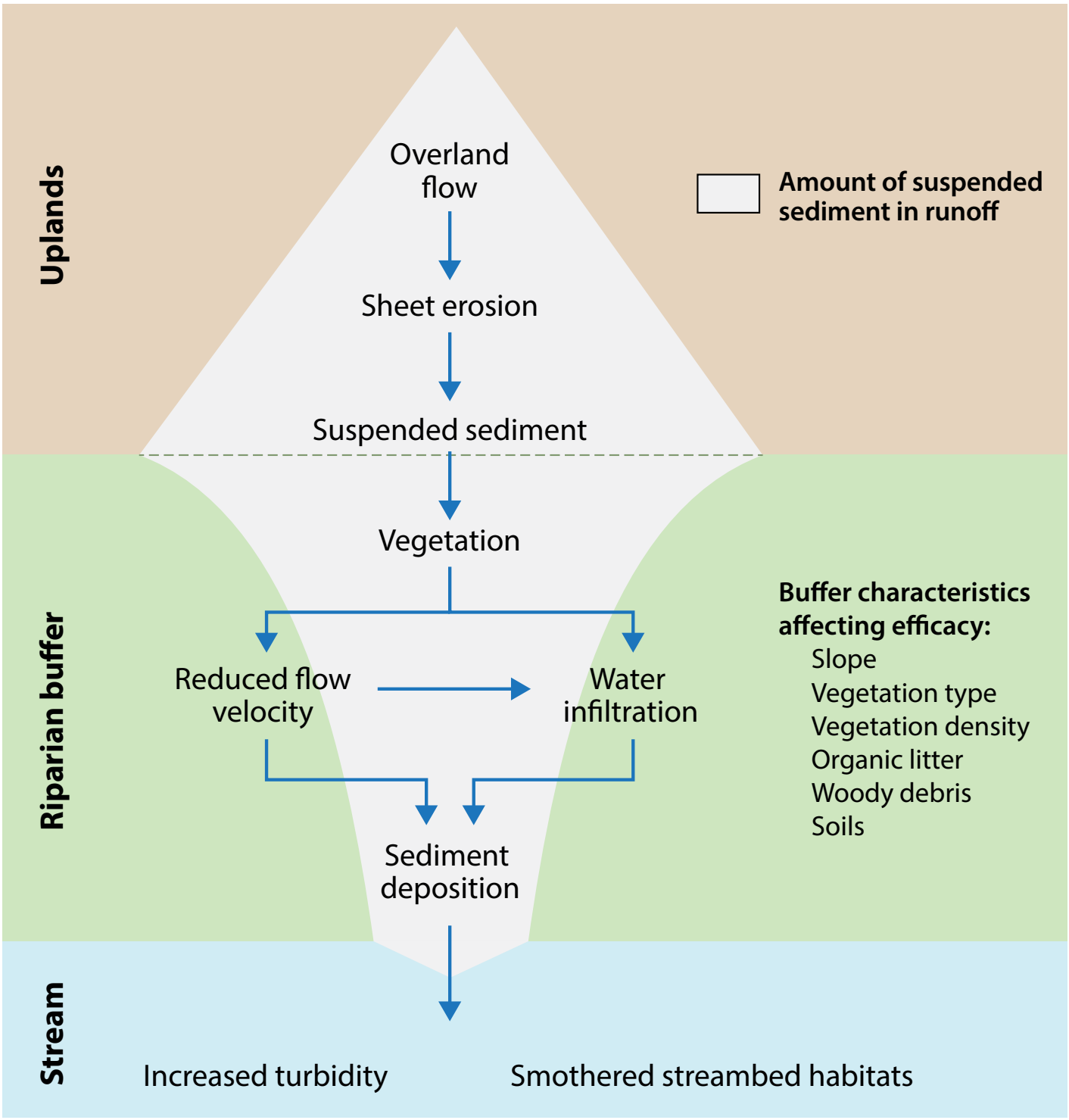


Figure 5.1 Efficacy of riparian buffer in removal of sediment from runoff. The amount of suspended sediment in runoff increases through sheet erosion of upland soils. Vegetation, woody debris, and organic litter in riparian buffer reduce flow velocity. Reduced flow velocity and increased water infiltration into soils causes deposition of suspended sediments. Sediments not removed from runoff increase turbidity and can smother gravel or cobble streambed habitats.

Riparian buffer widths required for sediment attenuation vary considerably depending on the site-specific conditions (e.g., slope, area of adjacent uplands, drainage paths, vegetation density). Sediment particle sizes are also a consideration in buffer width design – larger particles are deposited within the first 10 to 33 ft (3 to 10 m) of a buffer but smaller particles settle out at greater distances (Sheridan et al. 1999; Syversen et al. 2001; Dosskey et al. 2002; Yuan et al. 2009). The potential quantity of overland flow should also be a consideration when determining buffer widths, and hence, upland area should also factor into the determination of buffer width. Leeds et al. (1994) suggested that on agricultural lands the ratio of field drainage area to buffer area should be no greater than 50:1, and for consistently higher water quality the ratio should be on the order of 3:1 to 8:1. From research conducted on forested lands undergoing timber harvest, Clinton (2011) concluded that leaving a forested riparian buffer of 33 ft (10 m) would sufficiently reduce sediment transport to the adjacent stream, assuming responsible timber harvest practices, although greater widths have been recommended depending on the circumstance (Castelle et al. 1994). Furthermore, the relationship between buffer width and sediment attenuation is non-linear, necessitating a disproportionate increase in width to achieve an incremental increase in sediment removal. This relationship was described in a literature review of research on riparian buffers conducted by Sweeney and Newbold (2014). They concluded that a sediment removal efficiency of about 65% is typical for 30 ft (10 m) buffers but an 85% removal efficiency required more than twice that width, about 100 ft (30 m).

5.4.2. Excess Nutrients

Excess nutrients, in this context referring specifically to nitrogen and phosphorus, have long been recognized as significant water quality impairments. Eutrophication, the nutrient enrichment of aquatic systems, promotes algal blooms that shift community structure. Subsequent bloom die off leads to oxygen deficiency in the water column as oxygen is consumed by microorganisms during the decay of the excess organic matter. Hypoxia can have devastating consequences on aquatic animal communities, killing immobile organisms (e.g., clams) and mobile species (e.g., fish) that are not able to escape the deoxygenated zone. Excessive accumulation of cyanobacteria (formerly known as blue-green algae), resulting from shifts in nutrient ratios in the water, can release cyanotoxins which can cause dermal reactions, gastroenteritis, liver and kidney poisoning, and neurological impacts in humans or animals following water contact. Canine deaths due to cyanotoxin exposure have been confirmed throughout the country, with Washington reporting the highest number of cases among 27 states (Backer et al. 2013). In some cases, selected nutrients are toxic at concentrations within typical fertilizer application ranges. For example, embryos of the highly aquatic Oregon Spotted Frog *Rana pretiosa*, a federally threatened species in the Pacific Northwest, all died after 15-day exposure to nitrite (NO_2^-) concentrations lower than 2 mg/L (Marco et al. 1999).

Fertilizers and manures are major sources of excess nutrients entering riparian areas. Wastewater discharges and leaking septic tanks introduce nutrients to riverine systems, but those sources fall outside the scope of this review. Agricultural activities have long been blamed as the biggest nonpoint source for nutrients. The enormous contribution of phosphorus to the eutrophication of surface waters led to extensive promotion of various best management practices (BMPs)[6] for reducing off-field transport of phosphorus. Nevertheless, there has been a general lack of improvement in water quality of many receiving

6 In general usage "best management practice" (BMP) means one or more practices that are determined to be an effective and practicable means of preventing or reducing the amount of pollution generated by nonpoint sources to a level compatible with water quality goals. Under Washington State regulations, BMP means physical, structural, and/or managerial practices approved by the Washington Department of Ecology that, when used singularly or in combination, prevent or reduce pollutant discharges (WAC 173-201A-020).

streams. In addition to existing agricultural sources of phosphorus, it is increasingly evident that "legacy phosphorus" from past activities that accumulated in watersheds contributes to current water quality problems (Jarvie et al. 2013). Agriculturally generated nitrogen continues to present an issue, as it can leach through the soil and move with shallow groundwater flows through riparian soils and enter receiving waters. It is also becoming increasingly apparent that smaller hobby farms and lawn fertilizers used in suburban/urban areas can lead to severely degraded water quality (Cheng et al. 2014).

For a thorough discussion of nitrogen and phosphorus dynamics in natural, undisturbed riparian areas see Chapter 6. For this chapter it is salient to note the differing biogeochemical cycles exhibited by nitrogen and phosphorus: nitrogen displays complex transformations between various species including atmospheric forms whereas phosphorus undergoes relatively simple shifts between soluble, sorbed, precipitate and organic forms. Nitrogen and phosphorus are often casually grouped together as nutrients, but this discrepancy in chemical behavior leads to significantly different considerations when assessing their removal by riparian areas.

Nitrogen

Due to its soluble nature in its aqueous forms, a significant portion of the excess nitrogen entering streamside areas will enter riparian soils either through infiltration or via groundwater transport. Nitrogen then can undergo attenuation through a variety of mechanisms. It is widely accepted that denitrification acts as the primary pathway for removing nitrate (NO_3^-) from water in riparian areas (Fennessy and Cronk 1997; Cey et al. 1999; Wang et al. 2014). This process is governed by specific denitrifying bacteria that use nitrate during anaerobic respiration, reducing it to the gaseous forms of nitric oxide (NO) and nitrous oxide (N_2O) and ultimately molecular nitrogen (N_2). These gaseous species can then volatilize in harmless forms to the atmosphere and be completely eliminated as a potential pollutant. This process requires the presence of a shallow water table, anoxic conditions, denitrifying bacteria and an available carbon source—conditions commonly associated with riparian areas. Hydric soils, despite occupying a limited area within riparian areas, are important sites of anaerobic activity that promote denitrification. If groundwater bypasses riparian soils then nutrient pollution of surface waters may occur despite the presence of a riparian buffer (Burt et al. 1999). In a highly cited critical review of research on nitrate removal in riparian areas, Hill (1996) asserted that understanding denitrification requires a better understanding of groundwater interactions with riparian vegetation and soils.

Plant uptake of dissolved nitrogen in subsurface flows moving through riparian areas provides an additional mechanism that can remove considerable amounts of nitrate. A significant difference from denitrification though is that vegetative uptake is often viewed as transient storage for nitrogen because nitrogen assimilated by plants will be reintroduced to the ecosystem following leaf senescence or plant death. Both grasses and trees have been widely shown to remove nitrogen in riparian areas, but studies have yielded contradictory observations and conclusions regarding which vegetation type is more effective (Groffman et al. 1991; Osborne and Kovacic 1993; Schnaebel et al. 1997). A meta-analysis performed to assess the key riparian variables responsible for nitrogen removal concluded that forested buffers exhibited the greatest propensity for nitrogen uptake, and surpassed the efficacy of both grasses and communities composed of both trees and grass (Zhang et al. 2010). Although this study did not end the debate, many researchers believe that deeper and more expansive root structure allows trees to take up greater proportions of nitrogen. A riparian area's age may also be a variable affecting nitrogen removal. Cors and Tchon (2007) evaluated denitrification enzyme activity in two

riparian areas of different ages: 6 and 20 years old. They found the older system was significantly more effective at denitrification, which was attributed to a greater accumulation of carbon.

Research focusing on hot spots and hot moments has provided a more nuanced understanding of nitrogen dynamics in riparian areas. Hot spots and hot moments that develop in the hyporheic zone are increasingly being recognized as a contributing mechanism to nitrogen attenuation (McClain et al. 2003; Vidon et al. 2010; Gu et al. 2012). A landmark paper by Hedin et al. (1998) exemplified the concept of enhanced nitrogen removal at hot spots along the soil-stream interface in a mixed forested-agricultural watershed. A first-order stream exhibited two converging primary flow paths, one consisting of shallow subsurface flow containing high concentrations of chemical reducers (i.e., dissolved organic carbon, CH_4, and NH_4^+) and the other a near-stream upwelling of deep groundwater containing high concentrations of oxidizers (i.e., NO_3^-, N_2O, and SO_4^{2-}). A zone of high denitrification resulted that was less than 3 ft (1 m) wide and remained active for the two-year study period. Hedin et al. (1998) suggested that nitrate removal via denitrification could be sustained depending on the spatial location of high flow pathways, the propensity of the chemical environment to support rapid denitrification, and the availability of oxidizable carbon. Furthermore, they recommended that management actions enhancing natural carbon inputs could be adopted to optimize nitrate removal by denitrification.

Phosphorus

Unlike nitrogen, phosphorus possesses a binding affinity for soil particles and typically enters riparian areas adsorbed to soil particles carried by overland flow. Hence, phosphorus removal is closely connected to sediment removal by riparian areas. A comprehensive review of phosphorus dynamics in grass buffer strips surmised that that optimum phosphorus retention occurs in filter strips that are at least 16 to 33 ft (5 to 10 m) wide (Dorioz et al. 2006), but this recommendation is debatable. It is generally recognized that a positive correlation exists between buffer width and phosphorus retention in riparian areas, and hence, buffers greater than 33 ft (10 m) offer greater removal efficacy. Independent studies have consistently found 60% to 80% phosphorus removal by buffers roughly 15 to 53 ft (4.6 to 16.3 m) wide (Dillaha et al. 1989; Vought et al. 1994; Lee et al. 2003). Forested riparian ecosystems assessments have yielded less consistent results, with studies showing phosphorus removal ranging from 30% to 80% in deciduous riparian areas (Lowrance et al. 1984; Cooper and Gilliam 1987). This discrepancy corresponds with the premise that a robust stand of grass provides better attenuation of sediments and associated pollutants than forested riparian areas.



Unknown species of crayfish in the Deschutes River/Steve Boessow, WDFW

Even though these results appear convincing at first glance, a significant proportion of the body of research consists of short-term studies that fail to account for changes in riparian function over time. While it can confidently be stated that riparian areas offer effective short-term control of sediment-bound phosphorus, uncertainty exists regarding their long-term efficacy. Filter strips receiving sediment loads are well known to become less effective over time due to internal erosion and sediment accumulation. The continual incorporation of phosphorus into surface soils presumably would lead to a saturation of the system that could not only decrease removal of new phosphorus entering the

riparian area, but also lead to release and export of dissolved phosphorus to the stream that had previously been stored in riparian soils (Muscutt et al. 1993). Some studies have reported significant removal of soluble phosphorus in surface runoff (Peterjohn and Correll 1984). However, contradictory reports indicate little retention of soluble forms, with the majority moving through the area in surface runoff (Daniels and Gilliam 1996). Plants take up some of the phosphorus in the riparian soils, but this mechanism is not nearly as significant in removal as it is for nitrogen. Increased removal of soluble forms could potentially be achieved with various amendments, such as biochar (charcoal used as a soil amendment), that could enhance phosphorus sorption (Zhang et al. 2014).

A relatively new research topic related to phosphorus attenuation focuses on subsurface transport of soluble phosphorus forms. It was long accepted as dogma that phosphorus did not leach or move through the soil profile. Although scattered findings contradicted this view during the preceding decades (e.g., Peverill et al. 1977), this conviction remained recalcitrant and was still taught in university soil courses up until the last decade. This belief has now been dispelled by increasing evidence that phosphorus can move through the soil profile, particularly in coarse textured soils. A preponderance of the recent research on this topic has been conducted in upland soils, but the findings are relevant for riparian areas and are particularly true in coarse alluvial soils. This has been demonstrated by the rapid transport of soluble phosphorus forms through preferential flow paths (Fuchs et al. 2009). This movement can serve as an important transport mechanism that should be considered when determining potential phosphorus fluxes reaching the stream channel. Although extensive literature exists on phosphorus cycling in a variety of settings, relatively little information is available on phosphorus dynamics in the hyporheic zone and further research is needed to understand phosphorus flux through this interface between the stream and groundwater flowing through riparian areas (Zhang 2014).

While it can confidently be stated that riparian areas offer effective short-term control of sediment-bound phosphorus, uncertainty exists regarding their long-term efficacy. Riparian filter strips are well known to become less effective over time.

5.4.3. Metals

Metals (as well as metalloids that share similar properties, such as arsenic) are elements naturally found in geologic material. They enter the environment either through natural weathering processes or through anthropogenic activities. Localized metal deposits can result in elevated concentrations in streams that can be hazardous to biota. Metal pollution in aquatic ecosystems appeared as a serious environmental issue on a wide scale in the late 19th and early 20th century due to increasing industrial and mining activities. Contamination sources have grown over time to include a range of other activities, the most pertinent to this discussion on riparian areas being runoff from urban and agricultural lands. While mining activities present significant metal inputs into certain streams in Washington, protecting water quality from these sources requires the implementation of specific remediation techniques that are outside the scope of this chapter.

Metals present a significant environmental hazard that can lead to a variety of health issues in plants and animals. While some metals are essential elements required for normal growth and development of biota, these can also impart toxicological issues when concentrations exceed a given threshold. Among other health effects, metals can be carcinogenic, cause reproductive problems, and interfere with the normal function of the heart, bones, intestines, and kidneys. While debate continues over the specific mechanisms associated with metal toxicity in plants, it is generally recognized that oxidative stress represents a primary driver that results in cellular damage (Pinto et al. 2003). Some heavy metals bioaccumulate and biomagnify, which leads to elevated concentrations exhibited at higher trophic levels (Boening 2000). The propensity for metals to bioaccumulate can be magnified by biologically mediated transformation into organometallic complexes, such as methylmercury. Metal toxicity is often related to the chemical species formed, which often relates to their bioavailability. For instance, chromium(III) compounds are not considered a significant health risk while chromium(V) is a well-known carcinogen. Similarly, metal complexation with dissolved organic carbon often inhibits their bioavailability.

While copper's detrimental environmental impacts have been recognized for many decades (Sprague and Ramsay 1965), it has received increased attention in recent years as toxicity symptoms have become more pronounced. Copper is an essential mineral for organisms, contributing to enzymatic and metabolic function, but toxic effects have been observed at all levels of the aquatic food chain when it exceeds particular concentrations. Copper has been shown to have detrimental effects on plants, retarding growth at concentrations as low as 1.0 part per billion (ppb) and impeding photosynthesis at 5.0 ppb levels (USEPA 1980). While reductions in algal production can theoretically exert an indirect effect on zooplankton by limiting their food source, copper can impart a lethal effect on these organisms at low parts per billion levels (Ingersoll and Winner 1982). Similarly, significant mortality has been shown to occur in benthic macroinvertebrates at similar copper



Juvenile salmon need clean water/Ned Pittman, WDFW

concentrations (Clements et al. 1992). Copper presents a litany of issues to fish. Lethal concentrations vary considerably between fish species and fluctuate depending on environmental conditions. Sub-lethal effects are conveyed at lower concentrations, which include hindering osmoregulation, weakening immune response, altering enzymatic and metabolic activity, impairing olfaction (sense of smell), altering migration patterns and predator avoidance behavior, and modifying hatch rates (Lortz and McPherson 1977; Sorensen 1991; Rougier et al. 1994; Baldwin et al. 2003; Monteiro et al 2005; Sandahl et al. 2007; McIntyre et al. 2012). Synergistic impacts that occur when copper is present in combination with other pollutants highlights the current concern over this element (Hecht 2007). Effects similar to those observed in fish have been recorded in amphibians following exposure to rather low concentrations of copper ions (Cu^{2+}). For example, the concentration of copper at which half of larval Northern Leopard Frogs *Rana pipiens* would die following a seven-day exposure was estimated at 0.067 mg/L (Redick and La Point 2004). The same study revealed lethargy, loss of equilibrium, and loss of appetite at copper concentrations of 36 ppb. A widespread pattern in copper exposure studies with amphibians is a general impairment of predator evasion behaviors (Garcia-Muñoz et al. 2011).

Anthropogenic copper inputs to the environment include those of other metals, but what sets copper apart are two significant sources. The first is the agricultural use of copper-based pesticides. Copper sulfate and other copper-based pesticides are frequently used as a fungicide to protect a variety of crops, including fruits and potatoes. The second is the release of copper from vehicle brake pads. This unique source has received considerable attention as an environmental hazard worldwide, and has led to the 2010 adoption of Washington State's Brake Material Friction Act (RCW 70.285) that is phasing out copper in automobile brakes (Straffelini et al. 2015). Copper can also enter the environment through atmospheric deposition, which is a potential pathway in industrial and mining regions (USEPA 1980). These sources introduce copper into the environment as a nonpoint source pollutant, which makes copper very different from other metals. While the following discussion will continue to refer to metals in general, the reader should recognize that the nonpoint source nature of copper makes it the primary metal of concern in Washington in regards to attenuation in riparian areas.

Metals form various inorganic and organic species, the nature of which directly relates to its bioavailability and mobility through a riparian area. Metal speciation is driven through complex biogeochemical processes. Environmental conditions and the chemical nature of the surrounding constituents play a significant role in dictating the form that a metal might take. This is particularly relevant to riparian areas where fluctuating water tables alter redox conditions, and correspondingly metal dynamics in riparian soils. Daily oscillations related to the photocycle, for instance, have been shown to occur in aquatic ecosystems as a result of biogeochemical interactions involving temperature, acidity, and biofilms (Nimick et al. 2011). Consequently, zinc, manganese, and cadmium can increase several-fold between late afternoon and early morning. In contrast, arsenic undergoes the opposite diel pattern; meanwhile copper and lead do not undergo regular diel cycling.

The metal species resulting from soil acidity and redox conditions can form precipitates, exhibit an affinity to clay minerals and oxide/hydroxide compounds, and thus be more readily retained in riparian areas. Conversely, metals stay in solution as more mobile forms that leach and move toward the stream. Typically, metals more readily enter solution under acidic conditions. Meanwhile the ionic strength of the water (a measure of the concentration of all the ions in solution) presents a confounding variable in these processes. The impact of other ions manifests through enhanced metal desorption from soil particles with increasing

salinity. Carbonates in riparian soils promote metal retention by buffering acidity (i.e., preventing increased acidity), limiting metal solubility, and forming insoluble precipitates with metals.

Organic constituents in soil-water systems also play a major role in metal fate and transport processes. It has been clearly understood for some time that humic substances, a classification of complex and heterogeneous macromolecules that represent a substantial component of natural organic matter, have the capacity to bind significant amounts of metals (Reuter and Perdue 1977). While association of metal ions with soil organic matter can retain metals, humic substances can act as colloids and contribute to colloid-enhanced movement. The environmental factors and mechanisms involved in metal-humic interactions are multifaceted, but it is salient to recognize the impacts that organic matter in riparian soils can have on the movement of metals to the stream channel. A more detailed explanation of the inorganic and organic factors that influence metal behavior is presented in a review by Du Laing et al. (2009), which includes a specific focus on riparian areas.

Unlike organic contaminants that can degrade, metals are recalcitrant and removal in riparian areas depends largely on retention. Although the brief description of metal chemistry provided here elucidates the primary factors that affect their movement in the environment, management practices to enhance their attenuation are limited, and metal mobility will be driven overwhelmingly by environmental conditions. An exception to this statement is phytoremediation.

Phytoremediation of metals offers promise as a means to enhance metals removal in riparian areas. Although significant research on this process did not start in earnest until the late 1990s, since then hundreds of scientific papers have been published on the topic. Correspondingly, there is a plethora of review articles (e.g., Ghosh and Singh 2005; Sarma 2011; Koptsik 2014; Laghlimi et al. 2015). Four classes of phytoremediation can influence metal attenuation in soil, including phytoextraction (removal of metals from the soil-water system by plants), phytostabilzation (minimizing metal transport and sequestering them in the soil near the roots), phytovolatilization (uptake and transpiration by plants; this process is primarily limited to mercury and arsenic), and rhizofiltration (sorption, concentration and precipitation of metals in the root mass). Of these, the first two mechanisms are the most effective in attenuating metals (Laghlimi et al. 2015). In general, trees are a more effective form of vegetation due to their size, perennial nature, and the depth of root growth. Different metals will accumulate in different parts of a tree. For instance, copper tends to be immobilized and retained principally in the roots while zinc moves into the branches and leaf mass (Pulford and Watson 2003). Some plant and tree species act as hyper-accumulators that are tolerant of high metal concentrations in soils and can amass metals in their tissues through detoxification mechanisms (Sarma 2011). These species could be preferentially planted in areas where metals are a particular concern to help attenuate metal movement to the stream channel. As leaves will fall to the ground, riparian management could include the periodic removal of vegetative debris to off-site locations to avoid subsequent movement to the stream. Often there is no need to plant nonindigenous plants as a variety of common native riparian vegetative species can provide phytoremediation capabilities. For instance, willows (*Salix* spp.) have been shown to attenuate various metals in riparian areas to great effect (Bourret et al. 2009; Zhongmin et al. 2012).

Soil amendments offer another form of "green remediation" that has been increasingly used in soil systems since the turn of the century. A wide variety of amendments can be used either to mobilize metals by promoting uptake via phytoextraction or to immobilize (stabilize) metals in a solid phase. For instance, chelating agents have been applied at sites around the globe to enhance desorption, while phosphate



Tilton River/George Fornes, WDFW

fertilizers are common amendments intended to intensify metal sorption and form precipitates. Several topical reviews describing assorted soil additives have been published that provide more detail on this *in-situ* remediation technique (e.g., Bolan et al. 2014; Mahar et al. 2015). Similarly, over the last decade biochar has seen increased application in the context of attenuating metals (Ahmad et al. 2014). Although studies on the use of soil amendments to attenuate metals in riparian soils are limited, recent findings showed that additions of 11 different materials, such as biochar, bentonite, cement bypass kiln dust, and limestone to a floodplain soil could provide a potential remediation technique (Rinklebe and Shaheen 2015). An evaluation of the amendments in riparian soils heavily contaminated with copper (over 3,000 mg/kg) showed that most of the additives shifted the geochemical forms of copper through either increased sorption or by transformation to more plant available forms. Although the authors concluded that the low amendment rates that could practically be applied would inadequately immobilize copper, the increased copper concentration found in grass tissues at the same site indicates a means of enhanced phytoremediation.

Clearly, the use of soil amendments requires further field verification in riparian areas, but this approach to enhancing natural attenuation mechanisms shows promise.

5.4.4. Pesticides and Other Organic Compounds

An extensive array of organic contaminants exists in the environment that can threaten water quality in aquatic ecosystems. This category of compounds describes molecules that contain carbon covalently bonded to other elements, and includes both naturally derived and synthetic chemicals. This chapter focuses on anthropogenic compounds that exert a toxic effect on aquatic organisms.

The multitude of organic chemicals makes it impractical to touch on each class here, but common examples that present environmental health risks in aquatic habitats include polycyclic aromatic hydrocarbons (PAHs), polychlorinated biphenyls (PCBs), and pesticides. While the detrimental effects of many of these pollutants have been recognized for some time, studies continually identify emerging contaminants of concern ("emerging" does not only connote new compounds, but also chemicals that have been in use without realizing the extent of their toxicity). For instance, hazards associated with flame retardants, such as polybrominated diphenyl ethers (PBDEs), have been highlighted over the last decade (Covaci et al. 2011; Ye et al. 2015). Recent research emphasis also has been placed on a variety of trace organic compounds, including pharmaceuticals and personal-care products (PPCPs), as it is now recognized that these chemicals can exert negative impacts on fish and other aquatic organisms at both the individual and population levels even at extremely low (e.g. parts per trillions) concentrations (Mueller 2004; Kümmerer 2009a; Kümmerer 2009b; Luo et al. 2014). In addition, there is growing awareness that while individual pesticides may have little or no effect

when examined alone, that same pesticide as part of a pesticide mixture may be lethal to amphibians (Hua and Relyea 2014).

While only a brief discussion was provided above on the various organic pollutants that act as environmental contaminants, a little more information on pesticides is warranted, as they are more likely to be used in uplands and transported into riparian areas. Pesticides consist of any substance that is used to control fungal, plant, or animal pests. These chemicals represent a broad range of different chemicals that are derived from various sources such as plant extracts (nicotine, pyrethrum, neem oil), inorganics (e.g., copper sulphate; inorganic pesticides will not be discussed here), and synthetics. Synthetic pesticides are themselves a broad class that includes legacy organochlorines (chlorinated hydrocarbons such as DDT), organophosphates (e.g., Malathion), phenoxyacetic acids (e.g., MCP), carbamates (e.g., carbaryl), and neonicotinoids (e.g., imidacloprid). Pesticide pollution of streams can impact non-target organisms resulting in a wide variety of physiological and ecological problems (Mann et al. 2009), including altered growth (Alvarez and Fuiman 2005) and reproduction (Moore et al. 2007), altered community dynamics (Fleeger et al. 2003), and the loss of species (Relyea and Diecks 2008).

The ecological impacts of organic pollutants on aquatic organisms vary considerably, depending on not only the contaminant type but also the environmental conditions. Various compounds can be carcinogenic (causing cancer), mutagenic (altering genetic material and fomenting mutations), and teratogenic (stimulating abnormalities). Organic pollutants can also act as endocrine disrupting chemicals (EDCs), adversely impacting development, reproduction, neurologic, and immune system function in humans and wildlife (Colborn et al. 1993). Endocrine disruption has emerged as a key issue as studies have identified more cases of detrimental impacts, such as the discovery of atrazine-induced feminization of male Northern Leopard Frogs at very low concentrations (Hayes et al. 2003). This finding is controversial, but it has increased awareness that many organic compounds have potentially unrecognized endocrine-disrupting effects. Some organic contaminants, such as halogenated hydrocarbons, are capable of bioaccumulating in individuals and biomagnify up the food chain (Rahman et al. 2001).

To further complicate potential risk, pesticides rarely occur singly in aquatic environments. For example, a comprehensive decadal assessment of 178 streams in agricultural, urban, and mixed-land use watersheds found two or more pesticides more than 90% of the time and ten or more pesticides 20% of the time (USGS 2006). Ecological and toxicological research is increasingly recognizing the complexity of contaminant mixtures, which may have antagonistic, additive, or synergistic interactions in biota (Cedergreen 2014). For example, combining the pesticides diazinon and Malathion inhibits brain activity, and therefore swimming performance in fish at concentrations more than 50 times lower than the concentrations that cause an impact when these pesticides are used singly (Laetz et al. 2013). Although the examples given focused on pesticides, mixtures of hydrocarbons originating from roadways, parking lots and other locations can also be found in urban watersheds, including pollutants such as PAHs that originate from coal-tar-sealed parking lots (Scoggins et al. 2007). Amalgamations of these urban generated organic contaminants have been shown to impart both sub-lethal and lethal effects on aquatic organisms and disrupt stream communities (PSAT 2007; Scoggins et al. 2007; Spromberg et al. 2016).

The sheer number of different sub-classes of pesticides makes it impractical to provide information on the chemical behavior of all the potential contaminants that might be encountered in riparian areas. Pesticide pollution is extremely complex due to the multitude of types, the wide range of molecular sizes, the diversity of chemical structures, and the ability of these compounds to react and transform into new products. However,

some basic information on organic compounds will enable a better understanding of the effects riparian buffer size and structure have on pesticide pollutants. It is essential to identify the physicochemical properties of organic contaminants to adequately assess fate and transport pathways through riparian areas. Specific gravity, water solubility, vapor pressure, and partitioning coefficients such as the octanol/water partition (log K_{OW}) and organic carbon partition coefficients (K_{OC}) all serve as predictors of a substance's potential mobility and attenuation in riparian areas.

Natural organic matter has a significant impact on the degree of attenuation riparian soils impart on pesticides. The aforementioned K_{OC} represents the ratio of the amount of chemical adsorbed to the soil to the amount of chemical that remains in solution, related to the mass fraction of organic matter in the soil (Delle Site 2001). This value essentially indicates the affinity of a pollutant to soil organic matter and is a predictor of its potential mobility through the soil, where higher K_{OC} values correlate to less mobile organic contaminants and low K_{OC} values correlate to more mobile organic contaminants. Hydrophobic, nonpolar compounds, such as PAHs, are typically associated with particles in soil-water systems, whereas polar contaminants often exist in dissolved forms that exhibit a greater propensity for movement through the ecosystem.

The relationship between pesticides and their respective K_{OC} values can be confounded by humic substances, which are a heterogeneous mixture of chemically complex macromolecules that comprise a substantial component of natural organic matter. Humic substances have long been known to exert a significant impact on the movement of organic contaminants (Hayes 1970; Khan 1972). These amorphous compounds, which are classified into humic acid, fulvic acid, and humin fractions based on their molecular size and chemical behavior, can effectively bind organic pollutants and present either water-insoluble entities that are retained in the soil column or water-soluble colloids that can facilitate transport through riparian soils to the stream channel. Even when present in small quantities, these chemically reactive compounds can dramatically influence the binding, persistence, and translocation of organic pollutants. The interactions between humic substances and organic contaminants are beyond the scope of this chapter, but their potential to affect K_{OC} values by up to an order of magnitude is salient to predicting their attenuation by riparian buffers (Grathwohl 1990; Kopinke et al. 2001). Nevertheless, in general the attenuation of organic pollutants in riparian areas is positively correlated with soil organic matter.

Pesticides and other organic pollutants can also be retained in riparian areas through sorption to mineral components in the soil, although often to a lesser extent than to organic matter (Delle Site 2001). The surface area of soil particles enhances the binding of organic pollutants, which increases with finer soil textures such as those found in clays. The mineral composition of the soil particles also influences binding affinity by offering different forms of attachment sites. Those compounds that do not attach to soil material are susceptible to leaching, which can result in them entering the groundwater and being transported to the stream. Contaminants associated with inorganic particulates are usually much less bioavailable, although they can become bioavailable if particles are ingested by biota (Moermond et al. 2004).

Pesticides and other organic pollutants can undergo abiotic and biotic transformations that further compound the complexity of their chemistry. Abiotic processes include degradation due to chemical reactions such as hydrolysis (Mitchell et al. 2014; Mitchell et al. 2015). Biotic transformations include biologically mediated reactions, such as bacterial metabolism. Although the potential for biodegradation is dependent on the chemical structure of the contaminant, indigenous soil bacteria can use many organic compounds as a metabolic substrate. Repeated exposure to the same type of pesticides can foster microbial communities that

become contaminant specialists (Vidon et al. 2010). For example, soils receiving repeated applications of the pesticide 2,4-D harbor more 2,4-D-degrading microbes than similar plots receiving fewer applications (Gonod et al. 2006). Similarly, PAH-degrading bacteria were more abundant in rain gardens receiving stormwater runoff than upland control plots (LeFevre et al. 2012). The robust microbial communities found in riparian areas, resulting from conditions discussed previously, helps attenuate many organic compounds in riparian soils. Being biologically mediated, however, the degradation rates will fluctuate seasonally depending on temperature and soil moisture.

Phytoremediation by riparian vegetation provides an additional attenuation mechanism for organic contaminants. Although phytoremediation has received significant interest over the last two decades, the literature contains few papers on this method specific to pesticides in riparian areas. However, the principles are the same as those described in the vegetation section found earlier in this chapter, and presumably the results would be similarly positive. This premise was highlighted in a review article on the potential effectiveness of phytoremediation in riparian areas, where Karthikeyan et al. (2004) drew on similarities between streamside areas and other locations where phytoremediation has been effectively employed to treat pesticide-contaminated soil and water. Similarly, another review paper summarized a range of studies that investigated phytoremediation in aquatic settings, addressing plant species such as cattail (*Typha* spp.) and Cutgrass *Leersia oryzoides* which can be found along the riparian-aquatic ecosystem transition (Moore et al. 2011). A study directly examining the use of phytoremediation in riparian areas found that Tussock Sedge *Carex stricta*, Switchgrass *Panicum virgatum* and Gamagrass *Tripsacum dactyloides* led to approximately 70% reduction in total petroleum hydrocarbons under controlled riparian conditions, while there was only about 20% reduction associated with a Narrowleaf Willow *Salix exigua* and poplar (*Populus* spp.) (Euliss 2008). Following the same procedure in an uncontrolled riparian field site did not reproduce these promising results, but the authors presumed there was a continuous pollutant source re-contaminating the site during the study. A field study examining the phytoremediation potential of willows (*Salix* spp.) in riparian areas yielded a 49% decrease in PCB concentrations before contaminated groundwater reached the stream margin (Skłodowski et al. 2014). Although there is not enough information available in the literature to provide design guidelines for implementing a phytoremediation-based system, there is promise in this approach to attenuating organic contaminants in riparian areas and further research should be encouraged.

Mycoremediation, the degradation of contaminants by fungi, is a type of bioremediation that occurs in soils. This process likely takes place in riparian soils with high organic matter content where lignin-degrading fungi (more commonly known as wood-decay fungi, a class that includes brown rot, soft rot, and white rot) exist. These microorganisms possess the ability to breakdown organic contaminants, particularly PAHs, through the release of a variety of oxidizing enzymes (Haritash and Kaushik 2001). Research on promoting lignin-degrading fungi as a remediation agent started to appear in

The central problem faced by resource managers is determining the adequate riparian buffer width, composition, and structure to protect water quality with high degrees of efficacy, efficiency, and certainty.



Spawning Chum Salmon Oncorhynchus keta*/Ned Pitman, WDFW*

the literature in the 1990s, but did not receive much attention until after the turn of the century (Lamar et al. 1993; Boonchan et al. 2000; Canet et al. 2001). Results vary considerably, but it is not uncommon to observe 50% to 90% reductions in organic pollutants resulting from mycoremediation-mediated degradation (Lamar et al. 1993; Boonchan et al. 2000; Haritash and Kaushik 2001). Although this degradation process is mentioned here to highlight the mechanisms affecting organic pollutants in riparian soils, it has been suggested that mycoremediation could potentially be capitalized on as an engineered mitigation technique in riparian areas, but more research is needed (Jones 2009).

Despite the large body of knowledge that has been developed, the mechanistic understanding of pesticide transport through riparian areas is incomplete. The following summarizes our understanding of the typical transport pathways of a pesticide; this is essential information to consider when determining appropriate riparian widths for attenuation. Pesticide migration from terrestrial sources to stream channels can follow a number of different pathways. The specific transport mechanism governing pesticide movement from uplands through riparian areas and into surface waters is highly correlated to the type of pesticide in question. Surface runoff can carry pesticides off fields as either dissolved forms or attached to eroded soil particles. Leaching of compounds entails their vertical movement through the soil, after which they can either move toward the stream through the unsaturated zone or via groundwater flow. The chemicals that move in the dissolved form tend to be those that exhibit low to moderate sorption properties, as compounds that possess lower partition coefficients are prone to leach into the soil profile. Leaching is further promoted in regions with high precipitation and in soils that are coarse-textured, contain a low percentage of organic matter, or demonstrate a high degree of macropore flow. Pesticides that predominantly follow sediment-facilitated transport are generally those that display a strong affinity to soil particles (i.e., K_{OC} > 1,000 L/kg).

While the literature lacks information on the potential attenuation in riparian areas for most organic pollutants, there are a substantial number of papers on the movement of pesticides through buffer strips. A number of review papers evaluate pesticide attenuation in riparian areas, with a particular emphasis on managed vegetative filter strips (Krutz et al. 2005; Lacas et al.

2005; Reichenberger et al. 2007). Due to the complexity of the attenuation mechanisms involved, the removal rates within buffers vary considerably between disparate compounds, as well as when comparing the removal rates of the same pesticide at different locations. Depending on the conditions, mass removal rates for some pesticides can be negligible while others can reach 100%. Research has shown that herbicide type and filter strip width are primary factors affecting herbicide retention in riparian areas, while antecedent moisture conditions exert an additional effect wherein pesticide attenuation is generally negatively correlated with soil moisture. The type of vegetation appears to have negligible impact on pesticide retention, with studies showing that a grass-shrub-tree mixture exhibited comparable mitigation as grass only. Interestingly, one study found that pesticide mitigation was greater at higher incoming concentrations, which was attributed to better sorption to soil and plant material (Misra et al. 1996).

Due to confounding and often conflicting results, after 35 years of research, there remains a lack of consensus on the minimum filter strip widths needed for effective pesticide removal from surface and surface overland flow. The NRCS recommends a standard width of 49 ft (15 m) with the aim of achieving 50% effectiveness, but there is not much evidence to support this guidance (NRCS 2000). Another general recommendation for diffuse runoff suggests riparian widths of 33 and 66 ft (10 and 20 m) for hillslopes of under and over 328 ft (100 m) in length, respectively (Lacas et al. 2005). However, because this recommendation is based on only one experimental study, it may not be applicable to other locations with different hydrological, soil, and vegetative conditions.

Pesticide Spray Drift

Pesticide spray drift, the aerial transport of pesticide droplets off target areas during spray application, presents another pathway by which these chemicals can enter aquatic ecosystems. Unlike hydrological transport, pesticide physicochemical properties play a negligible role in aerial transport (although formulation does act as an influencing factor). Weather conditions (e.g., wind speed, temperature, and humidity), equipment type, application practices, and target crop all affect aerial transport. There is a better understanding of pesticide aerial drift to streams than that of hydrological pathways, either as a result of occurring in a less complex matrix, or as Reichenberger et al. (2007) asserts, due to aerial drift receiving more regulatory scrutiny.

Management of riparian areas can significantly reduce pesticide spray drift in many cases, particularly when conducted in conjunction with proper application practices. However, in their review of mitigation via windbreaks, Ucar and Hall (2001) found no general consensus on optimum riparian buffer widths to protect water quality. Their review reports that research has yielded buffer width recommendations that range from 20 to 150 ft (6 to 45 m) for ground application and 80 to over 4,000 ft (25 to over 1,200 m) for aerial application. Despite this lack of harmony in recommendations, individual cases have yielded positive results. Analysis of a forested riparian area in British Columbia found that a 25 ft (7.6 m) buffer limited the amount of herbicide reaching the stream to less than 0.1% of the aerial application (Feng et al. 1990). In an agricultural setting, a simple 10 ft (3 m) no-spray buffer reduced herbicide drift deposition to adjacent surface waters by 95%, and no measurable drift reached the stream at a width of 20 ft (6 m) as long as the wind-speed was below 15 mph (25 kph) in the direction towards the buffer (De Snoo and De Wit 1998). Many factors contribute to the effectiveness in reducing pesticide drift to acceptable levels. While wind-speed and application method exert significant impacts, vegetation height, density, orientation, and species composition all play pivotal roles. For instance, Ucar and Hall (2001) suggest that, in general, evergreen species display capture efficiencies 2 to 4 times greater than deciduous trees.

5.4.5. Pathogens

Pathogens impair more waterbodies in Washington than any other contaminant (USEPA 2015). Fecal contamination of surface waters can lead to the introduction of various pathogenic bacteria, fungi, viruses, protozoans, and worms that infect the gastrointestinal tract and present a health risk to both humans and wildlife. Common infections related to fecal pollution result from the presence of pathogenic bacteria such as *Escherichia coli* (*E. coli*), *Salmonella* spp. and *Vibrio* spp. or viruses such as Rotavirus. Primary pathogenic protozoans of concern include *Cryptosporidium parvum* and *Giardia lamblia,* which are able to form oocysts (protective spores) that allow them to survive outside of a host for long periods. Helminths represent a general class of parasitic worms, including flatworms and roundworms, which can act as intestinal parasites. The myriad pathogens that can be found in riverine systems following fecal contamination makes it impractical to list them here, but it is important to understand the four different pathogenic categories that can be conveyed to people through surface water contact or ingestion.

Pathogens comprise a diverse range of microorganisms that are typically found in low concentrations, making it impractical to test for specific pathogens when conducting water quality assessments. As an alternative, "pathogen indicator organisms" are used as a proxy to assess the potential presence of pathogens in a water sample. Commonly employed pathogen indicators include total coliforms, fecal coliforms, and *E. coli.* Total coliforms comprise a group of five genera of bacteria that easily can be analytically differentiated from other microorganisms, and while some occur naturally in soils, many are found in the gastrointestinal tract of warm-blooded animals and can serve as a general marker for fecal contamination. Fecal coliforms represent a sub-group of total coliforms that more specifically reside in the intestines of warm-blooded animals, making them a more accurate indication of the presence of fecal material in water. Washington water quality standards use fecal coliforms as indicator organisms to determine water quality impairment. *E. coli,* a species in the fecal coliform group, is a dominant inhabitant in the digestive tract and is generally considered the best indicator of fecal pollution of the three. As *E. coli* are indigenous enteric bacteria, they are not in themselves pathogenic although some strains are (e.g., *E. coli* O157:57). Although most of these indicator organisms are not pathogenic, it is common to refer to them as pathogens when discussing water quality (shortening the phrase "pathogens and pathogenic indicator organisms"), and while technically inaccurate, we will use that term in this section. We use the term in a way that should allow the reader to differentiate between whether we are referencing pathogens specifically or the broader group that includes pathogen indicator organisms.

As the pathogens in question are enteric, they are introduced into the environment through the feces of warm-blooded animals. Principal pathways for pathogens entering aquatic ecosystems are through direct defecation by livestock, wildlife, and pets in the riparian area and via overland flow carrying fecal material from upland pastures, animal feeding operations, fields that have received land-applied manures, or seepage from septic or sewage systems. Feces from domesticated dogs can be a predominant pathogen source in urban areas, as a study in Seattle attributed 30% of the fecal contamination to canines (Tobiason et al. 2002). Hobby farms also present an often-overlooked source adversely affecting water quality, and this has been shown to be an issue in Washington (Morace and McKenzie 2002).

The fate of pathogenic microorganisms in the environment is still not well understood in general and much uncertainty remains in the context of riparian areas. While many of the pathogens that can contaminate surface waters are obligate parasites,

some can persist outside of an animal's gastrointestinal tract in the environment. The length of time these microorganisms can survive under different conditions is a current topic of debate in the research community. The general assumption in the past was that these enteric organisms were not able to persist in the environment for more than a few days following excretion in feces. However, more recent research indicates that bacterial pathogens can survive for much longer periods, and it is generally recognized that persistence in the environment for two to three months is not uncommon. Longer survival rates are possible given the correct conditions, as demonstrated in a laboratory study where *E. coli* O157:H7 persisted for over 190 days in manure-amended soils (Jiang et al. 2002). General factors that influence the survival of pathogenic bacteria that enter riparian areas include soil moisture, temperature, pH, sunlight, nutrient availability, soil texture, and biological interactions. Moist, nutrient-laden, shady conditions such as those often found in riparian areas theoretically would provide an environment in which pathogens could survive longer, potentially being picked up by overland flow and introduced to adjacent stream channels.

Although considerable research has been conducted through the years on bacterial movement through environmental systems, research is in the nascent stages of examining the transport and fate of pathogens across the landscape and in riparian areas. Unc and Goss (2004) offer a concise review on the transport of bacteria from manure in relation to protecting water resources, and although the material presented does not focus on streamside areas it does provide fundamental information on the mechanisms involved in pathogen transport. The body of research that has examined pathogen attenuation in riparian areas is small although expanding, and almost all findings are related to vegetative filter strips and do not consider natural riparian ecosystems.

The capacity of vegetative filter strips to remove pathogens is not well established and research results have demonstrated that these systems exhibit great variability in their effectiveness in removing pathogens. A number of studies have shown that filter strips impart no significant influence on pathogen and pathogenic indicator organism concentrations moving toward a stream channel (Walker et al. 1990; Schellinger and Clausen 1992; Chaubey et al. 1995; Coyne at al. 1995; Entry et al. 2000). Contradictory findings have been generated by other studies that promote the idea that well maintained filter strips can serve as an effective BMP to prevent pathogens from reaching surface waterbodies (Coyne et al. 1998; Fajardo et al. 2001; Tate et al. 2006).

Inconsistent findings result from a number of factors. Soil infiltration, antecedent soil moisture conditions prior to a rain event, vegetation status, topography, and rainfall intensity and duration all have been identified as key controlling variables (Muñoz-Carpena et al. 1999; Guber et al. 2009). Each of these parameters relates to the concept that pathogens being carried in overland flow are removed by their infiltration into the soil where they typically are filtered or adsorbed to soil particles. High intensity rain events and concentrated flow can significantly reduce pathogen removal efficacy below that which would occur under low-flow conditions (Fox et al. 2011b). Vegetative filter strip width plays a significant role in pollutant removal, where a linear

Although considerable research has been conducted on bacterial movement through environmental systems, research is in the nascent stages of examining the transport and fate of pathogens across the landscape and in riparian areas.

decrease in pathogenic bacteria has been consistently observed with increasing buffer width (Young et al. 1980). However, a potential exists for trapped pathogens to later be remobilized in subsequent runoff events. Higher concentrations of pathogens have been recorded in runoff during a second runoff event, which suggests that filter strips could become indirect sources of pathogens under some conditions (Collins et al. 2004).

5.5. Effect of Riparian Buffer Width on Pollutant Removal

The pollutant removal function of riparian areas has been studied for at least 40 years (e.g., Doyle et al. 1975), and the enormous quantity of scientific research over the past four decades has motivated numerous reviews of the scientific literature (Norris 1993; Osborne and Kovacic 1993; Barling and Moore 1994; Vought et al. 1995; Fennesy and Cronk 1997; Lyons et al. 2000; Dosskey 2001; Hickey and Doran 2004; Lacas et al. 2005; Krutz et al. 2005; Polyakov et al. 2005; Hoffman et al. 2009; Dosskey et al. 2010). Despite the large quantity of research and number of literature reviews, no widely accepted recommendations have emerged on minimum buffer widths needed to protect water quality. The lack of agreement amongst scientists is due, in part, to the surprising complexity of the mechanisms that remove pollutants from surface and subsurface flows in riparian areas, to the variety of research methods used to study pollutant removal by riparian buffers, and to the many different environmental conditions at research sites.

The quantitative metric of pollutant removal by riparian areas is referred to as removal efficacy, removal efficiency, or percent removal. These measures are usually defined as:

$$E_R = \frac{m_{in} - m_{out}}{m_{in}} \times 100 \qquad (1)$$

where m_{in} and m_{out} are the mass or concentration of the pollutant entering and exiting a riparian buffer, respectively. The primary question addressed by nearly all research on the pollutant removal function of riparian areas, and by nearly all literature reviews, is how does riparian buffer width affect removal efficacy? The main answers are: 1) removal efficacy increases as buffer width increases, 2) topographic slope and vegetation type strongly affect removal efficacy, and 3) the relationship between removal efficacy and buffer width is highly variable.

In addition to the many literature reviews cited above, several statistical meta-analyses of research results (Mayer et al. 2007; Liu et al. 2008; Yuan et al. 2009; Zhang et al. 2010; Sweeney and Newbold 2014) provide synoptic perspectives on what is currently known about the relationship between buffer width and removal efficacy (Table 5.1). Research results from throughout the world were collected by all five meta-analyses, but the majority were from North America. The remainder of this section discusses the findings of those meta-analyses.

Four meta-analyses looked at the results of research on sediment removal. The meta-analyses found that buffer width alone explained 28% to 37% of the variance in sediment removal results. Models for removal efficacy versus buffer width predicted a wide range of buffer widths necessary for 90% efficacy: 33, 39, 75, and 170 ft (10, 12, 23, and 52 m) (Figure 5.2). Three of the meta-analyses found that adding slope as an independent variable significantly improved the fit of their models to the data. Two meta-analyses (Liu et al. 2008; Zhang et al. 2010) using the same studies but different modeling assumptions, found that optimum slope for sediment removal was about 10%. In other words, removal efficacy increased as slope increased from 1 to 10%, but then removal efficacy decreased as slope increased above 10%. However, extrapolating these findings to other locations should be done cautiously as this relationship may not hold under many conditions. Zhang et al. (2010) found that buffer width, slope,

and vegetation type together could explain 65% of the variance in sediment removal results. Curiously, they also found that buffers composed of grasses only or trees only were more efficacious at removing sediment than buffers composed of both grasses and trees (Figure 5.4).

Three separate meta-analyses looked at the results of research on nitrogen removal. The meta-analyses of Zhang et al. (2010) and Mayer at al. (2007) produced very different relationships for removal efficacy versus buffer width. Zhang et al. (2010) found that buffer width alone explained 44% of the variance in nitrogen removal results, but Mayer et al. (2007) found buffer width alone explained only 9%. Furthermore, Zhang et al. (2010) predicted that buffer widths of 80 ft (24 m) are necessary for 90% removal efficacy, while Mayer et al. (2007) predicted buffer widths of 436 ft (133 m) for the same efficacy (Figure 5.3). Separate models by Mayer et al. (2007) for surface and subsurface flows found a significant relationship (assuming $\alpha = 0.05$) between buffer width and removal efficacy for surface flows ($R^2 = 0.21$, $P = 0.03$) but not for subsurface flows ($R^2 = 0.02$, $P = 0.3$). Despite this result, Mayer et al. (2007) found that riparian buffers were more efficacious in removing nitrogen from subsurface waters than from surface waters. Mayer et al. (2007) found no significant relationship between nitrogen removal and buffer vegetation type but their collection of studies did show that buffers lacking trees (herbaceous cover only) were the least efficacious at removing nitrogen.

Zhang et al. (2010) found a relationship between vegetation type and nitrogen removal and that buffers composed of trees remove more nitrogen than buffers completely or partially composed of grasses. Zhang et al.'s model that included buffer width and vegetation type explained 49% of the variance in nitrogen removal results.

Comparing regression models for sediment and nitrogen removal (Figures 5.2 and 5.3) illustrates three important points regarding the pollutant removal function of riparian areas. First, the magnitude of removal efficacy for different pollutants can be very different. According to the models, 80% of sediment was removed at roughly 50 to 65 ft (15 to 20 m), but 80% removal of nitrogen may require buffer widths two to four times wider. Second, the variability of removal efficacy for various pollutants can be significantly different. The regression models for nitrogen removal show much more variation than the models for sediment removal. The wider variation is due, in part, to the greater complexity of the chemical and biological processes affecting nitrogen removal compared to the simpler physical processes affecting sediment removal. Hence, our ability to predict removal efficacy and our certainty about water quality protection can be very different for different pollutants. Third, for all pollutants the relationship between buffer width and removal efficacy follows a law of diminishing marginal returns. That is, the marginal (or incremental) amount of pollutant removal decreases as buffer width increases.

Zhang et al. (2010) also conducted meta-analysis for phosphorus and pesticides. Buffer width alone explained 35% of the variance in phosphorus removal results (Figure 5.5), and with the addition of vegetation as an independent variable, the model explained 47% of the variance. The buffer-width-only model predicts 89% phosphorus removal with a buffer 98 ft (30 m) wide.[7] Buffers with trees were found to remove more phosphorus than buffers completely or partially composed of grasses. The pesticide meta-analysis included 11 chemicals (norfluranzon, fluometuron, lindane, deisopropylatrazine, deethylatrazine, atrazine, permethrin, bromide, terbuthylazine, metolachlor, isoproturon). Buffer width alone explained 60% of the variance in pesticide removal results, and vegetation was found to be an insignificant predictor variable. The model predicts 92% pesticide removal with a buffer 65 ft (20 m) wide.

7 Because Zhang et al. (2010) assumed an asymptotic equation for their regression, the phosphorus model was invalid for efficacies greater than 89.5%.

Using data provided by Zhang et al. (2010), we calculated prediction intervals for their phosphorus model.[8] A prediction interval describes the precision of a model's predictions and the interval's width is a metric of uncertainty. For a buffer 33 ft (10 m) wide, the width of the 90% prediction interval is 64%. Therefore, while the model predicts that a 33 ft (10 m) buffer will provide an average removal efficacy of 70%, the actual removal efficacy obtained by another study on phosphorus removal (i.e., one which was not included in the meta-analysis) is likely to be somewhere between 38 and 100% (70% ± 32%). The low precision of the model's prediction interval is related to the unexplained variance that could be attributed to other variables not included in the regression, such as site slope and various soil properties.

Table 5.1. Descriptive information for functional relationships on sediment removal shown in Figure 5.2 and nitrogen removal shown in Figure 5.3. Reference numbers 1 through 4 correspond to numbers in Figures 5.2 and 5.3. In the equations, E_R is the removal efficacy, *width* is riparian buffer width, and *a*, *b*, *c*, *d*, and k_{50} are parameters determined through linear or nonlinear regression.

Pollutant	Meta-analysis	Form of equation	Model	*N****	R^2	*P* value
Sediment	(1) Liu et al. (2008)**	$E_R = a + b\ \ln(width)$	width	79	0.34	< 0.001
		$E_R = a + b \times width + c \times slope + d \times slope^2$	width & slope = 5% width & slope = 10% width & slope = 15%	79	0.43	< 0.0001
	(2) Yuan et al. (2009)	$E_R = a + b\ \ln(width)$	width	75	0.30	na*
			width & slope ≤ 5%	53	0.32	na
			width & slope > 5%	14	0.17	na
	(3) Zhang et al. (2010)**	$E_R = a\ (1 - e^{b \times width})$	width	81	0.37	< 0.0001
		$E_R = a\ (1 - e^{b \times width}) + c + d \times slope$	width & slope = 5% & grass or trees width & slope = 10% & grass or trees width & slope = 15% & grass or trees	81	0.65	< 0.001
	(4) Sweeney and Newbold (2014)	$E_R = \frac{width}{k_{50} + width}$	width	22	0.28	na
Nitrogen	(1) Mayer et al. (2007)	$E_R = a \times width^b$	width, surface water only	23	0.21	0.03
			width & herbaceous vegetation	32	0.21	0.009
			width & herbaceous/forest vegetation	11	0.39	0.04
	(2) Zhang et al. (2010)	$E_R = a\ (1 - e^{b \times width})$	width	61	0.44	< 0.0001
		$E_R = a\ (1 - e^{b \times width}) + c$	width & trees vegetation width & grass or mixed grass/trees veg.	61	0.49	< 0.001
	(3) Sweeney and Newbold (2014)†	$E_R = 100\ (1 - e^{b \times width/q})$	width & q set to 58‡ width & q set to 115	30	0.37	na*

* Signifies that *P* value was not reported in cited study.

** Nearly all the studies included by Liu et al. (2008) and Zhang et al. (2010) in their meta-analyses were the same studies.

*** *N* signifies number of studies in meta-analysis.

† Studies for subsurface nitrate removal only.

‡ q represents subsurface water flux. 58 and 115 L/m/day are median and mean subsurface water fluxes for studies collected by Sweeney and Newbold (2014).

[8] A prediction interval is a range that is likely to contain the dependent response value (Y_i) for a new observation (X_i). A prediction interval assumes that the new observation is taken from the same population used to create the regression equation.

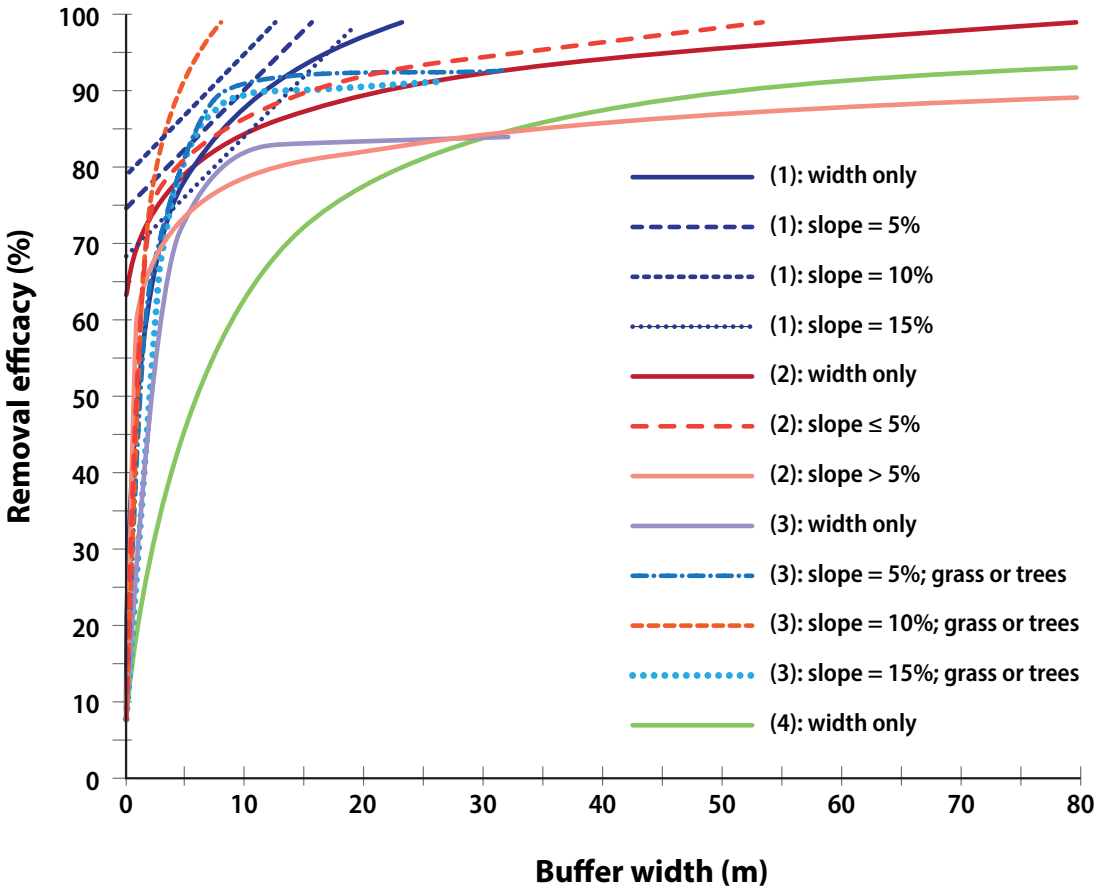


Figure 5.2. Relationships between sediment removal efficacy and riparian buffer width developed by four separate meta-analyses. Numbers in parentheses refer to different meta-analyses. See descriptive information in Table 5.1.

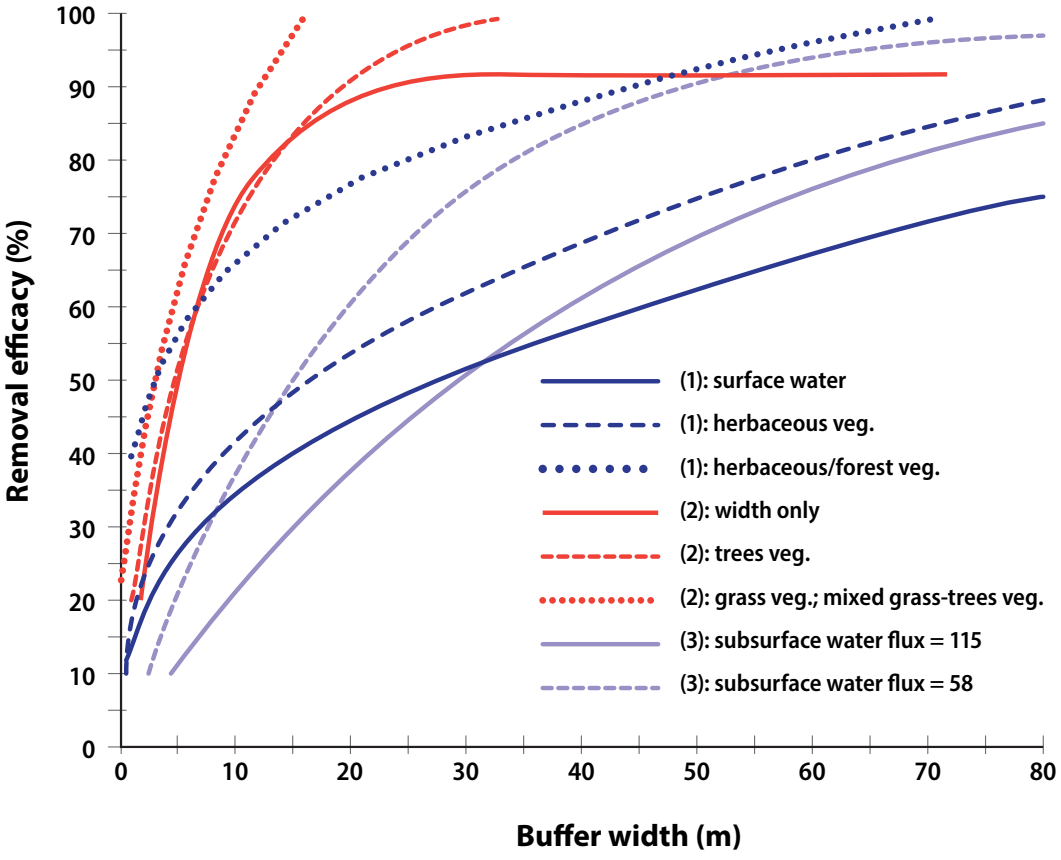


Figure 5.3. Relationships between nitrogen removal efficacy and riparian buffer width developed by three separate meta-analyses. Numbers in parentheses refer to different meta-analyses. See descriptive information in Table 5.1.

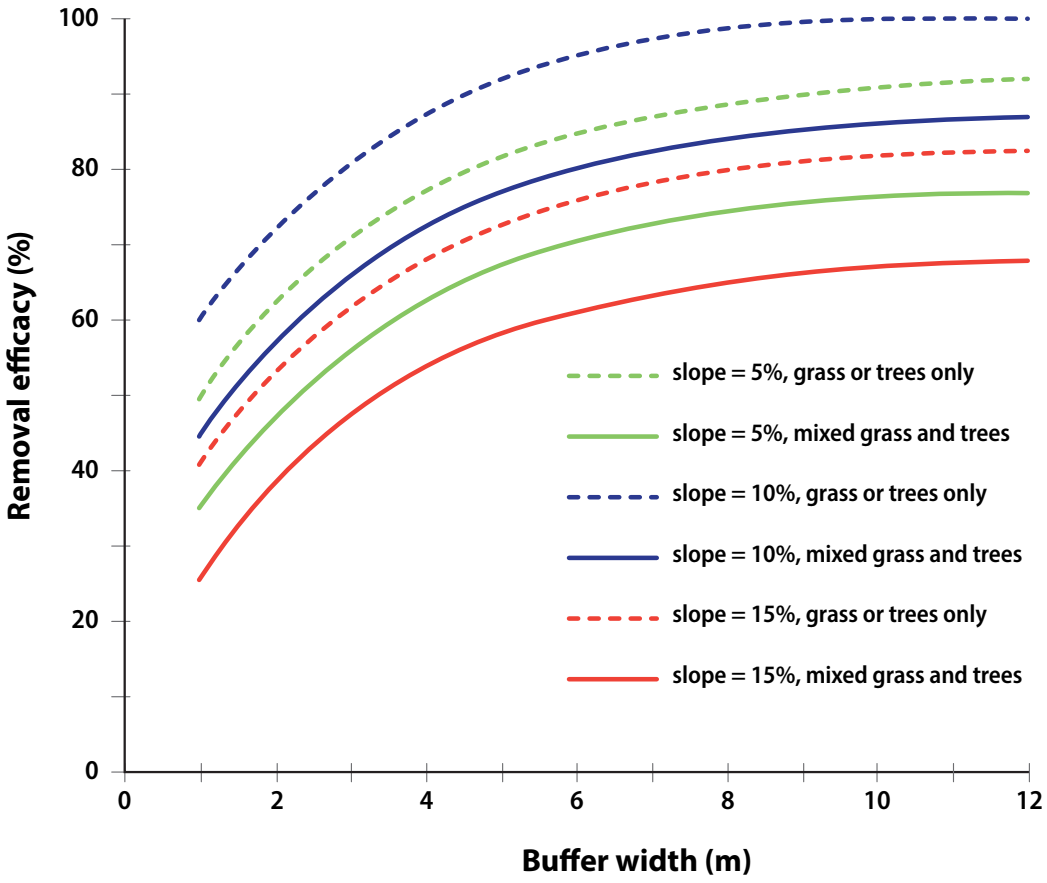


Figure 5.4. A result from meta-analysis of Zhang et al. (2010). Sediment removal efficacy as a function of buffer width, site slope, and buffer vegetation ($N = 81$, $R^2 = 0.65$, $P < 0.001$).

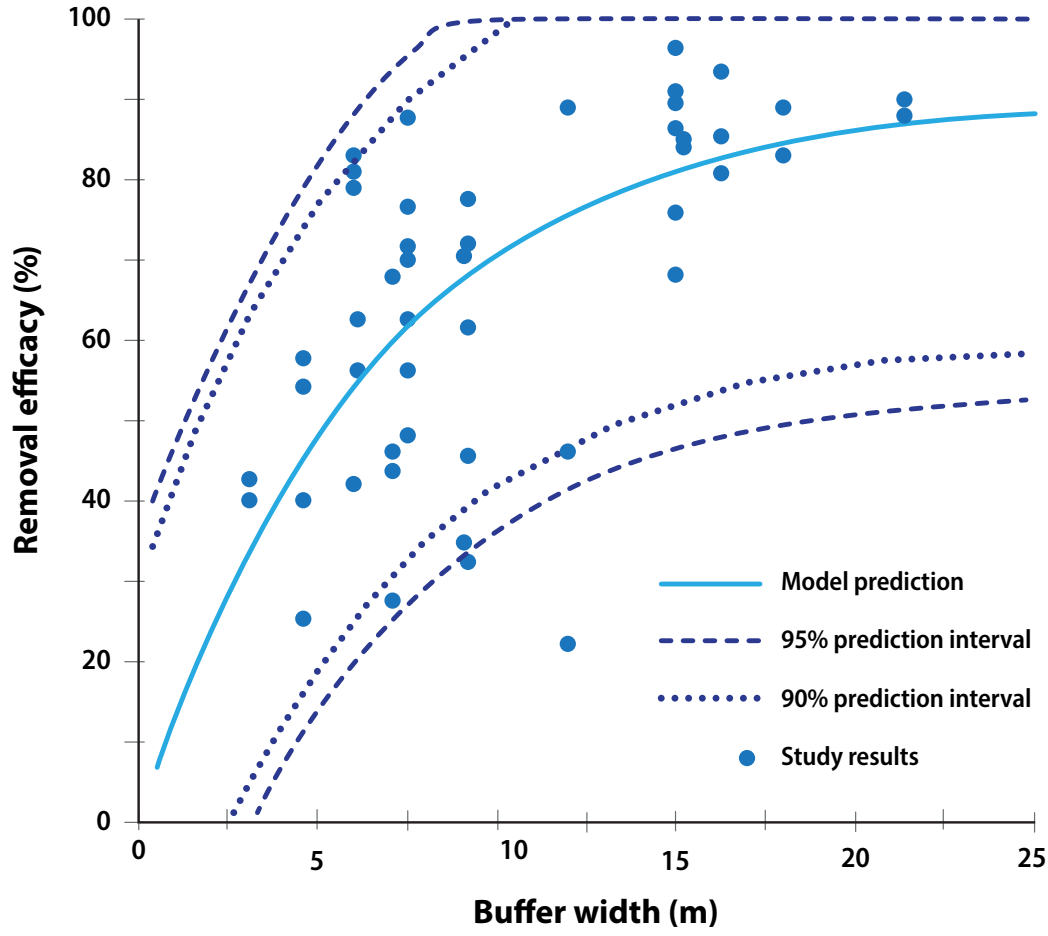


Figure 5.5. Meta-analysis of Zhang et al. (2010). Results of nonlinear regression for phosphorus removal efficacy as a function of buffer width ($N = 52$, $R^2 = 0.35$, $P < 0.0001$) with 90% and 95% prediction intervals.

5.6. Reanalysis of Meta-Analyses

A major assumption made by each of the meta-analyses was the type of equation that would result in the best fit to their data. Zhang et al. (2010), for instance, chose to use a nonlinear asymptotic equation of the form:

$$E_R = a\,(1 - e^{b \times width}) \qquad (2)$$

where E_R is removal efficacy, ***width*** refers to buffer width, and ***a*** and ***b*** are coefficients determined through nonlinear regression. In equation (2), *a* determines the maximum removal efficacy possible (i.e., it is an asymptote). Zhang et al. (2010) conducted their regression such that *a* could be less than 100%. For sediment, pesticide, nitrogen, and phosphorus pollutants, *a* equaled 91, 93, 92, and 89.5 percent, respectively. Hence, we could not determine buffer widths needed for removal efficacies greater than these values of *a* in their models. This limitation was particularly problematic for pesticides and phosphorus because Zhang et al. (2010) was the only meta-analysis for those pollutants.

To determine buffer widths needed for higher removal efficacies (90, 95, 99%), we reanalyzed Zhang et al.'s data with a nonlinear equation of the form:

$$E_R = a + b\ \ln(width) \qquad (3)$$

This form of model is the same used by Liu et al. (2008) and Yuan et al. (2009).[1] We performed linear regression in R (RCT 2013) using the lm function, but first we established that we could obtain the same regression results (same values for ***a*** and ***b***) as Zhang et al. (2010) using equation (2). This confirmed that the data we downloaded from the internet were the same data used by Zhang et al. (2010). We then redid the regression using equation (3). With the exception of sediment, the resulting models fit the data as well or better than the original models of Zhang et al. (2010) (Table 5.2). Graphical comparisons of our results and those of Zhang et al. (2010) are presented in Figure 5.6.

Table 5.2. Comparison of R^2 values for Zhang et al.'s (2010) model and our reanalysis using equation (3). *N* is the number of studies included in the meta-analysis.

Pollutant	*N*	R^2	
		Zhang et al. (2010)	Reanalysis
Sediment	81	0.37	0.31
Nitrogen	61	0.44	0.44
Phosphorus	52	0.35	0.39
Pesticides	49	0.60	0.61



Juvenile fish find shelter in a root wad/Terra Hegy, WDFW

1 Xuyang Zhang, the lead author of Zhang et al. (2010), also recommended that we use equation (3) because equation (2) cannot model 100% removal efficacy (X. Zhang, California Department of Pesticide Regulation, personal communication, May 14, 2019).

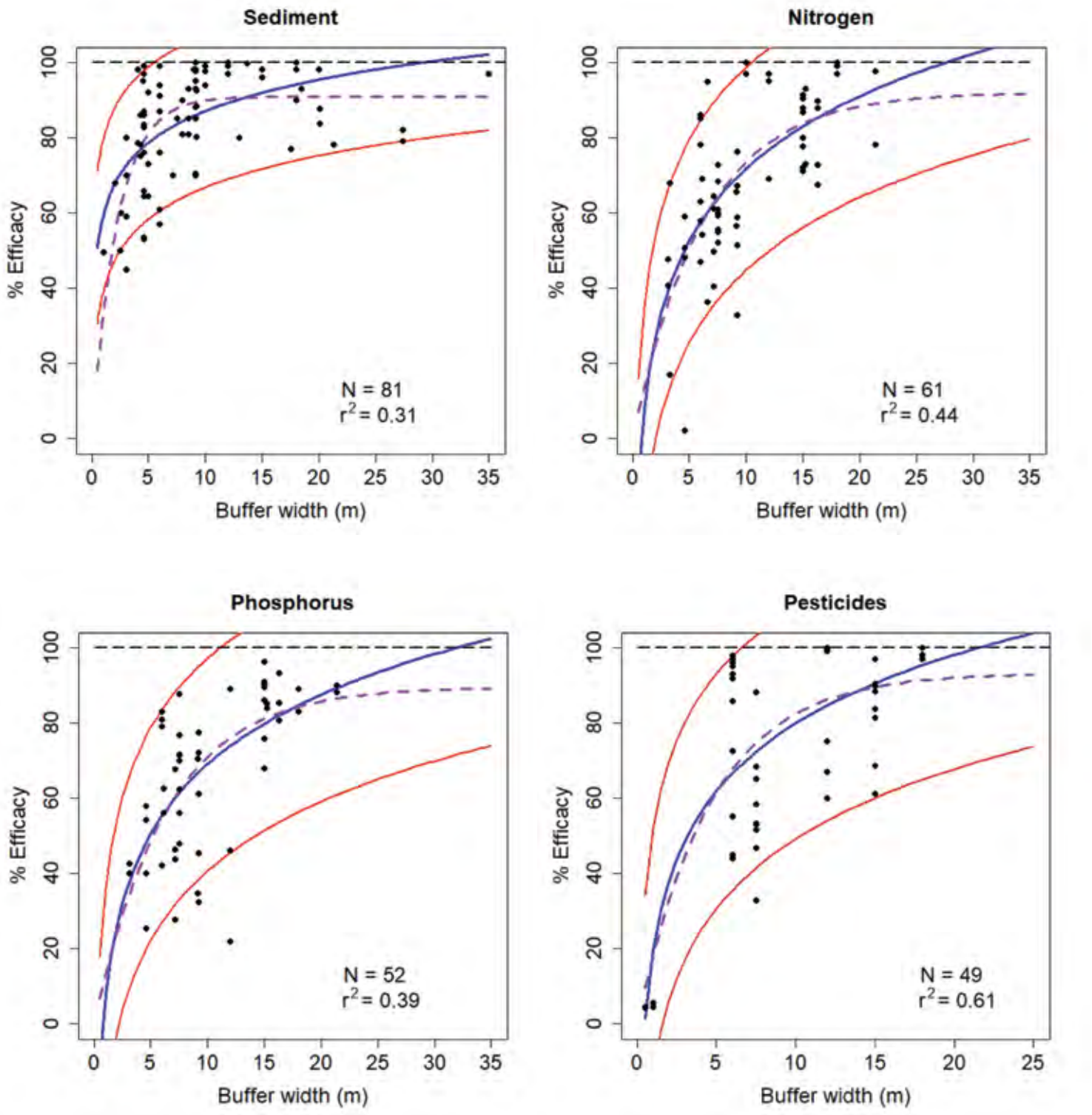


Figure 5.6. Relationship between removal efficacy and buffer width. Data from meta-analysis of Zhang et al. (2010) but reanalyzed using different form of nonlinear model. Line colors: blue: best fit model, red: 90% prediction interval, purple dashed: original model of Zhang et al. (2010), black dashed: 100% removal efficacy

We also reanalyzed two other meta-analyses – Mayer et al. (2007), and Sweeney and Newbold (2014) – for two reasons. The first reason was consistency across meta-analyses. The meta-analyses gave different answers for the relationship between removal efficacy and buffer width. For example, Zhang et al. (2010) predicted that buffer widths of 80 ft (24 m) are necessary for 90% removal efficacy of nitrogen, while Mayer et al. (2007) predicted buffer widths of 436 ft (133 m) for the same efficacy. Part of this discrepancy may be due to the type of equations adopted for their nonlinear or linear regressions, so we redid both meta-analyses using the same equation. Second, as noted earlier, a major assumption made by each of the meta-analyses was the type of equation that would result in the best fit to their data. We tested that assumption, and found that equation (3) often resulted in a better fit.

Mayer at al. (2007) chose to use a power function of the form:[2]

$$E_R = a\ width^b \qquad (4)$$

where ***a*** and ***b*** are coefficients determined through linear regression. We reanalyzed their data using equation (3). The resulting models fit the data as well or better than the original models of Mayer et al. (2007) (Table 5.3, Figure 5.7). For subsurface flow, the relationship between removal efficacy and buffer width was statistically insignificant ($P = 0.30$) and R^2 was only 0.02 for both their model and ours. We also note that both models produce somewhat absurd results – 60% of subsurface nitrogen can be removed with buffers only 2 ft wide but 90% removal requires buffers over 1200 ft wide. Hence, we will use neither model in further discussions of sub-surface nitrogen removal. For surface flow, the reanalysis resulted in a slightly better fit to the data – R^2 improved from 0.21 to 0.28.

We did not reanalyze the meta-analysis that Sweeny and Newbold (2014) did on studies of nitrogen removal from groundwater. While Sweeney and Newbold (2014)

Table 5.3. Comparison of R^2 values for Mayer et al.'s (2007) model and our reanalysis using equation (3). *N* is the number of studies included in the meta-analysis.

		Mayer et al. (2007)		Reanalysis	
Model	*N*	R^2	*P*	R^2	*P*
nitrogen, surface	23	0.21	0.03	0.28	0.009
nitrogen, subsurface	65	0.02	0.30	0.02	0.30

found a significant statistical relationship between nitrogen removal from subsurface flow and buffer width, other studies suggest the buffer width has little or no effect on nitrogen removal from subsurface flow (Hruby 2013, pp. 10-11).

For sediment removal, Sweeney and Newbold (2014) chose an equation of the form:

$$E_R = \frac{width}{k_{50} + width} \qquad (5)$$

where k_{50} equals the buffer width expected to remove 50% of sediments and it is determined through nonlinear regression. We reanalyzed their data using equation (3). The resulting model fits the data better than the original model of Sweeney and Newbold (2007). Their R^2 was 0.28 and the new R^2 is 0.33 (Figure 5.7).

Table 5.4 shows the buffer width needed to achieve desired levels of pollutant removal as predicted by meta-analyses and our reanalyses of meta-analyses. We combined predictions from multiple meta-analyses using a weighted average with the weights being the products of *N* and R^2. Note that values in Table 5.4 are predicted averages for removal efficacy. The actual efficacy realized by implementing a particular buffer width could be much better or worse. The amount of uncertainty in the realized removal efficacy is depicted by prediction intervals in Figures 5.6 and 5.7. The

2 The equation $E_R = a\ width^b$ can be transformed to the equation $\ln(E_R) = a' + b\ \ln(width)$, which is similar in structure to equation (3) and results in a similar fit to the data. Equation (3) was also the form used by Mayer et al. (2006).



Riparian areas capture pollutants/Marlin Greene, One Earth Images

reanalyzed meta-analysis of Zhang et al. (2010), for example, predicts that 90% of sediment can be removed with a 42 ft (13 m) wide buffer, however, according to the prediction interval, the buffer width needed for 90% removal could be as narrow as 8 ft (2.4 m) or as wide as 225 ft (69 m). Better models that include other independent variables, such as slope and vegetation (e.g., Zhang et al. 2010), will reduce this uncertainty, but there is a trade-off. The application of more complicated models leads to more complicated management. If, for example, managers adopted a model that includes vegetation type or vegetation structure, then, in addition to buffer width, they must also manage the condition of vegetation within the buffer.

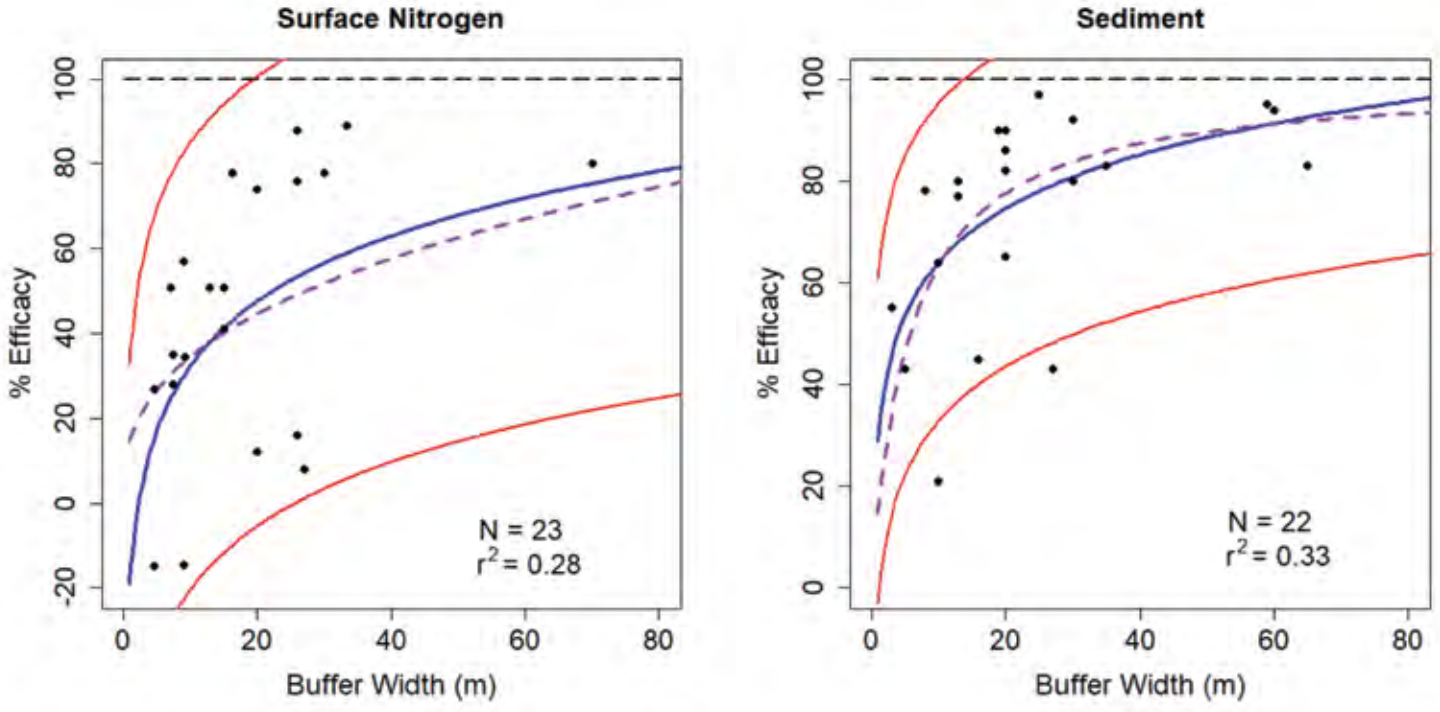


Figure 5.7. Relationship between removal efficacy and buffer width. Study results from meta-analyses reanalyzed using different form of equation in a linear regression. Left: nitrogen study results from Mayer et al. (2007). Right: sediment study results from Sweeney and Newbold (2014). Line colors: blue: best fit model, red: 90% prediction interval, purple dashed: original models from meta-analyses, black dashed: 100% removal efficacy.

Table 5.4. Buffer width in feet needed to achieve desired levels of pollutant removal from run-off. Buffer width calculated with model and/or data from the cited literature. Models had only one predictor variable, which was buffer width. Mean buffer width for sediment and nitrogen removal are weighted averages of widths determined by each meta-analysis. Weights were the product of *N* and R^2.

				Average Removal Efficacy (%)	80	90	95	99
Pollutant	**Meta-analysis**	***N***	***R^2***	**Buffer Width (ft)**				
Sediment	Liu et al. (2008)*	79	0.34		18	39	56	76
	Yuan et al. (2009)	75	0.30		18	74	149	261
	Zhang et al. (2010)*, *reanalyzed*	81	0.31		18	42	64	89
	Sweeney and Newbold (2014), *reanalyzed*	22	0.33		94	181	251	326
				Weighted mean	**25**	**62**	**101**	**153**
Nitrogen, surface	Mayer et al. (2007), *reanalyzed*	23	0.28		283	444	556	666
	Zhang et al. (2010), *reanalyzed*	61	0.44		44	63	76	88
				Weighted mean	**90**	**137**	**169**	**200**
Nitrogen, subsurface	Sweeney and Newbold (2014) ‡	30	0.37		112	161	210	322
Phosphorus	Zhang et al. (2010), *reanalyzed*	52	0.39		50	72	87	101
Pesticides	Zhang et al. (2010), *reanalyzed*	49	0.61		33	48	59	68

* Nearly all the studies included by Liu et al. (2008) and Zhang et al. (2010) were the same studies.

‡ The parameter q, which represents subsurface water flux, was set to 58, which is the median value for 30 studies analyzed by Sweeney and Newbold (2014).

5.7. Conclusions

There is a consensus in the scientific literature that riparian areas reduce the flow of pollutants to aquatic ecosystems, and that pollutant removal functions are contingent on complex interactions between hydrology, soil, and vegetation, and are influenced by many other factors as well. Because hydrology, soil, vegetation and other factors exhibit high spatial and temporal variability, the efficacy of pollutant removal functions provided by riparian areas differs substantially among sites, as well as within sites. Determining the potential for riparian areas to protect water quality is further complicated by the disparate behavior of different contaminant types in the environment. While space limitations required us to simplify this review of the scientific literature regarding pollutant removal functions of riparian areas, we provided the basic information needed for understanding these important ecological functions.

Our review of the literature presents a substantial body of scientific research with which to develop strategies, plans, or policies regarding the pollutant removal functions of riparian areas. The central problem faced by resource managers is determining the adequate riparian buffer width, composition, and structure to protect water quality with high degrees of efficacy, efficiency, and certainty. Riparian function is often simplistically characterized by buffer width and vegetation type, but these parameters only partially explain the effects that riparian areas have on pollutant removal. The current conservation paradigm remains strongly tied to the

premise that wider riparian areas are the only way to increase pollutant removal efficacy, but this is not always the case; other site-specific factors, such as conditions within the buffer, also exert a significant influence on removal efficacy. Therefore, consideration of the entire system (i.e., riparian area, uplands, vegetation, soils, ground and surface water pathways, topography, type of pollutant, etc.) is essential to developing cost-effective pollutant removal. In theory, buffer width and vegetation could be optimized for site conditions such that water quality is protected while minimizing economic costs for landowners.

Despite the many scientific uncertainties, management decisions must be made. Management decisions regarding pollutant removal by riparian buffers should be informed by science, but determining the "right" buffer width for pollutant removal cannot be purely scientific. Determining the "right" buffer width begins with choosing a desired removal efficacy, and that choice is normative. That is, the desired removal efficacy is a social choice influenced by cultural values, economic costs, and risk tolerance. Choosing a desired removal efficacy and determining the "right" buffer requires: 1) factual information regarding the anticipated impacts or outcomes of policy options (i.e., science); 2) an understanding of stakeholders' priorities and preferences (i.e., values); and 3) a process for using science and values to explore tradeoffs amongst policy options (Wilhere and Quinn 2018).

5.8. Literature Cited[3]

Ahmad, M., A.U. Rajapaksha, J.E. Lim, M. Zhang, N. Bolan, D. Mohan, M. Vithanage, S.S. Lee, and Y.S. Ok. 2014. Biochar as a sorbent for contaminant management in soil and water: a review. Chemosphere 99:19-33. (i)

Allaire, S.E., C. Sylvain, S.F. Lange, G. Thériault, and P. Lafrance. 2015. Potential efficiency of riparian vegetated buffer strips in intercepting soluble compounds in the presence of subsurface preferential flows. PLoS ONE 10: e0131840. (i)

Alvarez, M.D., and L.A. Fuiman. 2005. Environmental levels of atrazine and its degradation products impair survival skills and growth of Red Drum larvae. Aquatic Toxicology 74:229-241. (i)

Anbumozhi, V., J. Radhakrishnan, and E. Yamaji. 2005. Impact of riparian buffer zones on water quality and associated management considerations. Ecological Engineering 24:517-523. (i)

Angier, J.T., G.W. McCarty, C.P. Rice, and K. Bialek. 2002. Influence of a riparian wetland on nitrate and herbicides exported from an agricultural field. Journal of Agricultural and Food Chemistry 50:4424-4429. (i)

Au, D.W.T., C.A. Pollino, R.S.S. Wu, P.K.S. Shin, S.T.F. Lau, and J.Y.M. Tang. 2004. Chronic effects of suspended solids on gill structure, osmoregulation, growth, and triiodothyronine in juvenile Green Grouper *Epinephelus coioides.* Marine Ecology Progress Series 266:255-264. (i)

Backer, L.C., J.H. Landsberg, M. Miller, K. Keel, and T.K. Taylor. 2011. Canine cyanotoxin poisonings in the United States (1920s-2012): review of suspected and confirmed cases from three data sources. Toxins 5:1597-1628. (i)

Baldwin, D.H., J.F. Sandahl, J.S. Labenia, and N.L. Scholz. 2003. Sublethal effects of copper on Coho Salmon: impacts on non-overlapping receptor pathways in the peripheral olfactory nervous system.

[3] References are classified according to RCW 34.05.271 (see Appendix 1) denoted by a lower case roman numeral (i – viii) in parentheses at the end of the citation.

Environmental Toxicology and Chemistry 22:2266-2274. (i)

Barling, R.D., and I.D. Moore. 1994. Role of buffer strips in management of waterway pollution: a review. Environmental Management 18:543-558. (i)

BLM (Bureau of Land Management). 2003. Riparian area management: riparian-wetland soils. Technical Reference 1737-19. Denver. (viii)

Boening, D.W. 2000. Ecological effects, transport, and fate of mercury: a general review. Chemosphere 40:1335-1351. (i)

Bohn, C.C., and J.C. Buckhouse. 1985. Some responses of riparian soils to grazing management in northeastern Oregon. Journal of Range Management 38:378-381. (i)

Bolan, N., A. Kunhikrishnan, R. Thangarajan, J. Kumpiene, J. Park, T. Makino, M.B. Kirkham, and K. Scheckel. 2014. Remediation of heavy metal(loid)s contaminated soils–to mobilize or to immobilize? Journal of Hazardous Materials 266:141-166. (i)

Boonchan, S., M.L. Britz, and G.A. Stanley. 2000. Degradation and mineralization of high-molecular-weight polycyclic aromatic hydrocarbons by defined fungal-bacterial cocultures. Applied and Environmental Microbiology 66:1007-1019. (i)

Bourret, M.M., J.E. Brummer, and W.C. Leininger. 2009. Establishment and growth of two willow species in a riparian zone impacted by mine tailings. Journal of Environmental Quality 38:693-701. (i)

Bradford, S.A., and S. Torkzaban. 2008. Colloid transport and retention in unsaturated porous media: a review of interface-, collector-, and pore-scale processes and models. Vadose Zone Journal 7:667-681. (i)

Buffler, S., C. Johnson, J. Nicholson, and N. Mesner. 2005. Synthesis of design guidelines and experimental data for water quality function in agricultural landscapes in the Intermountain West. National Agroforestry Center, Lincoln, Nebraska. (viii)

Burt, T.P., L.S. Matchett, W.T. Goulding, C.P. Webster, and N.E. Haycock. 1999. Denitrification in riparian buffer zones: the role of floodplain hydrology. Hydrologic Processes 13:1451-1463. (i)

Canet, R., J.G. Brinsting, D.G. Malcolm, J.M. Lopez-Real, and A.J. Beck. 2001. Biodegradation of polycyclic aromatic hydrocarbons (PAHs) by native microflora and combinations of white-rot fungi in a coal-tar contaminated soil. Bioresource Technology 76:113-117. (i)

Castelle, A.J., A.W. Johnson, and C. Conolly. 1994. Wetland and stream buffer size requirements–a review. Journal of Environmental Quality 23:878-882. (i)

Cedergreen, N. 2014. Quantifying synergy: a systematic review of mixture toxicity studies within environmental toxicology. PLoS ONE 9:e96580. (i)

Cey E.E., D.L. Rudolph, R. Aravena, and G. Parkin. 1999. Role of the riparian zone in controlling the distribution and fate of agricultural nitrogen near a small stream in southern Ontario. Journal of Contaminant Hydrology 37:45–67. (i)

Chaubey, I., D.R. Edwards, T.C. Daniel, P.A. Moore, and D.J. Nichols. 1995. Effectiveness of vegetative filter strips in controlling losses of surface-applied poultry litter constituents. Transactions of the American Society of Agricultural Engineers 38:1687-1692. (i)

Cheng, Z.Q., E.L. McCoy, and P.S. Grewal. 2014. Water, sediment, and nutrient runoff from urban lawns established on disturbed subsoil or topsoil and managed with inorganic or organic fertilizers. Urban Ecosystems 17:277-289. (i)

Clements, W.H., D.S. Cherry, and J. Cairns, Jr. 1990. Macroinvertebrate community responses to copper in laboratory and field experimental streams. Archives of Environmental Contaminants and Toxicology 19:361-365. (i)

Clinton, B.D. 2011. Stream water responses to timber harvest: riparian buffer width effectiveness. Forest Ecology and Management 261:979-988. (i)

Colborn, T., F.S.V. Saal, and A.M. Soto. 1993. Developmental effects of endocrine-disrupting chemicals in wildlife and humans. Environmental Health Perspectives 101:378-384. (i)

Collins, R., A. Donnison, C. Ross, and M. McLeod. 2004. Attenuation of effluent-derived faecal microbes in grass buffer strips. New Zealand Journal of Agricultural Research 47:565-574. (i)

Cooper, J.R., and J.W. Gilliam. 1987. Phosphorus redistribution from cultivated fields into riparian areas. Soil Science Society of American Journal 51:1600-1604. (i)

Cors, M., and B. Tychon. 2007. Grassed buffer strips as nitrate diffuse pollution remediation tools: management impact on the denitrification enzyme activity. Water Science and Technology 55:25-30. (i)

Correll, D.L. 1997. Buffer zones and water quality protection: general principles. Pages 7-20 *in* N. Hancock, T. Burt, K. Goulding, and G. Pinay, editors. Buffer zones: their processes and potential in water protection. Quest Environmental, Hertfordshire, United Kingdom. (viii)

Covaci, A., S. Harrad, M.A.E. Abdallah, N. Ali, R.J. Law, D. Herzke, and C.A. de Wit. 2011. Novel brominated flame retardants: a review of their analysis, environmental fate and behavior. Environment International 37:532-556. (i)

Coyne, M.S., R.A. Gilfillen, R.W. Rhodes, and R.L. Blevins. 1995. Soil and fecal-coliform trapping by grass filter strips during simulated rain. Journal of Soil and Water Conservation 50:405-408. (i)

Coyne, M.S., R.A. Gilfillen, A. Villalba, Z. Zhang, R. Rhodes, L. Dunn, and R.L. Blevins. 1998. Fecal bacteria trapping by grass filter strips during simulated rain. Journal of Soil and Water Conservation 53:140-145. (i)

Daniels, R.B., and J.W. Gilliam. 1996. Sediment and chemical load reduction by grass and riparian filters. Soil Science Society of America Journal 60:246-251. (i)

De Snoo, G.R., and P.J. De Witt. 1998. Buffer zones for reducing pesticide drift to ditches and risks to aquatic organisms. Ecotoxicology and Environmental Safety 41:112-118. (i)

Delle Site, A. 2001. Factors affecting sorption of organic compounds in natural sorbent/water systems and sorption coefficients for selected pollutants—a review. Journal of Physical and Chemical Reference Data 30:187-439. (i)

Dillaha, T.A., R.B. Reneau, S. Mostaghimi, and D. Lee. 1989. Vegetative filter strips for agricultural nonpoint source pollution control. Transactions of American Society of Agricultural Engineers 32:513-519. (i)

Dorioz, J.M., D. Wang, J. Poulenard, and D. Trévisan. 2006. The effect of grass buffer strips on phosphorus dynamics—a critical review and synthesis as a basis for application in agricultural landscapes in France. Agriculture, Ecosystems and Environment 117:4-21 (i)

Dosskey, M.G. 2001. Toward quantifying water pollution abatement in response to installing buffers on crop land. Environmental Management 28:577-598. (i)

Dosskey, M.G., M.J. Helmers, D.E. Eisenhauer, T.G. Franti, and K.D. Hoagland. 2002. Assessment of concentrated flow through riparian buffers. Journal of Soil and Water Resources Association 57:336-343. (i)

Dosskey, M.G., P. Vidon, N.P. Gurwick, C.J. Allan, T.P. Duval, and R. Lowrance. 2010. The role of riparian vegetation in protecting and improving chemical water quality in streams. Journal of the American Water Resources Association 46:261-277. (i)

Doyle, R.C., D.C. Wolf, and D.F. Bezdicek. 1975. Effectiveness of forest buffer strips in improving the water quality of manure polluted runoff. Pages 299-302 *in* Managing livestock wastes. Proceedings of 3rd international symposium on livestock wastes. Food and Agricultural Organization of the United Nations, Rome. (viii)

Du Laing, G., J. Rinklebe, B. Vandecasteele, E. Meers, and F.M.G. Tack. 2009. Trace metal behavior in estuarine and riverine floodplain soils and sediments: a review. Science of the Total Environment 407:3972-3985. (i)

Ecology (Washington State Department of Ecology). 2007. Mission Creek watershed DDT total maximum daily load: water quality improvement report. Publication number 07-10-046. Olympia, Washington. (viii)

Entry, J.A., R.K. Hubbard, J.E. Thies, and J.J. Fuhrmann. 2000. The influence of vegetation in riparian filterstrips on coliform bacteria: II. Survival in soils. Journal of Environmental Quality 29:1215-1224. (i)

Euliss, K., C. Ho, A.P. Schwab, S. Rock, and M.K. Banks. 2008. Greenhouse and field assessment of phytoremediation for petroleum contaminants in a riparian zone. Bioresource Technology 99:1961-1971. (i)

Fajardo, J.J., J.W. Bauder, and S.D. Cash. 2001. Managing nitrate and bacteria in runoff from livestock confinement areas with vegetative filter strips. Journal of Soil and Water Conservation 56:185-191. (i)

Feng, J.C., D.G. Thompson, and P.E. Reynolds. 1990. Fate of glyphosate in a Canadian Forest Watershed. 1. Aquatic residues and off-target deposit assessment. Journal of Agricultural and Food Chemistry 38:1110-1118. (i)

Fennesy, M.S., and J.K. Cronk. 1997. The effectiveness and restoration potential of riparian ecotones for the management of nonpoint source pollution, particularly nitrate. Critical Reviews in Environmental Science and Technology 27:285-317. (i)

Fisher, R.F., and D. Binkley. 2000. Ecology and management of forest soils. Wiley, New York. (i)

Fischer, R.A., and J.C. Fischenich. 2000. Design recommendations for riparian corridors and vegetative buffer strips. U.S. Army Engineer Research and Development Center, Vicksburg, Mississippi. (viii)

Fleeger, J.W., K.R. Carman, and R.M. Nisbet. 2003. Indirect effects of contaminants in aquatic ecosystems. Science of the Total Environment 317:207-233. (i)

Fox, G.A., D.M. Heeren, R.B. Miller, A.R. Mittelstet, and D.E. Storm. 2011a. Flow and transport experiments for a streambank seep originating from a preferential flow pathway. Journal of Hydrology 403:360-366. (i)

Fox, G.A., E.M. Matlock, J.A. Guzman, D. Sahoo, and K.B. Stunkel. 2011b. *Escherichia coli* load reduction from runoff by vegetative filter strips: a laboratory-scale study. Journal of Environmental Quality 40:980-988. (i)

Fuchs, J.W., G.A. Fox, D.E. Storm, C.J. Penn, and G.O. Brown. 2009. Subsurface transport of phosphorus in riparian floodplains: influence of preferential flow paths. Journal of Environmental Quality 38:473-484. (i)

Garcia-Muñoz, E., F. Guerrero, and G. Parra. 2011. Larval escape behavior in anuran amphibians as a wetland rapid pollution biomarker. Marine and Freshwater Behaviour and Physiology 44:109-123. (i)

Ghosh, M., and S.P. Singh. 2005. A review of phytoremediation of heavy metals and utilization of its byproducts. Applied Ecology and Environmental Research 3:1-18. (i)

Gonod, L.V., F. Martin-Laurent, and C. Chenu. 2006. 2,4-D impact on bacterial communities, and the activity and genetic potential of 2,4-D degrading communities in soil. FEMS Microbiology Ecology 58:529-537. (i)

Gordon, N.D., T.A. McMahon, B.L. Finlayson, C.J. Gippel, and R.J. Nathan. 2004. Stream hydrology: an introduction for ecologists. Wiley, West Sussex, England. (i)

Grathwohl, P. 1990. Influence of organic matter from soils and sediments from various origins on the sorption of some chlorinated aliphatic hydrocarbons: Implications on K_{OC} correlations. Environmental Science & Technology 24:1687-1693. (i)

Groffman, P.M., E.A. Axelrod, J.L. Lemonyon, and W.M. Sullivan. 1991. Dentrification in grass and forest vegetated filter strips. Journal of Environmental Quality 20:671-674. (i)

Gu, C., W. Anderson, and F. Maggi. 2012. Riparian biogeochemical hot moments induced by stream fluctuation. Water Resources Research 48:W09546. (i)

Guan, K., S.E. Thompson, C.J. Harman, N.B. Basu, P.S.C. Rao, M. Sivapalan, A.I. Packman, and P.K. Kalita. 2011. Spatiotemporal scaling of hydrological and agrochemical export dynamics in a tile-drained midwestern watershed. Water Resources Research 47:W00J02. (i)

Guber, A.K., A.M. Yakirevich, A.M. Sadeghi, Y.A. Pachepsky, and D.R. Shelton. 2009. Uncertainty evaluation of coliform bacteria removal from vegetative filter strip under overland flow condition. Journal of Environmental Quality 38:1636-1644. (i)

Haritash, A.K., and C.P. Kaushik. 2001. Biodegradation aspects of polycyclic aromatic hydrocarbons (PAHs): a review. Journal of Hazardous Materials 169:1-15. (i)

Hawes, E., and M. Smith. 2004. Riparian buffer zones: functions and recommended widths. Yale School of Forestry and Environmental Studies, New Haven, Connecticut. (viii)

Hayashi, M., and D.O. Rosenberry. 2002. Effects of ground water exchange on the hydrology and ecology of surface water. Ground Water 40:309–316. (i)

Hayes, M.H.B. 1970. Adsorption of triazine herbicides on soil organic matter, including a short review on soil organic matter chemistry. Residue Reviews 32:137-174. (i)

Hayes, T., K. Haston, M. Tsui, A. Hoang, C. Haeffele, and A. Vonk. 2003. Atrazine-induced hermaphroditism at 0.1 ppb in American Leopard Frogs *Rana pipiens*: laboratory and field evidence. Environmental Health Perspectives 111:568-575. (i)

Hecht, S.A., D.H. Baldwin, C.A. Mebane, T. Hawkes, S.J. Gross, and N.L. Scholz. 2007. An overview of sensory effects on juvenile salmonids exposed to dissolved copper: applying a benchmark concentration approach to evaluate sublethal neurobehavioral toxicity. Tech Memo NMFS-NWFSC-83. National Marine Fisheries Service, Seattle. (viii)

Hedin, L.O., J.C. von Fischer, N.E. Ostrom, B.P. Kennedy, M.G. Brown, and G.P. Robertson. 1998. Thermodynamic constraints on nitrogen transformations and other biogeochemical processes at soil-stream interfaces. Ecology 79:684-703. (i)

Hickey, M.B., and B. Doran. 2004. A review of efficiency of buffer strips for the maintenance and enhancement of riparian ecosystems. Water Quality Research Journal of Canada 39:311-317. (i)

Hoffmann, C.C., C. Kjaergaard, J. Uusi-Kämppä, H.C.B. Hansen, and B. Kronvang. 2009. Phosphorus retention in riparian buffers: review of their efficiency. Journal of Environmental Quality 38:1942-1955. (i)

Hill, A.R. 1996. Nitrate removal in stream riparian zones. Journal of Environmental Quality 25:743-755. (i)

Hruby, T. 2013. Update on wetland buffers: the state of the science, final report. Washington State Department of Ecolgy, Olympia, Washington. (viii)

Hua, J., and R. Relyea. 2014. Chemical cocktails in aquatic systems: pesticide effects on the response and recovery of >20 animal taxa. Environmental Pollution 189(June):18-26. (i)

Huggenberger, P., E. Hoehn, R. Beschta, and W. Woessner. 1998. Abiotic aspects of channels and floodplains in riparian ecology. Freshwater Biology 40:407-425. (i)

Ingersoll, C.G., and R.W. Winner. 1982. Effect on *Daphnia pulex* (De Geer) of daily pulse exposures to copper or cadmium. Environmental Toxicology and Chemistry 1:321-327. (i)

Jarvie, H.P., A.N. Sharpley, B. Spears, A.R. Buda, L. May, and P.J.A. Kleinman. 2013. Water quality remediation faces unprecedented challenges from "legacy phosphorus". Environmental Science & Technology 47:8997–8998. (i)

Jaynes, D.B., and T.M. Isenhart. 2014. Reconnecting tile drainage to riparian buffer hydrology for enhanced nitrate removal. Journal of Environmental Quality 43:631-638. (i)

Jiang, X., J. Morgan, and M.P. Doyle. 2002. Fate of *Escherichia coli* O157:H7 in manure-amended soil. Applied and Environmental Microbiology 68:2605-2609. (i)

Johnson, C.W., and S. Buffler. 2008. Riparian buffer design guidelines for water quality and wildlife habitat functions on agricultural landscapes in the Intermountain West. RMRS-GTR-203. U.S. Forest Service, Rocky Mountain Research Station, Fort Collins, Colorado. (viii)

Jones, G.K. 2009. Bioremediation of contaminated riparian zones using mycorrhizal fungi–an exploration of the feasibility of restoration through mycoremediation. Master's thesis. The Evergreen State College, Olympia, Washington. (i)

Kalbus, E., C. Schmidt, J.W. Molson, F. Reinstorf, and M. Schirmer. 2009. Influence of aquifer and streambed heterogeneity on the distribution of groundwater discharge. Hydrology and Earth System Sciences 13:69-77. (i)

Karthikeyan, R., L.C. Davis, L.E. Erickson, K. Al-Khatib, P.A. Kulakow, P.L. Barnes, S.L. Hutchinson, and A.A. Nurzhanova. 2004. Potential for plant-based remediation of pesticide-contaminated soil and water using nontarget plants such as trees, shrubs, and grasses. Critical Reviews in Plant Sciences 23:91-101. (i)

Khan, S.U. 1972. Adsorption of pesticide by humic substances—a review. Environmental Letters 3:1-12. (i)

Kopinke, F.D., A. Georgi, and K. Mackenzie. 2001. Sorption of pyrene to dissolved humic substances and related model polymers. 1. Structure-property correlation. Environmental Science & Technology 35:2536-2542. (i)

Koptsik, G.N. 2014. Problems and prospects concerning the phytoremediation of heavy metal polluted soils: a review. Eurasian Soil Science 47:923-939. (i)

Krutz, L.J., S.A. Senseman, R.M. Zablotowicz, and M.A. Matocha. 2005. Reducing herbicide runoff from agricultural fields with vegetative filter strips: a review. Weed Science 53:353-367. (i)

Kuglerová, L., A. Ågren., R. Jansson, and H. Laudon. 2014. Towards optimizing riparian buffer zones: ecological and biogeochemical implications for forest management. Forest Ecology and Management 334:74-84. (i)

Kümmerer, K. 2009a. Antibiotics in the aquatic environment—a review—Part I. Chemosphere 75:417-434. (i)

Kümmerer, K. 2009b. Antibiotics in the aquatic environment—a review—Part II. Chemosphere 75:435-441. (i)

Lacas, J., M. Voltz, V. Gouy, N. Carluer, and J. Gril. 2005. Using grassed strips to limit pesticide transfer to surface water: a review. Agronomy for Sustainable Development 25:253-266. (i)

Laetz, C.A., D.H. Baldwin, V. Hebert, J.D. Stark, and N.L. Scholz. 2013. Interactive neurobehavioral toxicity of diazinon, malathion, and ethopop to juvenile Coho Salmon. Environmental Science & Technology 47:2925-2931. (i)

Laghlimi, M., B. Baghdad, H. El Hadi, and A. Bouabdli. 2015. Phytoremediation mechanisms of heavy metal contaminated soils: a review. Open Journal of Ecology 5:375-388. (i)

Lamar, R.T., J.W. Evans, and J.A. Glaser. 1993. Solid-phase treatment of a pentachlorophenol-contaminated soil using lignin-degrading fungi. Environmental Science & Technology 27:2566-2571. (i)

Landmeyer, J.E. 2011. Introduction to phytoremediation of contaminated groundwater: historical foundation, hydrologic control, and contaminant remediation. Springer Science& Business Media, New York. (i)

Lee, K.H., T.M. Isenhart, and R.C. Schultz. 2003. Sediment and nutrient removal in an established multi-species riparian buffer. Journal of Soil and Water Conservation 58:1-8. (i)

Lee, P., C. Smith, and S. Boutin. 2004. Quantitative review of riparian buffer width guidelines from Canada and the United States. Journal of Environmental Management 70:165-180. (i)

Leeds, R., L.C. Brown, M.R. Sulc, and L. VanLieshout. 1994. Vegetative filter strips: application, installation and maintenance. Publication number AEX-467-94. Ohio State University Extension, Columbus, Ohio. (viii)

LeFevre, G.H., R.M. Hozalski, and P.J. Novak. 2012. The role of biodegradation in limiting the accumulation of petroleum hydrocarbons in raingarden soils. Water Research 46:6753-6762. (i)

Lewandowski, J., L. Angermann, G., Nutzmann, and J.H. Fleckenstein. 2011. A heat pulse technique for the determination of small-scale flow directions and flow velocities in the streambed of sand-bed streams, Hydrological Processes 25:3244-3255. (i)

Liu, X., X. Zhang, and M. Zhang. 2008. Majors factors influencing the efficacy of vegetated buffers on sediment trapping: a review and analysis. Journal of Environmental Quality 37:1667-1674. (i)

Lortz, H.W., and B.P. McPherson. 1977. Effects of copper and zinc on smoltification of Coho Salmon. EPA-600/3-77-032. U.S. Environmental Protection Agency, Corvallis, Oregon. (i)

Lowrance, R., R. Todd, J. Fail, Jr., O. Hendrickson, Jr., R. Leonard, and L. Asmussen. 1984. Riparian forests as nutrient filters in agricultural watersheds. Bioscience 34:374-377. (i)

Luo, Y.L., W.S. Guo, H.H. Ngo, L.D. Nghiem, F.I. Hai, J. Zhang, S. Liang, and X.C.C. Wang. 2014. A review on the occurrence of micropollutants in the aquatic environment and their fate and removal during wastewater treatment. Science of the Total Environment 473:619-641. (i)

Lyons, J., S.W. Trimble, and L.K. Paine. 2000. Grass versus trees: managing riparian areas to benefit streams of central North America. Journal of the American Water Resources Association 36:919-930. (i)

Mahar, A., W. Ping, L.I. Ronghua, and Z. Zengqiang. 2015. Immobilization of lead and cadmium in contaminated soil using amendments: a review. Pedosphere 25:555-568. (i)

Malanson, G.P. 1993. Riparian landscapes. Cambridge studies in ecology. Cambridge University Press, Cambridge, United Kingdom. (i)

Mann, R.M., R.V. Hyne, C.B. Choung, and S.P. Wilson. 2009. Amphibians and agricultural chemicals: review of the risks in a complex environment. Environmental Pollution 157:2903–2927. (i)

Marco, A., C. Quilchano, and A. Blaustein. 1999. Sensitivity to nitrate and nitrite in pond-breeding amphibians from the Pacific Northwest, USA. Environmental Toxicology and Chemistry 18:2836-2839. (i)

Mayer, P.M., S.K. Reynolds, M.D. McCutchen, and T.J. Canfield. 2006. Riparian buffer width, vegetative cover, and nitrogen removal effectiveness: a review of current science and regulations. EPA/600/R-05/118. U.S. Environmental Protection Agency, Cincinnati, Ohio. (viii)

Mayer, P.M., S.K. Reynolds, M.D. Marshall, D. McCutchen, and T.J. Canfield. 2007. Meta-analysis of nitrogen removal in riparian buffers. Journal of Environmental Quality 36:1172-1180. (i)

McClain, M.E., E.W. Boyer, C.L. Dent, S.E. Gergel, N.B. Grimm, P.M. Groffman, S.C. Hart, J.W. Harvey, C.A. Johnston, and E. Mayorga. 2003. Biogeochemical hot spots and hot moments at the interface of terrestrial and aquatic ecosystems. Ecosystems 6:301-312. (i)

McInnis, M.L., and J. McIver. 2001. Influence of off-stream supplements on stream banks of riparian pastures. Journal of Range Management 54:648-652. (i)

McIntyre, J.K., D.H. Baldwin, D.A. Beauchamp, and N.L. Scholz. 2012. Low level copper exposure increases visibility and vulnerability of juvenile Coho Salmon to Cutthroat Trout predators. Ecological Applications 22:1460-1471. (i)

Menichino, G.T., A.S. Ward, and E.T. Hester. 2014. Macropores as preferential flow paths in meander bends. Hydrological Processes 28:482-495. (i)

Merritt, W.S., R.A. Letcher, and A.J. Jakeman. 2003. A review of erosion and sediment transport models. Environmental Modelling & Software 18:761-799. (i)

Misra, A.K., J.L. Baker, S.K. Mickelson, and H. Shang. 1996. Contributing area and concentration effects on herbicide removal by vegetative buffer strips. Transactions of the American Society of Agricultural Engineers 39:2105-2111. (i)

Mitchell, S.M., J.L. Ullman, A.L. Teel, and R.J. Watts. 2014. pH and temperature effects on the hydrolysis of three - lactam antibiotics: ampicillin, cefalotin and cefoxitin. Science of the Total Environment 466-467:547-555. (i)

Mitchell, S.M., J.L. Ullman, A.L. Teel, and R.J. Watts. 2015. Hydrolysis of amphenicol and macrolide antibiotics: chloramphenicol, florfenicol, spiramycin, and tylosin. Chemosphere 134:504-511. (i)

Moermond, C.T.A., F. Roozen, J.J.G. Zwolsman, and A.A. Koelmans. 2004. Uptake of sediment-bound bioavailable polychlorobiphenyls by Benthivorous Carp (*Cyprinus carpio*). Environmental Science & Technology 38:4503-4509. (i)

Monteiro, S.M., J.M. Mancera, A. Fontainhas-Fernandes, and M. Sousa. 2005. Copper induced alterations of biochemical parameters in the gill and plasma of

Oreochromis niloticus. Comparative Biochemistry and Physiology C—Toxicology & Pharmacology 141:375-383. (i)

Moore, M.T., R. Kröger, and C.R. Jackson. 2011. The role of aquatic ecosystems in the elimination of pollutants. Pages 288-304 ***in*** F. Sánchez-Bayo, P.J. van den Brink, and R.M. Mann, editors. Ecological impacts of toxic chemicals. Bentham Science, Oxford, Mississippi.

Moore, A., N. Lower, I. Mayer, and L. Greenwood. 2007. The impact of a pesticide on migratory activity and olfactory function in Atlantic Salmon (*Salmo salar L.*) smolts. Aquaculture 273:350-359. (i)

Morace, J.L., and S.W. McKenzie. 2002. Fecal-indicator bacteria in the Yakima River Basin, Washington—an examination of 1999 and 2000 synoptic-sampling data and their relation to historic data. Water Resources Investigations Report 02-4054. U.S. Geological Survey, Portland, Oregon. (viii)

Mueller, S.O. 2004. Xenoestrogens: mechanisms of action and detection methods. Analytical and Bioanalytical Chemistry 378:582-597. (i)

Muñoz-Carpena, R., J.E. Parsons, and J.W. Gilliam. 1999. Modeling hydrology ad sediment transport in vegetative filter strips. Journal of Hydrology 214:111-129. (i)

Muscutt, A.D., G.L. Harris, S.W. Bailey, and D.B. Davies. 1993. Buffer zones to improve water-quality—a review of their potential use in UK agriculture. Agriculture Ecosystems & Environment 45:59-77. (i)

Newcombe, C.P., and D.D. MacDonald. 1991. Effects of suspended sediments on aquatic ecosystems. North American Journal of Fisheries Management 11:72-82. (i)

Nimick, D.D., C.H. Gammons, and S.R. Parker. 2011. Diel biogeochemical processes and their effect on the aqueous chemistry of streams: a review. Chemical Geology 283:3-17. (i)

Norris, V. 1993. The use of buffer zones to protect water quality: a review. Water Resources Management 7:257-272. (i)

NRC (National Research Council). 2002. Riparian areas: functions and strategies for management. National Academy Press, Washington, D.C. (i)

Osborne, L.L., and D.A. Kovacic. 1993. Riparian vegetated buffer strips in water-quality restoration and stream management. Freshwater Biology 29:243-258. (i)

Peterjohn, W.T., and D.L. Correll. 1984. Nutrient dynamics in an agricultural watershed: observations on the role of a riparian forest. Ecology 65:1466-1475. (i)

Peverill, K.I., L.A. Douglas, and N.B. Greenhill. 1977. Leaching losses of applied P and S from undisturbed cores of some Australian surface soils. Geoderma 19:91-96. (i)

Pilon-Smits, E. 2005. Phytoremediation. Annual Review of Plant Biology 56:15-39. (i)

Pinto, E., T.C.S. Sigaud-Kutner, M.A.S. Leitão, O.O. Okamoto, D. Morse, and P. Colepicolo. 2003. Heavy metal-induced oxidative stress in algae. Journal of Phycology 39:1008-1018. (i)

Polyakov, V., A. Fares, and M.H. Ryder. 2005. Precision riparian buffers for the control of nonpoint source pollutant loading into surface water: a review. Environmental Reviews 13:129-144. (i)

PSAT (Puget Sound Action Team). 2007. 2007 Puget Sound update: ninth report of the Puget Sound Ambient Monitoring Program. Puget Sound Action Team, Olympia, Washington. (viii)

Pulford, I.D., and C. Watson. 2003. Phytoremediation of heavy metal-contaminated land by trees—a review. Environment International 29:529-540. (i)

Rahman, F., K.H. Langford, M.D. Scrimshaw, and J.N. Lester. 2001. Polybrominated diphenyl ether (PBDE) flame retardants. Science of the Total Environment 275:1-17. (i)

RCT (R Core Team). 2013. R: a language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. (viii)

Redding, J.M., C.B. Schreck, and F.H. Everest. 1987. Physiological effects on Coho Salmon and steelhead

of exposure to suspended solids. Transactions of the American Fisheries Society 116:737-744. (i)

Redick, M.S., and T.W. La Point. 2004. Effects of sublethal copper exposure on behavior and growth of *Rana pipiens* tadpoles. Bulletin of Environmental Contamination and Toxicology 72:706-710. (i)

Reichenberger, S., M. Bach, A. Skitschak, and H. Frede. 2007. Mitigation strategies to reduce pesticide inputs into ground- and surface water and their effectiveness; a review. Science of the Total Environment 384:1-35. (i)

Relyea, R.A., and N. Diecks. 2008. An unforeseen chain of events: lethal effects of pesticides on frogs at sublethal concentrations. Ecological Applications 18:1728-1742. (i)

Reuter, J.H., and E.M. Perdue. 1977. Importance of heavy metal-organic matter interactions in natural waters. Geochimica et Cosmochimica Acta 41:325-334. (i)

Rinklebe, J., and S.M. Shaheen. 2015. Miscellaneous additives can enhance plant uptake and affect geochemical fractions of copper in a heavily polluted riparian grassland soil. Ecotoxicology and Environmental Safety 119:58-65. (i)

Rougier, F., D. Troutaud, A. Ndoye, and P. Deschaux. 1994. Nonspecific immune-response of Zebrafish, *Brachydanio rerio* (Hamilton-Buchanan) following copper and zinc exposure. Fish & Shellfish Immunology 4:115-127. (i)

Salt, D.E., R.D. Smith, and I. Raskin. 1998. Phytoremediation. Annual Review of Plant Physiology and Plant Molecular Biology 49:643-668. (i)

Sandahl J.F., D.H. Baldwin, J.J. Jenkins, and N.L. Scholz. 2007. A sensory system at the interface between urban stormwater runoff and salmon survival. Environmental Science & Technology 41:2998-3004. (i)

Sarma, H. 2011. Metal hyperaccumulation in plants: a review focusing on phytoremediation technology. Journal of Environmental Science and Technology 4:118-138. (i)

Schellinger, G.R., and J.C. Clausen. 1992. Vegetative filter treatment of dairy barnyard runoff in cold regions. Journal of Environmental Quality 21:40-45. (i)

Schnaebel, R.R., J.A. Shaffer, W.L. Stout, and L.F. Cornish. 1997. Denitrification distributions in four valley and ridge riparian ecosystems. Environmental Management 21:283-290. (i)

Schultz, R.C., J.P. Colletti, T.M. Isenhart, C.O. Marquez, W.W. Simpkins, and C.J. Ball. 2000. Riparian forest buffer practices. Pages 189-281 *in* H.E. Garett, W.J. Rietveld, and R.F. Fisher, editors. North American agroforestry: an integrated science and practice. American Society of Agronomy, Madison, Wisconsin. (viii)

Schuster, S., and M.E. Grismer. 2004. Evaluation of water quality projects in the Lake Tahoe Basin. Environmental Monitoring and Assessment 90:225-242. (i)

Scoggins, M., N.L. McClintock, L. Gosselink, and P. Bryer. 2007. Occurrence of polycyclic aromatic hydrocarbons below coat-tar-sealed parking lots and effects on stream benthic macroinvertebrate communities. Journal of the North American Benthological Society 26:694-707. (i)

Sen, T.K., and K.C. Khilar. 2006. Review on subsurface colloids and colloid-associated contaminant transport in saturated porous media. Advances in Colloid and Interface Science 119:71-96. (i)

Sheridan, J.M., R. Lowrance, and D.D. Bosch. 1999. Management effects on runoff and sediment transport in riparian forest buffers. Transactions of the American Society of Agricultural Engineers 42:55-64. (i)

Skłodowski, M., E. Kiedrzynska, M. Kiedrzynski, M. Urbaniak, K.M. Zielinska, J.K. Kurowski, and M. Zalewski. 2014. The role of riparian willows in phosphorus accumulation and PCB control for lotic water quality improvement. Ecological Engineering 70:1-10. (i)

Sorensen, E.M. 1991. Metal poisoning in fish. CRC Press, Boca Raton, Florida. (i)

Sprague, J.B., and A. Ramsay. 1965. Lethal levels of mixed copper-zinc solutions for juvenile salmon. Journal of the Fisheries Research Board of Canada 22:425-432. (i)

Spromberg, J.A., D.H. Baldwin, S.E. Damm, J.K. McIntyre, M. Huff, C.A. Sloan, B.F. Anulacion, J.W. Davis, and N.L. Scholz. 2016. Coho Salmon spawner mortality in western US urban watersheds: bioinfiltration prevents lethal storm water impacts. Journal of Applied Ecology 53:398–407. (i)

Straffelini, G., R. Ciudin, A. Ciotti, and S. Gialanella. 2015. Present knowledge and perspectives on the role of copper in brake materials and related environmental issues: a critical assessment. Environmental Pollution 207:211-219. (i)

Susarla, S., V.F. Medina, and S.C. McCutcheon. 2002. Phytoremediation: an ecological solution to organic chemical contamination. Ecological Engineering 18:647-658. (i)

Sweeney B.W., T.L. Bott, J.K. Jackson, L.A. Kaplan, J.D. Newbold, L.J. Standley, W.C. Hession, and R.J. Horwitz. 2004. Riparian deforestation, stream narrowing, and loss of stream ecosystem services. Proceedings of the National Academy of Science 101:14132-14137. (i)

Sweeney, B.W., and J.D. Newbold. 2014. Streamside buffer width needed to protect stream water quality, habitat, and organisms: a literature review. Journal of the American Water Resources Association 50:560-584. (i)

Syversen, N., L. Oygarden, and B. Salbu. 2001. Cesium-134 as a tracer to study particle transport processes within a small catchment with a buffer zone. Journal of Environmental Quality 30:1771-1783. (i)

Tabacchi, E., L. Lambs, H. Guilloy, A. Planty-Tabacchi, E. Muller, and H. Décamps. 2000. Impacts of riparian vegetation on hydrological processes. Hydrological Processes 14:2959-2976. (i)

Tate, K.W., E.R. Atwill, J.W. Bartolome and G. Nader. 2006. Significant *Escherichia coli* attenuation by vegetative buffers on annual grasslands. Journal of Environmental Quality 35:795-805. (i)

Tobiason, S.A., C. Nickerson, R. Zisette, and M. Samadpour. 2002. Stormwater bacteria source tracing at Seattle-Tacoma International Airport. Proceedings of the Water Environment Federation's technical exhibition and conference. Water Environment Federation, Alexandria, Virginia. (viii)

Trimble, G.R., and R.S. Sartz. 1957. How far from a stream should a logging road be located? Journal of Forestry 55:339-341. (i)

Ucar, T., and F.R. Hall. 2001. Windbreaks as a pesticide drift mitigation strategy: a review. Pest Management Science 57:663-675. (i)

UKEA (United Kingdom Environmental Agency). 2009. The hyporheic handbook: a handbook on the groundwater–surface water interface and hyporheic zone for environment managers. Science report SC050070. Integrated Catchment Science Programme, Bristol, United Kingdom. (viii)

Unc, A., and M.J. Goss. 2004. Transport of bacteria from manure and protection of water resources. Applied Soil Ecology 25:1-18. (i)

NRCS (National Resources Conservation Service). 2000. Conservation buffers to reduce pesticide losses. Washington, D.C. (i)

USEPA (U.S. Environmental Protection Agency). 1980. Ambient water quality criteria for copper. EPA 440/5-80-036. Washington D.C. (viii)

USEPA (U.S. Environmental Protection Agency). 2003. Evaluation of sediment transport models and comparative application of two watershed models. EPA/600/R-03/139. Cincinnati, Ohio. (viii)

USEPA (U.S. Environmental Protection Agency). 2015. Washington causes of impairment for 303(d) listed waters. Available: **http://iaspub.epa.gov/tmdl_waters10/attains_state.control?p_state=WA#causes/.** (January 2019). (viii)

USGS (U.S. Geological Survey). 2006. Pesticides in the nation's streams and ground water 1992-2001 – a summary. Fact Sheet 2006-3028. Sacramento, California . (i)

Vervoort, R.W., D.E. Radcliffe, and L.T. West. 1999. Soil structure development and preferential solute flow. Water Resources Research 35:913-928. (i)

Vidon, P., C. Allan, D. Burns, T.P. Duval, N. Gurwick, S. Inamdar, R. Lowrance, J. Okay, D. Scott, and S. Sebestven. 2010. Hot spots and hot moments in riparian zones: potential for improved water quality management. Journal of the American Water Resources Association 46:278-298. (i)

Vidon, P., and P.E. Cuadra. 2011. Phosphorus dynamics in tile-drain flow during storms in the US Midwest. Agricultural Water Management 98:532-540. (i)

Vogt, T., M. Schirmer, and O.A. Cirpka. 2012. Investigating riparian groundwater flow close to a losing river using diurnal temperature oscillations at high vertical resolution. Hydrology and Earth System Sciences 16:473-487. (i)

Vought, L.B.-M., J. Dahl, C.L. Pedersen, and J.O. Lacoursière. 1994. Nutrient retention in riparian ecotones. Ambio 23:343-348. (i)

Vought. L.B.-M., G. Pinay, A. Fuglsang, and C. Ruffinoni. 1995. Structure and function of buffer strips from a water quality perspective in agricultural landscapes. Landscape and Urban Planning 31:323-331. (i)

Walker, S.E., S. Mostaghimi, T.A. Dillaha, and F.E. Woeste. 1990. Modeling animal waste management practices–impacts on bacteria levels in runoff from agricultural lands. Transactions of the American Society of Agricultural Engineers 33:807-817. (i)

Wang, Z., Z. Wang, and Y. Pei. 2014. Nitrogen removal and microbial communities in a three-stage system simulating a riparian environment. Bioprocess and Biosystem Engineering 37:1105-1114. (i)

Waters, T.F. 1995. Sediment in streams: sources, biological effects and control. American Fisheries Society Monograph 7. American Fisheries Society, Bethesda, Maryland. (i)

Welsch, D.J. 1991. Riparian forest buffers: function and design for protection and enhancement of water resources. NA-PR-07-91. U.S. Forest Service, Radnor, Pennsylvania. (viii)

Welsh, H.H., and L.M. Ollivier. 1998. Stream amphibians as indicators of ecosystem stress: A case study from California's Redwoods. Ecological Applications 8:1118-1132. (i)

Wilhere, G.F., and T. Quinn. 2018. How wide is wide enough?: values, science, and law in riparian habitat conservation. Natural Resources Journal 58:279-318. (i)

Williams, D.G., and R. Scott. 2009. Vegetation-hydrology interactions: dynamics of riparian plant water use. Pages 37-56 *in* J. Stromberg and B. Tellman, editors. Ecology and conservation of the San Pedro River. University of Arizona Press, Tucson, Arizona. (i)

Wroblicky, G.J., M.E. Campana, H.M. Valett, and C.N. Dahm. 1998. Seasonal variation in surface-subsurface water exchange and lateral hyporheic area of two stream-aquifer systems. Water Resources Research 34:317-328. (i)

Young, R.A., T. Huntrods, and W. Anderson. 1980. Effectiveness of vegetated buffer strips in controlling pollution from feedlot runoff. Journal of Environmental Quality 9:483-487. (i)

Yuan, Y., R.L. Bingner, and M.A. Locke. 2009. A review of effectiveness of vegetative buffers on sediment trapping in agricultural areas. Ecohydrology 2:321-336. (i)

Zhang, Z. 2014. Nonpoint source and water quality monitoring. Pages 261-299 *in* S. Eslamian, editor. Handbook of engineering hydrology: environmental hydrology and water management. CRC Press, Boca Raton, Florida. (i)

Zhang, M., B. Gao, J. Fang, A.E. Creamer, and J.L. Ullman. 2014. Self-assembly of needle-like layered double hydroxide (LDH) nanocrystals on hydrochar: characterization and phosphate removal ability. RSC Advances 4:28171-28175. (i)

Zhang, X., X. Liu, M. Zhang, and R.A. Dahlgren. 2010. A review of vegetated buffers and a meta-analysis of their mitigation efficacy in reducing nonpoint source pollution. Journal of Environmental Quality 39:76-84. (i)

Zhongmin, J., C. Hua, W. Hong, and L. Changxiao. 2012. Photosynthetic responses of the riparian Salix variegate to cadmium stress in Three Gorges Reservoir region. Scientia Silvae Sinicae 48:152-158. (i)



Okanogan National Forest/Scott Fitkin, WDFW

Chapter 6. Nutrient Dynamics in Riparian Ecosystems

By: Paul M. Mayer, Jana E. Compton, and George F. Wilhere

6.1. Introduction

Riparian ecosystems play a vital role in the dynamics of nutrients within watersheds, especially for the three primary macronutrients carbon (C), nitrogen (N), and phosphorus (P). Because they are positioned at the interface between the stream and upland areas, riparian ecosystems mediate the movement of materials and energy between land and water. Riparian areas can be sources or sinks of energy, water, nutrients, organic matter, and organisms within a watershed. Organic matter from riparian areas, an important source of energy and nutrients, makes its way into streams via plant litterfall, or through transport by water, wind, or animals. Organic matter in streams provides habitat and food for microbes, insects, fish, amphibians, birds, and other organisms, and decomposes to release plant-available inorganic nutrients like ammonium, nitrate, and phosphate. Riparian areas also store energy and nutrients from organic matter coming from upland and instream sources through biotic uptake, sorption and exchange, and slowing or trapping particles. Riparian areas also are sites with high rates of nutrient transformation, including conversion of inorganic nitrogen into the gases N_2 or N_20 via denitrification. Riparian ecosystems are influenced by upland activities that supply nutrients that follow flow paths through these ecosystems, eventually reaching streams via surface and subsurface flows. Age, vegetation composition, topography, soil type, and condition of the riparian ecosystem all factor into the fate and transport of nutrients. In addition, the position in the drainage network and connectivity of the riparian area, along with disturbance and management history, affect nutrient processing rates.

Nutrients and the hydrological and biogeochemical processes that dictate their transport and fate are the subject of much current research in riparian ecology (Mayer et al. 2010a, 2014) because of their critical importance for growth and maintenance of life in the riparian ecosystem and the subsequent effects on stream biota and water quality. Although many micro- and macro-nutrients cycle through riparian areas, this chapter addresses only the three primary macronutrients C, N, and P.

Streams in the Pacific Coastal Ecoregion of Washington State are generally oligotrophic, well shaded, and sensitive to nutrient enrichment (Welch et al. 1998). When more N and P enters a riparian ecosystem than can be immediately utilized or stored, degradation of aquatic habitat conditions can occur and negative consequences within or beyond the riparian ecosystem may result. Excess N and P input to streams and estuaries may lead to harmful algal blooms, hypoxia, fish kills, and contamination of drinking water supplies. Although stream nutrient concerns have a somewhat lower profile in the Pacific Northwest (PNW) relative to other areas of the US, such as the Chesapeake Bay or Great Lakes watersheds, approximately 20% of assessed rivers and 8% of assessed lakes in Washington are regarded by the state as having impaired conditions related to an overabundance of nutrients (USEPA ATTAINS database).

Here, we describe nutrient cycles in riparian areas in the PNW, focusing on C, N, and P from natural and anthropogenic sources. Other nutrients, such as calcium, sulfur, or molybdenum, are not as widely studied but have been shown to be important in areas of the PNW for forest growth or other ecosystem processes (Silvester 1989; Chappell et al. 1991; Perakis et al. 2006). When possible, we discuss implications of common land management activities on nutrient dynamics by contrasting disturbed versus undisturbed riparian ecosystems. We also discuss new information gained from recent stable isotope studies and meta-analyses of riparian nutrient removal that have greatly improved our understanding of the permanence and effectiveness of nutrient removal processes in PNW riparian ecosystems.

6.1.1. Nutrient Dynamics in the Pacific Northwest

Figure 6.1 illustrates processes occurring in a largely undisturbed PNW forested riparian ecosystem and associated stream and upland. Water traveling through the riparian area (surface and subsurface flow) is the main transport mechanism for dissolved C, N, and P. These nutrients can be taken up directly by primary producers and decomposers, passively transported to groundwater or the hyporheic zone, or carried to surface waters via subsurface, overland, or channelized flow. The hydrologic regime dictates the timing and magnitude of nutrient movement into aquatic systems, and can create instream pulses of C, N, and P both in particulate and dissolved form (Kaushal et al. 2010).

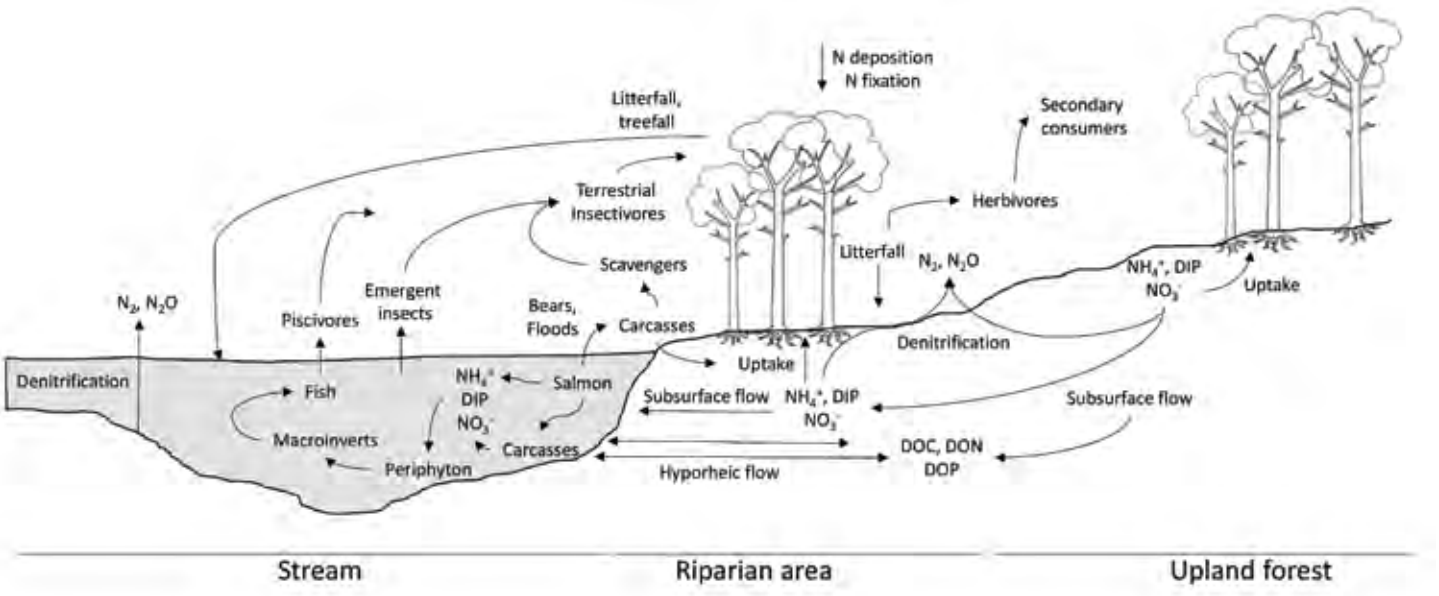


Figure 6.1. Nutrient cycle of an undisturbed PNW forested riparian ecosystem and connected stream and upland forest. Modified from Moyle et al. (2009). DIP = dissolved inorganic phosphorus; DOC, DON, DOP = dissolved organic carbon, nitrogen and phosphorus, respectively.



Most streams in the Pacific Northwest are nutrient-poor ecosystems/Ned Pittman, WDFW

Soil compaction and impervious surfaces typically reduce retention capacity of nutrients in space and time by preventing infiltration and thereby limit the interaction of nutrients with soils, roots, and soil biota. Riparian ecosystems exhibit a continuum of physical characteristics which have implications for nutrient dynamics. Riparian ecosystems along low-order streams, for example, are often narrower and steeper than those along mainstem rivers with wide, level floodplains. Consequently, surface and subsurface hydrological regimes controlling biogeochemical processes in riparian areas also differ along a continuum. Along small, steep forested streams, the water table is usually low and aerobic processes dominate, whereas level areas adjacent to larger rivers may provide water table conditions favoring anaerobic processes that reduce N via denitrification, a microbial transformation of dissolved nitrate N to gaseous molecular N (Burt et al. 2002; Hefting et al. 2004). The hyporheic zone is an area beneath the stream and riparian area where surface water and ground water continually interact. This zone can have a large influence on chemical characteristics of the surface water and, therefore, plays a role in determining biological attributes of streams (Wondzell et al. 2011).

As nutrient molecules move downstream, they may be taken up by algae and microbes living on rocks and wood in the channel in slick mats called biofilms (Cardinale et al. 2002). The polysaccharide layers of biofilms are sites of active nutrient turnover where microscopic algae, fungi, and bacteria consume N and P, die and release nutrients that then move further downstream. Microbial communities may be consumed by grazers such as larval aquatic insects or snails, which in turn may be consumed by larger predators such as fishes or birds. As prey and predators are consumed or die, they release nutrients to the aquatic and terrestrial environments through decay and in this way C, N, and P cycle in a process of uptake and release called nutrient spiraling (Newbold et al. 1982). The distance a molecule moves downstream during a complete cycle is its spiraling length, a metric that explicitly relates nutrient utilization to nutrient supply (Newbold et al. 1982). Long spiraling lengths indicate that: 1) nutrient uptake is inefficient because the system is saturated with nutrients and organisms

can no longer fully exploit the incoming nutrient loads, 2) conditions are not optimal for uptake, such as when water flow is too fast, or 3) the stream does not support a community of organisms that effectively processes the nutrients.

In anthropogenically undisturbed Pacific Northwest watersheds, nutrients are ultimately derived from atmospheric and geologic sources, while plants play an important role in the initial uptake of N and P from these sources (McClain et al. 1998). Spatial variation in vegetation, geologic substrates, and human activities drive the variation in stream N and P concentrations and fluxes across the PNW (Wigington et al. 1998; Wise and Johnson 2011). The geology and geomorphology of a watershed and stream channel set the conditions for mineral composition of the groundwater reaching the stream because the shape and slope of the channel and banks affect water movement and velocity. Some bedrock types yield high stream P (Ice and Binkley 2003), leading to high regional P variability in riparian ecosystems and streams. Some types of vegetation can fix atmospheric gaseous N via symbiotic relationships with bacteria in their root systems, and in turn produce more biologically available N than they consume, thereby contributing to N loads in watersheds. A prime example is N_2-fixing Red Alder *Alnus rubra*, an important source of dissolved N in streams in western Oregon and Washington (Compton et al. 2003; Wise and Johnson 2011; Greathouse et al. 2014).

Nitrogen may occur in organic forms as microbial, plant, or animal tissue and in dissolved organic forms, or, if inorganic, primarily as nitrate ($N0_3^-$) and ammonium (NH_3^+), which are forms that can be assimilated by organisms into organic molecules. Forests in the PNW generally have fairly tight N and P cycles with little N or P lost or leached from the system. Rather, there are low rates of N and P inputs and outputs, but high rates of internal cycling (Sollins et al. 1980; Compton and Cole 1998). Triska et al. (1984) showed that N inputs to a stream reach in an old-growth forest watershed in Oregon's Cascade Mountains were dominated by dissolved organic N from groundwater (69% of inputs), with litterfall and precipitation playing smaller roles.

Human activities like timber harvest, farming, or urban development alter nutrient cycles (Figure 6.2), producing higher fluxes, shorter storage durations, and higher concentrations of nutrients in subsurface flow, some of which will enter streams. Disturbances through forestry, grazing, agriculture or urbanization can alter the timing and routing of water through a landscape (Tague and Grant 2004), which can influence nutrient uptake and delivery to streams. Agriculture can contribute to excess nutrients in riparian and aquatic ecosystems through increased runoff of N and P from fertilizer and livestock manure (Wise and Johnson 2011). Point sources and urban stormwater runoff are the dominant sources of N within urban areas. For P, geologic materials dominate natural sources, with point sources such as urban runoff, farm manure, and fertilizer important in areas under anthropogenic land uses. Timber harvest increases stream nitrate and to a lesser extent phosphate concentration (Fredricksen et al. 1975; Scrivener 1975; Martin and Harr 1989). These increases generally persist for a short time, although Brown et al. (1973) saw increases in nitrate persist for six years post-timber harvest and burning.

Historically, a major source of allochthonous[1] nutrients and energy-rich carbon compounds was anadromous salmon (Cederholm et al. 1999; Gende et al. 2002). Anadromous, semelparous fish return from the ocean to spawn and die in their natal streams. The mass of every salmon carcass, of which 95% is accumulated in the marine environment (Naiman et al. 2002), is deposited in oligotrophic freshwater environments. The magnitude of nutrient and chemical energy losses to freshwater ecosystems caused by declines in salmon populations can best be appreciated by comparing current and historical salmon run sizes. Gresh et al. (2000)

1 Allochthonous means originating or formed in a place other than where found. Hence, in the context of aquatic ecosystems, allochthonous nutrients found in a stream originated in terrestrial ecosystems. In contrast, autochthonous means originating or formed in the place where found.



Historically, carcasses of adult salmon delivered approximately 100,000 tons of nutrients to rivers and streams of Washington/Ned Pittman, WDFW

estimated that the current biomass of salmon runs for all Pacific salmon species (Chinook *Oncorhynchus tshawytscha,* Coho *Oncorhynchus kisutch,* Sockeye *Oncorhynchus nerka,* Chum *Oncorhynchus keta,* and Pink *Oncorhynchus gorbuscha*) in Puget Sound, the Washington Coast, and the Columbia River Basin are 25, 5, and 1% of historical biomass (circa early 1900s), respectively. This represents a loss of 122,470 US tons per year (111,104 metric tons) of marine-derived nutrients and chemical-energy in these watersheds. Naiman et al. (2002) estimated that in the Willapa Bay Watershed the biomass of Chinook, Coho, and Chum Salmon carcasses in streams decreased from 2,920 to 226 US tons (2,649 to 205 metric tons per year), and that marine derived N and P decreased by more than 90%.

Figure 6.2 represents nutrient cycling in a watershed with more human-associated disturbance, including an

absence of salmon returns; by comparing Figures 6.1 and 6.2, changes in the cycling loop and intra-system transfers are evident when salmon are missing. Much of the cycling of marine-derived nutrients is mediated by predators and scavengers that move large amounts of marine-derived nutrients substantial distances into the terrestrial environment either as salmon carcasses or as metabolic waste products, i.e., urine and feces (Naiman et al. 2002). In several small streams on the Olympic Peninsula, Cederholm et al. (1989) observed that Coho Salmon carcasses were consumed by 22 species of mammals and fish (e.g., American Black Bear *Ursus americanus,* Northern River Otter *Lontra canadensis,* Mink *Mustela vison,* Bald Eagles *Haliaeetus leucocephalus,* and Ravens *Corvus corax*), and that 40% of salmon carcasses were moved by scavengers from the water to riparian areas. Flooding also can deposit salmon carcasses in riparian areas (Ben-David et al. 1998). Salmon carcasses provide N and P nutrients for microbes, plants, and animals, and influence all trophic levels in riparian ecosystems (Willson and Halupka 1995; Compton et al. 2006). Trees and shrubs in riparian areas along spawning sites in the Kadashan and Indian rivers of southeast Alaska derived approximately 23% of their foliar nitrogen from decayed salmon carcasses, and growth rates of Sitka Spruce *Picea sitchensis* were significantly increased (Helfield and Naiman 2001). On average, 17% of the nitrogen incorporated into the riparian vegetation of a stream in western Washington was derived from carcasses of spawning salmon, and significant percentages of marine-derived N (up to 30%) and C (up to 39%) were found in aquatic insects, Cutthroat Trout *Oncorhynchus clarkii*, and juvenile salmon (Bilby et al. 1996).

Other animals subsidize riverine food webs by transporting nutrients across watersheds or by altering the hydrology (Chapter 8 in this document; Naiman and Rogers 1997; Masese et al. 2015). As ecosystem engineers, American Beaver *Castor canadensis* have a significant influence on stream nutrients. Beaver can influence biogeochemical cycles by impounding streams and changing hydrologic regimes and organic matter and sediment transport (Pollock et al. 2007).

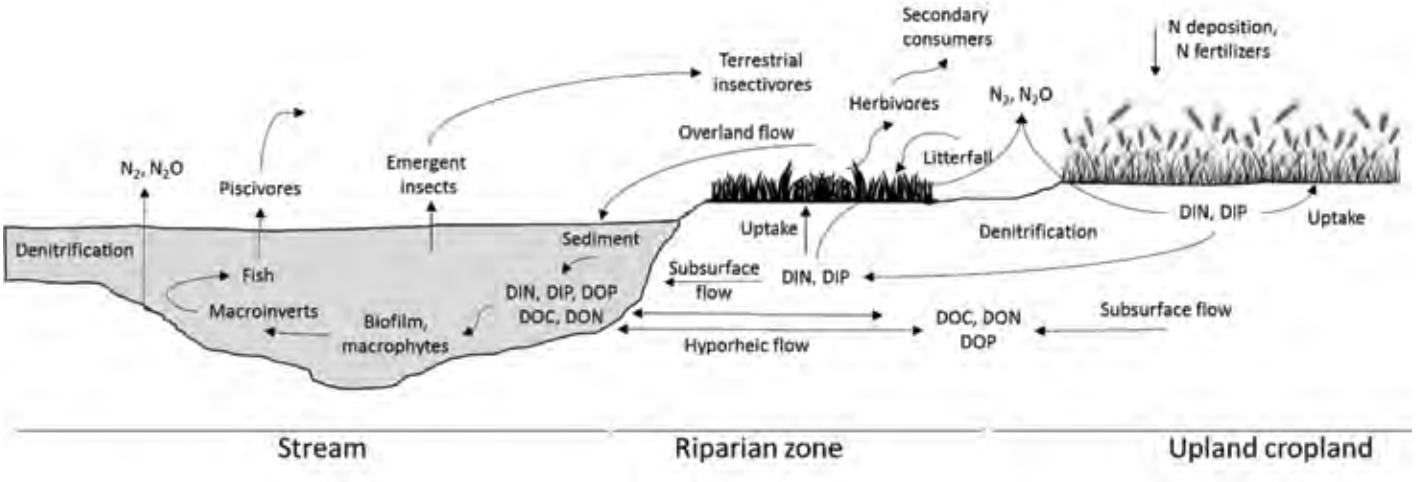


Figure 6.2. Nutrient cycle of a disturbed PNW riparian ecosystem and connected stream and upland cropland. Much of the cycling of marine-derived nutrients is facilitated by predators and scavengers that move nutrients into the terrestrial environment either as salmon carcasses or as urine and feces. Modified from Moyle et al. (2009). DIP = dissolved inorganic phosphorus; DIN = dissolved inorganic nitrogen (nitrate and ammonium); DOC, DON, DOP = dissolved organic carbon, nitrogen and phosphorus, respectively.

Retention of total N and P increased 72% and 43%, respectively after Beaver populations recovered in a Minnesota watershed (Naiman et al. 1994) and organic matter (carbon) retention increased three-fold after a stream was impounded by Beaver (Naiman et al. 1988). However, Beaver impoundments also influence N dynamics by flooding riparian forests, creating anoxic conditions in forest soils leading to an increase in denitrification and subsequent reduction in N (Naiman et al. 1988). Elk *Cervus canadensis*, deer (*Odocoileus* spp.), and livestock can also be important sources of N and P when found in close proximity to streams.

Riparian vegetation can affect uptake and delivery of nutrients to streams. Riparian plant roots can slow water movement and stabilize soils as well as take up dissolved nutrients. The types of vegetation and growth patterns in riparian areas determine the amount and timing of litterfall and woody material delivery to a stream. The height and density of vegetation dictate shading and solar input to the stream, thus affecting conditions for plant growth and N and P uptake. The key limiting nutrients for primary production in PNW streams are N and P (Welch et al. 1998), but there has not been enough experimental work conducted across the region to determine precisely when and where this occurs.

Shallow groundwater adjacent to stream channels often is a hot spot for N removal processes and a storage zone for other solutes.

6.1.2. Carbon

The cycling of C in riparian and aquatic ecosystems is complex and can differ among locations and through time because C can be available in different forms and is produced by different sources, thereby affecting its transport and fate. Carbon is tightly linked to N and P, driving biological transformations of these nutrients. Organic C regulates ecosystem functions in streams and rivers because dissolved organic carbon (DOC) is a primary energy source for microorganisms. Riparian vegetation in forests influences DOC composition and contributes a substantial proportion of stream organic C budgets (McDowell and Likens 1988). DOC in streams is a mixture of recalcitrant, (i.e., difficult to process components) and more easily metabolized labile fractions that drive biogeochemical processes involving nitrogen (Kaushal and Lewis 2005). For example, availability of dissolved and particulate organic C can limit denitrification, a microbial process critical to maintaining water quality, which has important implications for managing N in streams (Newcomer et al. 2012). Denitrification occurs only under anaerobic conditions where microbes shift from respiring oxygen to respiring nitrate, releasing nitrous oxide, and inert N_2 gas. These conditions may be ephemeral, fluctuating in response to water tables and associated changes in redox potential (Mayer et al. 2010b).

Anoxic conditions also promote the production of methane. Production of methane and nitrous oxides, increase in riparian areas with increased organic C supply (Kaushal et al. 2014). Dissolved organic carbon also can increase biological oxygen demand, thereby reducing oxygen for fish (Stanley et al. 2012).

Various organic C types from biofilm, leaves, and soil organic matter may have differential effects on ecosystem functions in forested streams (McDowell and Likens 1988), agricultural streams (Royer and David 2005), and urban streams. For example, C derived from

grasses supports more denitrification than C from tree leaves (Newcomer et al. 2012). Because the microbes that influence the transport and fate of N in riparian ecosystems require C as an energy source, C and N are inextricably linked in a biogeochemical sense.

Shading of small headwater streams in forested watersheds can obscure 95% of sunlight (Murphy 1998); hence, in-stream productivity is typically light-limited. Consequently, the main energy source for such streams is allochthonous chemical energy contained in litter from riparian areas (Conners and Naiman 1984; Bisson and Bilby 1998). In headwater streams, litter directly supports an animal community compromised predominantly of invertebrate detrivores which, in turn, support a community of invertebrate predators (Wallace et al. 1997). Detrivores, microbes, and physical breakup convert the coarse particulate organic material (CPOM) of litter to fine particulate organic material (FPOM) which is utilized by invertebrate communities downstream (Bisson and Bilby 1998; Richardson and Danehy 2007). Headwaters comprise 60 to 80% of the cumulative length of a watershed's drainage network (Benda et al. 2005); hence, headwaters contribute a substantial amount of chemical energy to mainstem rivers and associated biota. For example, Wipfli (2005) estimated that every kilometer of fish-bearing stream received enough energy from headwaters to support 100 to 2,000 young-of the-year salmonids.

Carbon cycles through riparian ecosystems via CO_2 uptake from the atmosphere through photosynthesis, litterfall, decomposition and/or consumption. Riparian litter is a critically important source of C for streams as energy for invertebrates and microbes that form the basis of food webs. Deciduous-dominated riparian forests grow quickly and initially deliver more litter to streams and have a more pronounced seasonal litter contribution than coniferous-dominated forests (Hart et al. 2013). Conifers, however, play an important structural role as large wood in streams. Deciduous species like Red Alder can increase fine litter flux and



The main energy source for small headwater streams is allochthonous chemical energy provided by leaf litter/Marc Hayes, WDFW

nutrient delivery to terrestrial and aquatic food webs, thus complementing the year-round shade and wood provided by conifers (Hart et al. 2013).

Chemical energy, required by heterotrophic organisms (those that do not produce their own food from sunlight), is contained within the various C compounds of organic matter. The fundamental effects of organic matter on ecosystem composition, structure, and functions have motivated conceptual theories to describe riverine ecosystems (Pingram et al. 2012). The River Continuum Concept (RCC; Vannote et al. 1980) describes the balance of allochthonous C (produced externally to the stream) to autochthonous C (produced in-stream) in riverine ecosystems from headwaters to mainstem rivers. This balance plays a key role in structuring the invertebrate community. According

to RCC, in narrow headwater streams (first to third order), nearly all C is allochthonous produced by litter from riparian vegetation because shade severely limits the production of autochthonous C produced through in-stream photosynthesis. Because medium-sized streams (fourth to sixth order) are wider, shading decreases, in-stream photosynthesis increases, and the density of litter inputs decreases. Hence, the quantities of allochthonous and autochthonous C may be about equal. In large rivers (≥ seventh order), shading effects only a small portion of surface water, however, turbidity and water depth limit photosynthetic production. Consequently, according to RCC, the main source of energy in large rivers is allochthonous C from upstream. The RCC also posits that the quantity and quality of organic matter, which changes along the river continuum, affects the composition of the aquatic invertebrate community.

Litter from riparian areas is clearly an important source of limiting nutrients and organic matter for aquatic ecosystems. Consequently, providing adequate amounts of litter to streams is an important issue for riparian area management and addressing this issue requires an understanding of litter delivery into streams. FEMAT (1993:V-26) developed a conceptual model, known as the FEMAT curves, that depicts relationships between riparian ecological functions, including litterfall, and distance from a stream channel. Bilby and Heffner (2016) studied factors influencing litter delivery into streams in young and mature conifer forests of the western Washington Cascades and found that litter travel increased with increasing tree height, topographic slope, and wind speed. They estimated that riparian buffer widths needed to capture 95% of annual litter input from mature conifer forests to streams are between 60 to 83 ft (18 to 25 m) depending on a site's slope and wind exposure. The mean tree height of their three mature forest sites was 154 ft (47 m). Hence, riparian buffer widths needed to meet the 95% capture objective range from 39 to 54% of mean tree height. Bilby and Heffner (2016) warn that they may have underestimated litter travel distances because they released litter from only the bottom of the tree canopy, but litter travels farther with increasing height, and therefore, litter produced within the tree canopy is likely to travel farther.

While stream flows carry organic matter, insects, and other invertebrates downstream to subsidize food webs in higher order streams, there may also be upstream movement of aquatic organisms that subsidizes food webs in lower order streams. In a Welsh mountain stream, for example, amphipods *Gammarus pulex* showed net upstream movement whereas stonefly (*Trichoptera* spp.) females showed no upstream flight preference, but females moving upstream contained twice as many eggs (Dudley-Williams and Williams 1993). In many cases, however, such as with mayflies (family Baetida), seasonal upstream movements of adults via an aerial pathway are pronounced (Hershey et al. 1993). Such upstream movement of nutrients and chemical energy may be important, but has been little studied.

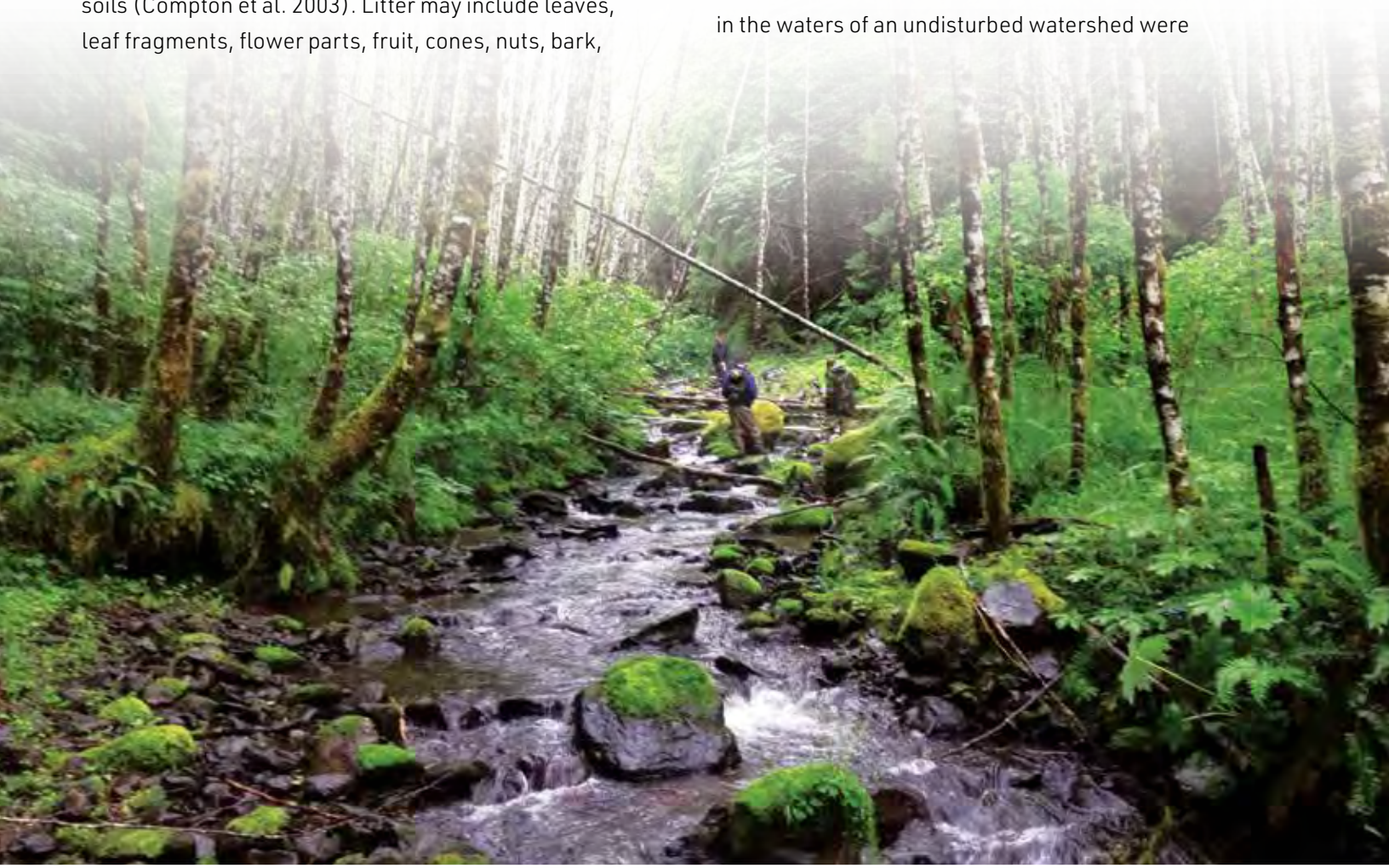
Large wood in stream channels can affect nutrient cycling by slowing the downstream transport of water, sediment, organic matter, and other materials (Chapter 3). Large wood in riparian areas ultimately decomposes, providing nutrients to the forest floor thereby increasing moisture holding capacity (Harmon et al. 1986). Woody material in streams can be a direct source of labile C to streams that can fuel microbial processes, though most C in wood is relatively recalcitrant, taking years or decades to decompose. Wood slows the flow of water thereby extending the residence time of water in the channel and facilitating accumulation of finer organic and inorganic sediments (Chapter 2) that support biofilms.

6.1.3. Nitrogen

Nitrogen is a component of proteins, necessary for all life, and often is a limiting nutrient for both terrestrial and aquatic organisms. N limitation of plant growth is common in PNW forests (Peterson and Hazard 1990). Ultimately, N comes from atmospheric N_2, which has a very strong triple bond that, aside from lightning and industrial processes, only a few specialized N-fixing organisms can break.

Nearly all N in lotic ecosystems of Washington is derived from allochthonous sources, and in undisturbed headwater watersheds, the source of nearly all N is terrestrial. Nitrogen can enter a river or stream via several pathways: litterfall, movement of soluble N from riparian soils into groundwater and hyporheic zones, and leaching and subsurface transport from upland soils (Compton et al. 2003). Litter may include leaves, leaf fragments, flower parts, fruit, cones, nuts, bark, branches and twigs (Benfield 1997), however, leaves account for 72% of total litter in broad-leafed forests and 80% in needle-leaved forests (Xiong and Nilsson 1997). Litter may enter surface waters through direct fall, lateral movement along the ground, or mobilization during floods.

For a headwater stream in the western Cascades of Oregon, Triska et al. (1984) found that more than 90% of annual N inputs to the stream were derived from biotic processes in the adjacent forest. Seventy-three percent of N entering the stream was dissolved organic N in water flowing through the subsurface from forest to stream and 21% was contained in organic matter (e.g., leaf litter, needles, and coarse woody debris) from the riparian forest. The headwater stream exported 74% of its annual N inputs to downstream waters; 22% of the exported N was contained in particulate organic matter. Edmonds et al. (1995) found that nitrate concentrations in the waters of an undisturbed watershed were



N-fixation by Red Alder is an important component of nutrient cycling in forests of western Washington and Oregon/Ned Pittman, WDFW

seasonal, with in-stream concentrations being highest in the fall and lowest in the summer when N uptake by terrestrial vegetation was greatest.

Red Alder fixes N_2 and enriches soil with N compounds through root and nodule secretions. Red Alder leaves contain N concentrations roughly 2 to 3.5 times greater than leaves or needles of other tree species (Tarrant et al. 1951). Because aquatic ecosystems in undisturbed watersheds are often N-limited, Red Alder can be a major source of allochthonous N to aquatic ecosystems, and more Red Alder litter can increase ecosystem productivity. For example, Wipfli and Musslewhite (2004) found that headwater streams with more Red Alder canopy cover exported greater biomass of both terrestrial and aquatic invertebrates to fish-bearing waters than riparian areas with less alder. This subsidy of prey from headwaters to fish-bearing streams is needed to maintain fish productivity (Wipfli and Baxter 2010).

Nitrogen cycles in the environment through multiple redox states, in solid, dissolved, and gaseous forms, and originates from multiple sources, making for one of the most challenging biogeochemical cycles to monitor and characterize (Figure 6.3). Shallow groundwater adjacent to stream channels often is a hot spot for N removal processes and a storage zone for other solutes (Hinkle et al. 2001; Zarnetske et al. 2011). The groundwater–surface water interface is characterized by dynamic gradients of dissolved oxygen, N, and organic C concentrations where biogeochemical reactions take place, including metabolism of organic C, denitrification, and nitrification (Sobczak et al. 2003). Denitrification is generally considered the most important biological process through which ecosystems lose N. Denitrification, and disturbances like tree harvest and fire, remove N from an ecosystem, whereas N uptake by plants eventually returns N to the system through litterfall or senescence and subsequent microbial decay. Organic C is required as an energy source for denitrification. Small streams can lose nitrate

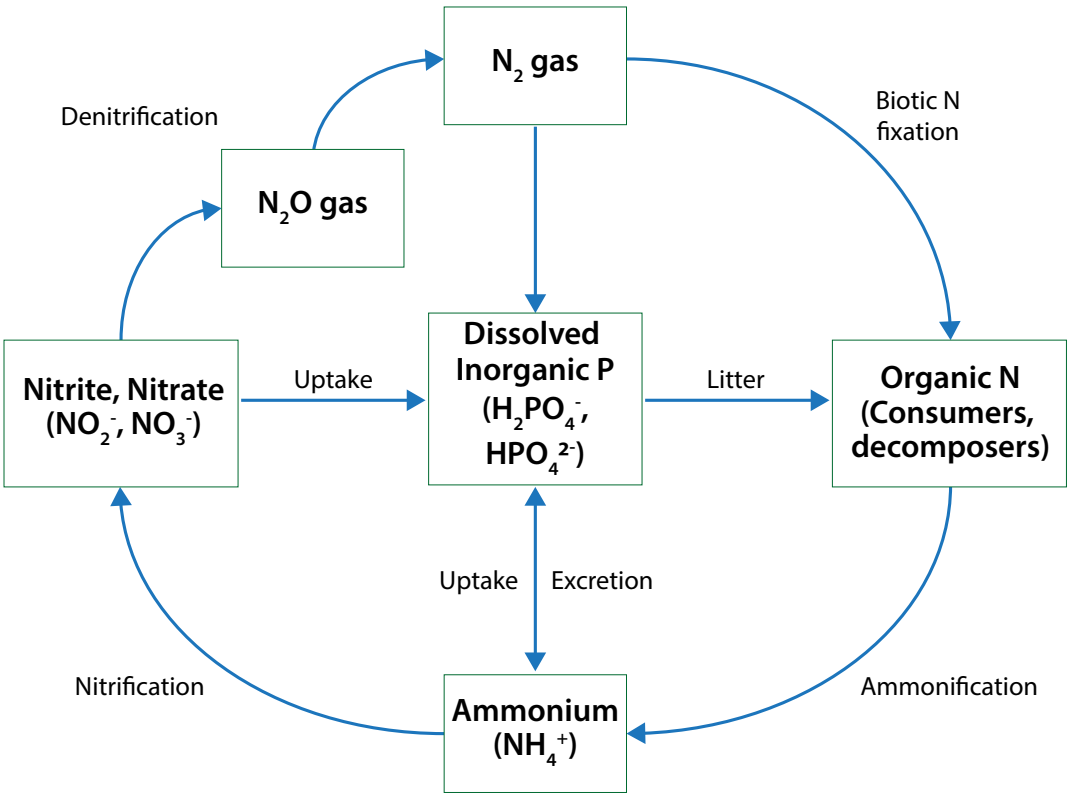


Figure 6.3. Nitrogen cycle pools and processes in ecosystems.

N efficiently because of their high ratio of streambed area to water volume, which brings more surface water in contact with the hyporheic zone. Small streams have a large cumulative influence on N transformation and loss because they account for most of the stream length within a network (Alexander et al. 2000; Peterson et al. 2001). Larger streams lose nitrate N because of longer transport distances over which more biological reactions can occur that consume N coupled with longer water residence times and higher N concentration which fuels the denitrification along with organic C (Mulholland et al. 2008).

Increased groundwater–surface water interaction can alter dissolved oxygen concentrations and redox conditions (Striz and Mayer 2008; Zarnetske et al. 2012), transporting N- and C-containing organic matter to microbes in subsurface sediments, leading to N loss via denitrification under favorable oxidation–reduction conditions (Hedin et al. 1998). The conditions that favor denitrification may change rapidly over time and space. Therefore, "hot spots" may form where denitrification occurs in small patches of the stream (e.g. under leaf packs) or "hot moments" where denitrification rates are high but for short periods of time due to rapid dynamic water movement (McClain et al. 2003; Vidon et al. 2010). However, biochemical processes in urban riparian soils such as denitrification may be impaired because of increased rates of erosion and limited groundwater–surface water interaction due to high proportions of impervious surfaces (Groffman et al. 2002).

The importance of riparian vegetation on transforming N inputs has been examined (Sweeney et al. 2004; Mayer et al. 2007; Sweeney and Newbold 2014). Riparian area characteristics such as width of vegetation, soil carbon, and hydrologic flowpaths, can influence the amount of N removed. Mayer et al. (2007) surveyed the available scientific literature containing data on riparian management and N concentration in streams and groundwater to identify relations between N uptake and riparian width, hydrological flow path, and vegetative cover. Removal efficiencies ranged from <0 (i.e., where the riparian ecosystem appeared to be a N source) to 100%, with a median removal rate of 91%. Wide vegetated riparian areas (>165 ft; 50 m) more consistently removed significantly higher proportions of N entering riparian areas than narrow bands of vegetation (0 - 82 ft; 0 - 25 m). The critical conclusions from this review were that riparian areas were effective at trapping and removing N when they were vegetated, wider, and allowed for subsurface movement of water where the interaction of nutrients dissolved in the water had prolonged contact with soils. Therefore, the hydrologic connection of riparian areas and streams is key to effective nutrient capture. Where channels are incised, riparian areas tiled for drainage, or where floodplains are disconnected via reinforced banks or channelization, nutrients will flow downstream with little interaction with riparian areas.

Subsurface hydrology (saturated vs. unsaturated soil conditions) and redox condition appear to be significant determinants of N-removal efficiency, regardless of vegetation (Mayer et al. 2007; Mayer et al. 2010b). When the water table fluctuates in response to precipitation events, buried relict hydric soil may become saturated, producing sub-oxic or anoxic conditions (Hefting et al. 2004; Weitzman et al. 2014), facilitating N removal. Where flow paths move through wetland riparian soils, great potential exists to remove large quantities of N in proportion to the loads (Jordan et al. 2011); where flows occur via deeper groundwater dynamics or via tile



Riparian vegetation: Red Elderberry Sambucus racemosa*/ Ned Pittman, WDFW*

drainage, N in solution may bypass the C-rich riparian soils and flow through zones where less potential exists for nutrient removal (Wigington et al. 2005). Hydrologic connectivity between riparian areas and streams is a critical factor in determining N removal rates.

Denitrification rates in the stream channel are linked to the organic C content of benthic sediments, respiration rates, and extent of stream water interaction with the streambed (Alexander et al. 2000; Mulholland et al. 2008), conditions that can be fostered by woody material (e.g., sticks, branches or tree trunks), and debris dams in streams. Woody material may function as microsites or hotspots of elevated biogeochemical cycling including denitrification (Groffman et al. 2005), and provides substrates for bacteria and fungi, which in turn consume N in streams (Ashkenas et al. 2004).

Biofilms are a matrix of algae, bacteria, and fungi embedded in a slick polysaccharide film that coats hard substrates in streambeds. These microbial communities consume, respire, and reduce inorganic N (Mulholland et al. 1995). Physical habitat heterogeneity and the biodiversity of the biofilms influence N uptake (Cardinale et al. 2002; Cardinale 2011). Biofilm structure, composition, and capacity for biogeochemical cycling are influenced by substrate composition, light penetration, nutrient concentration, flow rates, seasonality, sediment composition, and the community of invertebrate grazers in the vicinity (Sabater et al. 2002). Biofilms formed on wood substrates have been found to have higher respiration rates and greater N demand than biofilms developed on rock substrates (Sabater et al. 1998). Lazar et al. (2014) found that biofilms on wood substrates in a forested stream had significantly higher denitrification rates than those on non-organic substrates such as stone. In an old-growth forest system in Oregon, aquatic mosses and biofilm on large wood showed the highest N uptake rates among biota while, both vertebrate and invertebrate consumers took up substantial amounts of N, especially small invertebrate grazers (Ashkenas et al. 2004).

Furthermore, N in the stream was transported to the upland through uptake by terrestrial plants, likely through long, subsurface flow paths, demonstrating a strong link between terrestrial and aquatic systems (Ashkenas et al. 2004).

In addition to the biofilms on the streambed, microbial communities within the hyporheic zone can be hotspots for N dynamics. At the HJ Andrews Experimental Forest in Oregon, Zarnetske et al. (2011) found that the hyporheic zone was an important site for N dynamics in small forested streams, with residence time determining the dominance of different N transformation processes. Water pathways with residence times of less than 7 hours tended to be dominated by DO and DOC use as well as ammonium and nitrate production, while pathways with longer residence times removed N via denitrification. Further modeling suggested that water residence times and oxygen uptake rates of microbes are important determinants of whether hyporheic zones are net sources or sinks of nitrate N (Zarnetske et al. 2012). In large rivers like the Willamette, hyporheic zones can be important areas for nitrate removal from regional groundwater prior to entry into surface flow (Hinkle et al. 2001), as well as important for N removal and cooling as water moves in and out of hyporheic areas on its path downstream (Fernald et al. 2006).

The relationships between land use and N transport and fate can be complex, and are mediated by aquatic and riparian biota. Sobota et al. (2012) showed that N uptake differs substantially across forested, agricultural, and urban streams in the Willamette River basin in Oregon. Most nitrate N in forested streams was transported downstream without being taken up. N storage was high in algal biomass in unshaded agricultural and urban streams but turnover and subsequent recycling back to the stream may ultimately be high (Sobota et al. 2012). Collectively, this work indicates that uptake via heterotrophic organisms living on large wood is critical to long-term N capture in forested streams. Once the canopy is opened up, autotrophic algal production

becomes a more important process for uptake of excess nutrients, which leads to shorter-term storage and potential for negative consequences associated with freshwater algal blooms.

6.1.4. Phosphorus

Phosphorus (P) is an important component of adenosine triphosphate (ATP) and necessary for energy transformations in plant and animal cells. Like N, low P availability often limits primary production on land and can be particularly limiting to productivity in freshwater. This is because P tends to form complexes and be retained in soils and thus does not move as readily into ground and surface waters from the landscape as does nitrate N. P cycles in the environment through multiple organic and inorganic forms (Figure 6.4). P occurs in the environment in organic forms (e.g., organo-phosphate and polyphosphates like ATP) in plant and animal biomass, sewage, and pesticides. Inorganic forms of P, such as phosphate (PO_4^{3-}), and orthophosphate, are biologically reactive and thus can be used directly by plants and microorganisms (Carpenter et al. 1998). Orthophosphate is derived from phosphate-bearing minerals, fertilizers, detergents, and industrial chemicals. In the Pacific Northwest, bedrock is the major source of stream P loads, with fertilizer, manure, and wastewater inputs important in some locations (Wise and Johnson 2011). Overabundance of P can result in abnormally high primary production in water, leading to water quality problems such as algal blooms, production of cyanotoxins, and low oxygen events (Carpenter et al. 1998; Jacoby and Kann 2007).

P is commonly a limiting nutrient in aquatic ecosystems because it is highly insoluable and has an affinity for binding to soil particles. Nevertheless, riparian areas are sources of allochthonous P to streams in undisturbed watersheds. The amount of P that is contributed by riparian areas to aquatic habitats through litterfall

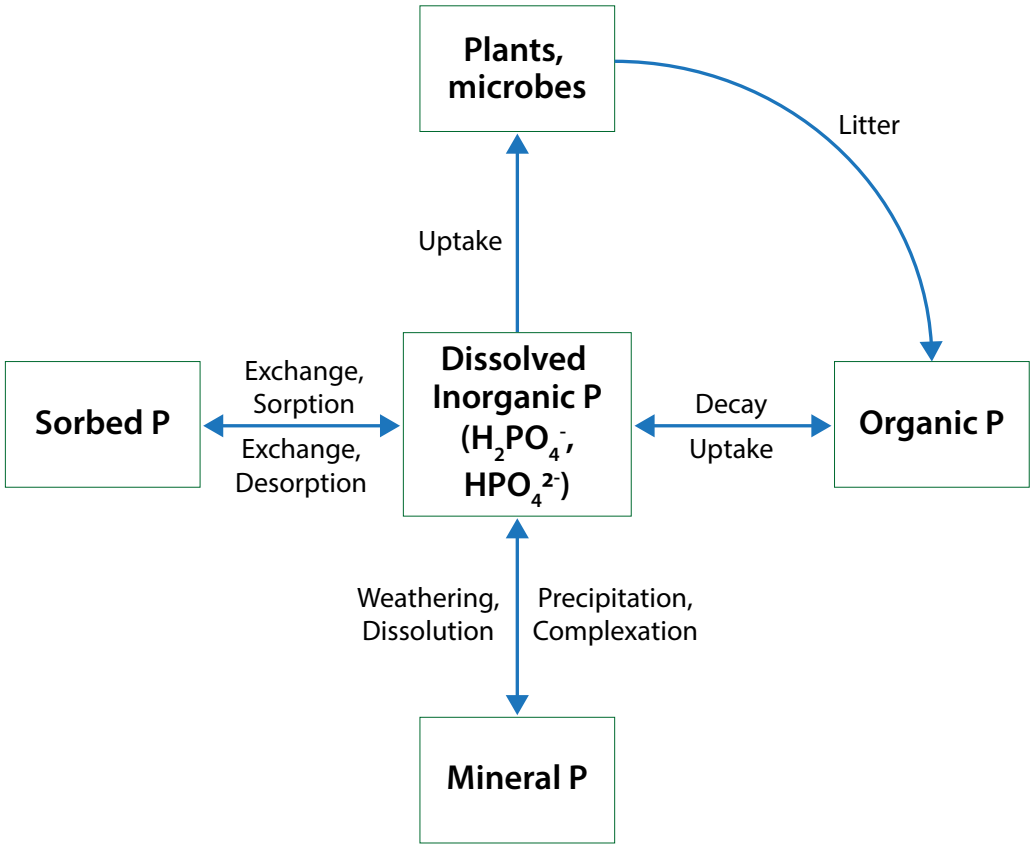


Figure 6.4. Phosphorus cycle pools and processes in ecosystems.

relative to other sources under natural, undisturbed conditions has yet to be quantified for riparian ecosystems in the Pacific Northwest.

P attenuation refers to declines in P concentration in water and soil through physical, chemical, and biological processes. Mineral content and pH are important factors determining P attenuation in soil. Because of their volcanic origins and the weathering environments, many soils in the PNW can bind tightly to large quantities of anions like phosphate, replacing reactive soluble P forms for particulate P forms, which are less biologically reactive (Johnson and Cole 1980; Bohn et al. 1985). Sorption, the chemical attachment of molecules to soil particles, may occur quickly (e.g., days) and includes adsorption and substitution between P and other anions on mineral surfaces. Sorption may also occur slowly (e.g., weeks), such as mineral dissolution and precipitation reactions between P and soil cations such as Ca and Mg or Al, Fe, and Mn oxide compounds depending on soil pH (Bohn et al. 1985). Phosphate is most soluble in slightly acid to neutral pH soils. Under reducing conditions, Fe is reduced and the P-Fe oxide compounds may dissolve, thereby releasing P (Denver et al. 2010). Minimally disturbed forests have a relatively tight P cycle, with low inputs from precipitation, and even lower leaching rates (Yanai 1992; Compton and Cole 1998). In the volcanically influenced soils of the Cascades, most of the ecosystem P is contained in soil, and organic and inorganic forms of sorbed P are the dominant forms as opposed to primary minerals or microbial P (Compton and Cole 1998). There is substantial recycling of P by plants and soil and biotic release of organic P via phosphatase enzyme activities is an important component of this cycle (Giardina et al. 1995). Several studies have shown that Red Alder increases rates of P cycling (Giardina et al. 1995; Zou et al. 1995), further supporting the important role that Red Alder plays in regulating both N and P nutrient cycles of the PNW. Vegetated riparian areas generally are expected to retain P by slowing water flow and by plant and microbial uptake.

Unlike N, which is ultimately constrained by atmospheric fixation and regulated by biologic cycling, P availability is controlled by weathering and a complex set of chemical and biological processes. P retention is regulated by the equilibrium P concentration (EPC), the concentration at which P sorption equals desorption (Hoffmann et al. 2009). Once soil P has reached its sorption capacity, excess P may be exported in water (Domagalski and Johnson 2012). Biological processes also play a role in P attenuation and release (Schechter et al. 2013). Bacteria, fungi, algae, and plants incorporate P into biomass; however, plants vary in P demand and uptake effectiveness, exhibiting numerous strategies for sustaining growth and maintenance (Shen et al. 2011). P is released from organic matter through decomposition, which is dependent on pH, litter quality (C:N:P ratios), Ca content, redox potential, soil moisture, and temperature (Schechter et al. 2013). Increases in P loading as well as soil disturbance and erosion have the potential to reduce this generally tight P cycle and increase transfer to aquatic ecosystems (Figure 6.2).

Microbial and plant uptake represent short-term, transient P pools (Richardson and Marshall 1986). Phosphate may be assimilated into plant tissues or in microorganisms but released upon death and senescence. Peat accumulation and P sorption and precipitation are important long-term P sequestration mechanisms (Richardson and Marshall 1986; Reddy et al. 1995). Long-term storage of P depends on sorption to inorganic sorbents; P sequestration is mainly associated with adsorption to Fe and Al oxides in acidic soils or precipitation of Ca phosphates in alkaline soils (Giesler et al. 2005). Phosphorus retention mechanisms differ widely depending on hydrological pathway through the riparian area. Sorption and desorption reactions are more important during subsurface flow, while sedimentation of particulate P may be the major retention mechanism during overland flow. Significant amounts of P can be stored in stream sediments and may be resuspended and released during storms. Retention of total P in riparian areas is controlled

mainly by sedimentation processes, dependent on morphology (e.g., width) and vegetation characteristics. However, riparian areas can become a net source of dissolved P released from soil or from plant material (Hoffman et al. 2009). Retention of dissolved P in riparian areas is often not as significant as retention of particulate P (Hoffman et al. 2009). Inundation of riparian areas or floodplains can deposit particulate P whereas plant uptake may temporarily immobilize P (Hoffman et al. 2009). Overall, riparian ecosystem retention efficiency varies widely and some riparian areas may become sources of P, especially ortho-phosphate (Schechter et al. 2013). Total P moving through the soil is not necessarily related to the width of the riparian area but rather on flow path and soil types (Hoffman et al. 2009; Schechter et al. 2013).

6.2. Hydrologic Connectivity and Nutrient Dynamics

Nutrients cycle at various spatial and temporal scales. Soils, vegetation, and water flows largely dictate the sources and processing of nutrients. Nutrients may enter the riparian ecosystem from the atmosphere (e.g., nitrogen oxides produced from fossil fuel combustion or ammonia released from agricultural areas), from terrestrial sources when rainwater flushes nutrients from upland soils and vegetation, or from floods that

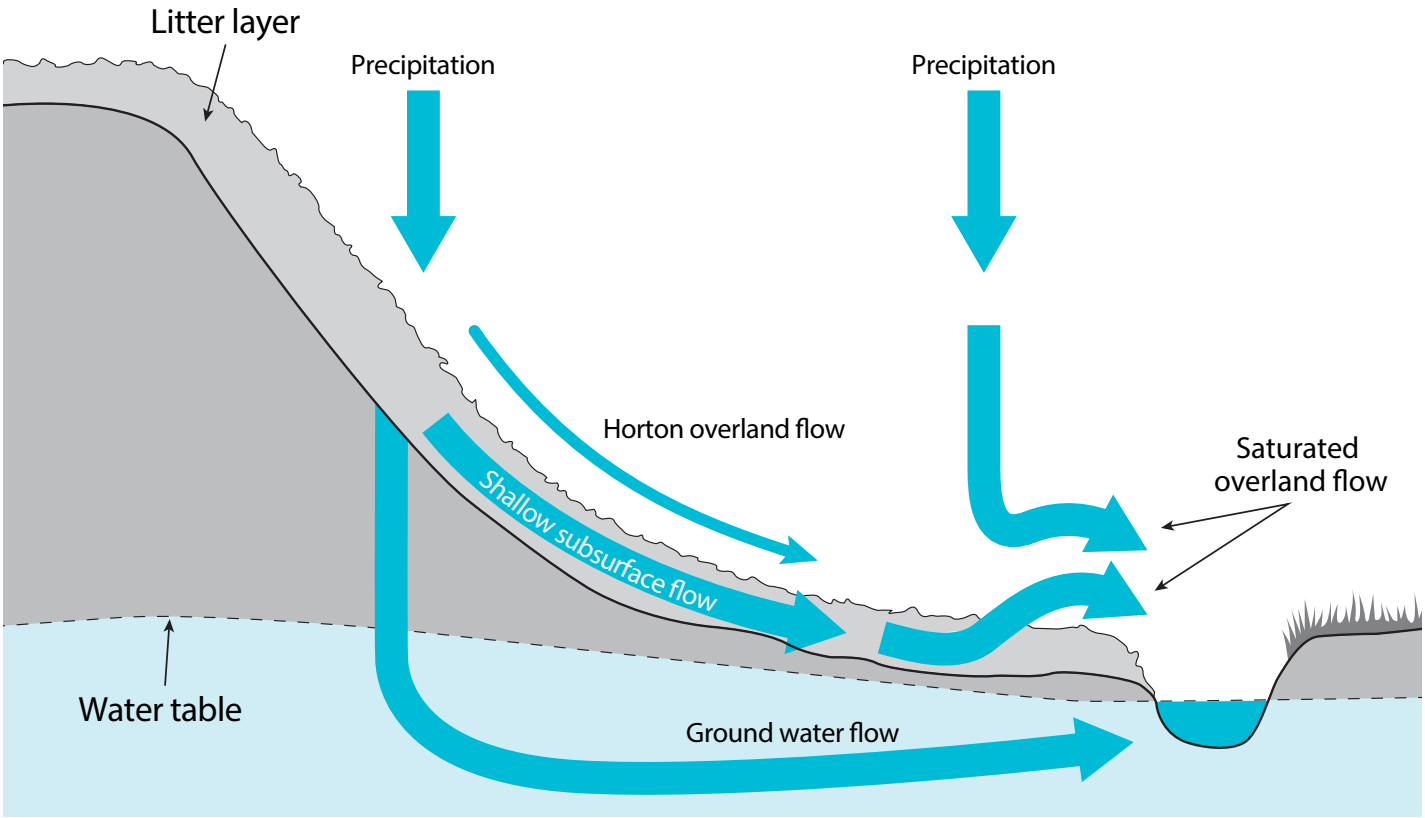


Figure 6.5. Water flow paths. Precipitation reaches a stream as surface runoff and by infiltration into the ground where it contributes to groundwater flow. The amount of water following each flow path depends on the capacity of the soil to absorb water, the amount of storage in surface depressions, and the amount, intensity, and duration of precipitation (image adapted from Stream Corridor Restoration Handbook; FISWRG, 1998).

bring in nutrients from upstream areas (Figure 6.5). As water moves downstream, it moves into and out of the hyporheic zone, carrying with it dissolved nutrients that react with the sediments and biota living in the interstitial spaces of the sediments (Fernald et al. 2006). Wondzell (2011) suggests that hyporheic exchange is likely to be most important in small streams but that hyporheic exchange through sand-bedded streams is substantial and may have an important influence on nutrient loads of large rivers. Regardless, large fractions of N are removed via denitrification in hyporheic sediments at all scales from headwater streams to large rivers (Peterson et al. 2001; Mulholland et al. 2004; Alexander et al. 2007).

Hydrology is the driving force for a range of physical and biogeochemical processes controlling retention and flux of nutrients entering the riparian ecosystem (Chapter 2). Nutrients may originate from neighboring areas via local flow systems throughout the riverscape, from regional groundwater flow systems, especially along reaches of the higher stream orders, or from a recirculation of river water in riparian areas during flooding (Dahl et al. 2007). Depending on flood intensity and frequency, water may overflow the streambanks and move into the floodplain where sediments may be deposited or, conversely, litter, woody material, and sediments may be mobilized and transported into the main channel.

Many floodplains in the Pacific Northwest are highly altered by human activities and are often artificially disconnected from stream channels by levees. Subsequently, natural flooding processes and nutrient exchange, both deposition and production, are severely altered often with negative consequences to riparian habitat.

Discharge volume, stream flow velocity, and temporal variability in flow, coupled with nutrient concentrations dictate the mass loading of each nutrient flowing downstream. Headwater streams commonly make up 75% or more of the total stream channel length in drainage basins (Benda et al. 2004) and have a disproportionately profound influence on the water quality and quantity for downstream ecosystems (Peterson et al. 2001). Alexander et al. (2007) found that fluxes from first-order headwater streams accounted for 70% of water volume and 65% of the N flux occurring from second-order streams. Research comparing perennial, intermittent, and ephemeral stream nutrient cycling processes indicates that flow intermittency can affect the concentrations, fluxes, and forms of nutrients moving from streams into downstream ecosystems (Von Schiller et al. 2011).

In western Oregon and Washington, floodplains experience extremes in water and sediment flux (Naiman et al. 2010). Floodplains often have saturated soils and shallow, upwelling groundwater. Such wet conditions influence N processing by creating anoxic, denitrifying conditions in organic soil horizons (Burt et al. 2002). However, many floodplains of the PNW are highly altered by human activities and are often artificially disconnected from the stream channel via levees constructed to convert lands to agriculture or other uses. Subsequently, nutrient exchange during flood events between aquatic and riparian ecosystems, via both mobilization and deposition of dissolved and suspended organic matter, is severely altered. River restoration often focuses on reconnecting floodplains and associated riparian areas to stream channels in order to restore natural hydrology and re-establish nutrient cycling functions (Bernhardt et al. 2005; Craig et al. 2008). The hydrologic interactions of uplands and

riparian soils control nutrient cycling and transport (Mayer et al. 2007; Weitzman et al. 2014). Therefore, it is critical to maintain riparian vegetation and to control soil erosion and nutrient runoff from uplands (Mayer et al. 2007; Hoffman et al. 2009; Zhang et al. 2010; Sweeney and Newbold 2014).

Impacts to riparian ecosystems may include historic events not well documented and not easily recognized today. Such impacts may lead to erroneous understanding of baseline conditions or misidentification of pristine areas. For example, recent research suggests that legacy sediments, referring to sediments deposited in floodplains from historic upland erosion in response to deforestation and construction of milldams and ponds, have altered nutrient cycling in riparian ecosystems throughout the mid-Atlantic region of the US (Walter and Merritts 2008; Merritts et al. 2011). Much of the fine sediment carried by these streams during storms is from streambank erosion, which often includes legacy sediments, thereby contributing substantially to sediment and nutrient loads in streams (Gellis and Noe 2013). While milldams may not have been as common in the Pacific Northwest, splash dams created to move logs downstream were common throughout the region historically until the mid-20th century (Phelps 2011). These dams and other historic logging activities may have altered riparian systems in ways not easily recognized today but which may have had a significant legacy effect on sediment deposition in floodplains. For example, splash dam releases exceeded the effects of 100-year flood events in headwater regions and were comparable to 100-year flows in lower reaches (Phelps 2011). Splash dams also may have contributed to simplification of stream channels when rocks and debris jams were removed to facilitate log transport (Sedell and Luchessa 1981; Wohl 2000). Overall, the long-term effects of splash dams are not well documented nor are they accounted for in current riparian assessments.



South Fork Sauk River/Wendy Cole, WDFW

Precipitation and runoff are master variables regulating transport and transformation of C, N, and P in watersheds (Dosskey et al. 2010; Vidon et al. 2010). The interaction between land use and climate variability can increase the amplitude and frequency of nutrient pulses, effecting rapid and large changes in concentrations and fluxes of materials (Kaushal et al. 2014). Shifting patterns in runoff and temperature due to land use and climate variability can amplify pulses of greenhouse gases (GHG) such as CO_2, CH_4, and N_2O emanating from watersheds (Kaushal et al. 2014). For example, Vidon et al. (2014) showed strong N_2O pulses in response to storm events in a riparian wetland. Warming increases production of some GHGs in wetlands (Inglett et al. 2012) because temperature affects reaction kinetics and equilibria. Higher stream temperatures may increase rates of both bacterial consumption of nutrients and production of GHGs in streams and rivers (Kaushal et al. 2014). Recent research shows that groundwater may also warm in response to climate (Menberg et al. 2014).

Most N and P enters receiving waterbodies during storm events and during cooler seasons when temperatures are lower than optimal for microbial activity (Kaushal et al. 2010) or when plants are senescent. During drought, residence times may be long, leading to more denitrification in riparian soils, however N loads may be small overall because stream flow may be much lower than normal (Mayer et al. 2010b; Filoso and Palmer 2011). However, drought may also lower moisture levels in riparian soils, potentially reducing the occurrence of anoxic conditions required for denitrification (Groffman et al. 2003). Conversely, high flow conditions during "flashy" storm events may greatly compromise nutrient retention processes (Booth 2005) flushing far more solutes downstream including N and P (Cooper et al. 2014). Consequently, high flows are also responsible for the vast majority of particulate C, N, and P transport in most streams (Alexander et al. 2000; Moore and Wondzell 2005).

Stream channel geomorphology and geologic setting, especially stream channel width, depth, and sediment lithology strongly influence groundwater behavior. In turn, nutrient movement in riparian ecosystems is dependent upon groundwater, which can be highly variable and follow preferential flow paths. Striz and Mayer (2008) showed that groundwater movement may shift considerably depending on seasonal precipitation trends. Streams may be gaining, that is, receiving water from the uplands when precipitation is high, or losing surface water to the ground when soils are dry and drought conditions prevail. Water movement through deep groundwater flow paths back to the stream can take years or decades (Hinkle 2009) and in some cases there is very little exchange with regional deep groundwater (Vaccaro 2011).

Mass removal of nutrients and contaminants in streambed sediments is dependent upon residence times because microbial processes, such as denitrification, require time for complete reaction (Zarnetske et al. 2012). Nutrient concentrations in soils and water may vary on time scales across minutes and hours as plants or algae take up nutrients. Yet, seasonal and annual cycles are also evident based on flow and temperatures. Nutrients may also vary on spatial scales of millimeters to meters depending on plant distribution or litter deposition, and can also vary at regional and global scales depending on land use, geomorphology, and precipitation patterns.

A better understanding of the role hyporheic connections play in the processing of nutrients will improve our ability to design riparian management strategies that protect water quality.

6.3. State of Riparian Nutrient Dynamics Science

Recent advances in stream nutrient research reveal spatially and temporally variable processes and resulting pulses of nutrient transformation, storage, and release that can differ among locations and through time at the same locations. We also know that freshwater and riparian ecosystems vary tremendously across the PNW based on soils, climate, organisms, and human activity. Because most stream nutrient research originates from case studies, the application of case study results to novel conditions should be done cautiously.

Most studies of riparian nutrient dynamics have been conducted in forested watersheds; grassland and desert ecosystems in our region are less well studied but share some common processes and dynamics. Much of the information provided here demonstrates that riparian areas can have important effects on nutrient transfer from land to water, which subsequently have implications for ecosystem goods and services (e.g., water for drinking, swimming, fishing, boating, etc.) and habitat conditions for aquatic species.

Generally, if the goal of riparian management involves nutrients, management should include efforts to shorten nutrient spiraling lengths, increase nutrient retention, provide substrates to support riparian food webs, and maintain natural shading in order to minimize algal blooms. However, stimulating algal and plant growth is one way to shorten nutrient spiraling lengths by enhancing nutrient uptake, at least temporarily as nutrients will be returned after senescence. A longer-term goal of riparian management is to avoid excessive nutrient delivery to streams. Maintaining riparian



The larvae of many caddisfly species use silk to make protective cases, which are often strengthened with gravel, sand, and twigs/ Ned Pittman, WDFW

vegetation, soil conditions, and flowpaths, etc. will fascilitate the removal of nutrients from surface and subsurface flow before entering the channel. If nutrient input is successfully controlled, light levels promoting algal blooms become much less of an issue.

Some of the critical gaps in our understanding occur where physical sampling for detecting water and material movement is most difficult. This occurs in the soil subsurface, the streambed, and hyporheic zones where determining flow dynamics requires multiple sampling wells (Striz and Mayer 2008) or surrogate measures such as stream temperature (Stonestrom and Constantz 2003). A better understanding of the role hyporheic connections play in the processing of nutrients will improve our ability to design riparian management strategies that protect water quality (Hinkle et al. 2001; Zarnetske et al. 2011, 2012), particularly by expanding these studies to better

represent the range of conditions in Washington. However, the use of stable isotopes of N, P, C, and also O and H in water have helped to illuminate some of the more obscure processes like water movement into and out of trees (Brooks et al. 2010) and the uptake of N along entire stream reaches (Ashkenas et al. 2004). Satellite monitoring data (e.g. GRACE) and lidar imaging, which can provide high-resolution topographic data for inaccessible areas, are proving to be valuable tools for the study of nutrient dynamics at the watershed scale. Drone technology may eventually further provide local and current information on condition and environmental variables. Coupling these new data sources with the development of powerful computer models (e.g., VELMA) that predict watershed-scale nutrient movement (Abdelnour et al. 2011; Abdelnour et al. 2013) will greatly enhance our ability to extrapolate field level data to watershed scales and to test land use riparian management scenarios and climate change impacts on nutrient cycling behavior.

6.4. The Role of Management

Litter from riparian areas is clearly an important source of limiting nutrients and chemical energy for aquatic ecosystems. Inorganic nutrients, such as those in artificial fertilizers, do not mimic the foodweb role of litter because inorganic nutrients feed the autotrophic components of foodwebs, such as algae. Litter feeds heterotrophic components of foodwebs, such as benthic macroinvertebrates, many of which are prey for resident salmonids and juvenile salmon. Consequently, providing adequate amounts of litter to streams is an important issue for riparian area management. The results of Bilby and Heffner (2016) suggest that 95% of full litter delivery to streams can be achieved with buffer widths between 40 to 60% of site-potential tree height, depending on site conditions. Numerous factors dictate the transport and fate of nutrients through riparian systems. Managing riparian systems to limit negative impacts of nutrients on downstream resources is inherently complex. The role of management is largely to offset the impacts of human activities that increase nutrient loads and runoff, exacerbate the impacts of nutrients, and/or alter the fluxes of nutrients. Table 6.1 identifies impacts of human activities in the context of factors influencing riparian areas and describes practical management and restoration approaches that are known to mitigate nutrient impacts. The primary objective with respect to offsetting nutrient impacts among all categories of land use is to maintain existing riparian systems, restore degraded systems, and plant riparian buffers where they do not currently exist. Overall, management should focus on where in the watershed important nutrient dynamics that affect aquatic system integrity (or fish life) occur, and how to reduce or ameliorate various human disturbances that can affect nutrient dynamics at those places.

Although salmon runs and associated nutrient fluxes have declined over time in Oregon, Washington, Idaho, and California (Gresh et al. 2000), salmon could still play an important role in stream ecosystems by greatly increasing the quantity of salmon carcasses planted in streams or by greatly increasing harvest escapement (Gende et al. 2002). Addition of inorganic nutrients will not mimic the food web role of salmon in PNW watersheds because they do not directly mimic the complex organic matter from salmon carcasses supplied to heterotrophs such as aquatic insects and juvenile salmonids (Compton et al. 2006). Maintaining structures, such as large wood, and processes that retain nutrients are expected to allow greater utilization of salmon-derived nutrients in aquatic food webs.

Table 6.1. Major factors influencing nutrient dynamics in riparian ecosystems and the role of management in reducing impacts

Factors influencing riparian areas	Impacts of human activities	Role of management in reducing impacts
Land use - agriculture	Excess nutrient application and leaching into groundwater and surface water	Improve nutrient management to reduce nutrient loading - right time, right place, right source, right rate (4Rs)
	Compaction and vegetation damage from poor livestock management near streams	Protect and restore riparian areas to attenuate sediment and nutrient loads
	Riparian disturbance or lack of natural vegetation in riparian area	Protect and restore riparian areas to reduce light inputs that drive algal overproduction and eutrophication
Land use - urbanization	Impervious surfaces increase nutrients and sediment transfer to surface waters	Disconnect direct runoff from impervious surfaces to streams to control nutrient and sediment inputs
	Increased nutrient application via yard fertilizer and pet waste	Educate the public and incentivize behaviors to reduce nutrient loads
	Leaky and ineffective sewer and septic systems	Improve sewer systems, sewage treatment, storm drainage, and septic systems
Land use - forestry (harvest and road building)	Small increase in nutrient loadings	Seek alternatives to clear cutting and protect riparian areas
	Small to moderate increase in sediment transport	Seek alternatives to clear cutting; improve harvest practices, slope and soil management, and road construction; and protect riparian areas
Forest age and composition	Recent clear-cuts may lose the most nutrients	Extend harvest rotations because mature forests likely retain more nutrients than young forests
	Red Alder fixes large amounts of N, which remains in the system and contributes to productive soils of the Coast Range and western Cascades mountains	Recognize the role that Red Alder forests can play in stream nutrient levels
Climate and seasonality	Rapid movement of water during fall and winter rains, sometimes bypass riparian zones	Slow water movement across the landscape
	Rapid N cycling during the summer but low flows mean this inorganic nitrogen accumulates in the soil, fall rains displace this N and transport it to streams	Consider timing of fertilizer applications
	Spring season usually has peak algal blooms because nutrient supplies are high as is light availability before full leaf out.	
	Slower processing of nutrients in cold weather, although conifer trees take up nurients year round	
Elevation and topography	Steep slopes lead to higher rates of runoff and sediment transport	Minimize disturbance to vegetation and soils on steeper slopes through forest and pasture management

Table 6.1. CONTINUED
Major factors influencing nutrient dynamics in riparian ecosystems and the role of management in reducing impacts

Factors influencing riparian areas	Impacts of human activities	Role of management in reducing impacts
Hydrology	Reduced connection between the channel and floodplain can limit nutrient uptake	Reconnect flood plains to increase water residence times, which can increase ground water-surface interactions and nutrient uptake
Nutrient concentrations, forms, and inputs	High concentration and multiple sources of bioavailable nutrient forms may overload capacity of riparian systems to process nutrient loads	Consider terrestrial versus atmospheric sources; carefully manage synthetic fertilizer and manure applications, and balance N and P
Soil properties and geology	Low permeability reduces infiltration and interaction with soils	Practice good soil management because rich, fertile soils can contribute organic carbon for denitrification
	Sandy soils can transmit more water and nutrients (e.g., pumice soils and septic systems)	Recognize that some soils are better at adsorbing P (e.g., volcanic and highly weathered soils)
Biota	Declines in salmon runs reduces supply of nutrients and organic matter for invertebrates, birds, mammals, and other fish	Restore salmon populations, which increases nutrients in ecosystem: nutrients are assimilated by vegetation, consumed by animals, and converted by microbial processes

6.5. Conclusions

Riparian areas are important sources and sinks of organic matter and nutrients for streams. Numerous sources of C, N, and P exist, each taking various organic and inorganic forms, and each moving through the environment continuously along multiple paths at various temporal and spatial scales. Transfers may be via subsurface flow, direct input of materials via litterfall, treefall, or animal movement. Nutrient and energy subsidies from riparian areas to streams and rivers have profound effects on the composition, structure, and functions of aquatic ecosystems.

In watersheds where excess nutrients are polluting surface waters, hydrology and flow paths are critically important when considering potential for nutrient removal by riparian areas. If a riparian area is physically disconnected from the stream, flow paths may not carry materials through the riparian area, particularly into the hotspots with appropriate conditions for denitrification, and thus N removal will not occur as readily. Thus, maintaining hydrologic connections between riparian areas and stream channels are critical. This includes allowing natural seasonal patterns of flow including flooding.

Historically, many watersheds in Washington have seen substantial inputs of salmon-derived N, P, and organic matter. Riparian areas serve as the critical connection for transferring these nutrients to uplands via animal consumption, plant uptake, and biogeochemical cycling.

Results of a large review of riparian ecosystem studies across the globe indicated that vegetated riparian areas were more effective in trapping N than unvegetated ecosystems, but that the type of vegetation did not matter tremendously. Wider riparian areas were more effective in N removal across studies (see Chapter 5).

N-fixation by Red Alder is an important component of nutrient cycling in forests of western Washington and

Oregon. In the PNW, deciduous riparian forests tend to produce more litter with higher nutrient content and nutritional quality for stream food webs than conifer riparian areas. However, conifers have a longer lifespan, produce larger wood and are a more consistent source of shade. In riparian areas with a mixture of deciduous and conifer trees, deciduous species enhance litter flux and nutrient delivery to terrestrial and aquatic food webs, thus, complementing the provision of shade and large wood by conifers. Both the food web and structural roles of tree species should be considered in riparian management plans in order to support aquatic production.

Structurally diverse habitats with variability in geomorphology and soils are likely to support correspondingly diverse biota including vegetation, animals, and microbial communities that will be best able to process and assimilate nutrient loads. Headwaters are especially controlled by riparian processes and thus, are important zones of active nutrient processing that can significantly affect downstream transport of nutrients. Therefore, maintaining riparian areas in headwater systems may be disproportionately important to stream function. Similarly, maintaining hydrologic connection of streams with their floodplains is important because rich, organic sediments are deposited on floodplains during flood events. Conversely, channelization and stream incision from erosion disconnects streams from their floodplains, causes flashy flows, further incises stream channels while starving floodplains of regular resupply of organic matter, and can lower groundwater tables below the rooting zone thereby contributing to the reduction of riparian vegetation in arid climates.

While more research will be necessary to answer important questions about nutrients in riparian ecosystems, the science is very clear about the importance of the condition of riparian areas on the flows of nutrients through stream systems. Riparian areas and their streams are much more than conduits for nutrients from the uplands to downstream systems; they are vitally important locations for the short- and long-term supply, storage, and transformation of nutrients.



Perennial fruiting bodies, or conks, of a polypore fungi/Ned Pittman, WDFW

6.6. Literature Cited[2]

Abdelnour, A., M. Stieglitz, F. Pan, and R. McKane. 2011. Catchment hydrological responses to forest harvest amount and spatial pattern. Water Resources Research 47: W09521 (i).

Abdelnour, A., R. McKane, M. Stieglitz, F. Pan, and Y. Cheng. 2013. Effects of harvest on carbon and nitrogen dynamics in a Pacific Northwest forest catchment. Water Resources Research 49:1292-1313. (i)

Alexander, R.B., R. A. Smith, and G.E. Schwartz. 2000. Effect of stream channel size on the delivery of nitrogen to the Gulf of Mexico. Nature 403:758–761. (i)

Alexander, R.B., E.W. Boyer, R.A. Smith, G.E. Schwarz, and R.B. Moore. 2007. The role of headwater streams in downstream water quality. Journal of the American Water Resources Association 43:41-59. (i)

Ashkenas, L.R., S.L. Johnson, S.V. Gregory, J.L. Tank, and W.M. Wollheim. 2004. A stable isotope tracer study of nitrogen uptake and transformation in an old-growth forest stream. Ecology 85:1725-1739. (i)

Beechie, T., and T.H. Sibley. 1997. Relationships between channel characteristics, woody debris and fish habitat in northwestern Washington streams. Transactions of the American Fisheries Society 126:217-229. (i)

Benda, L., N.L. Poff, D. Miller, T. Dunne, G. Reeves, G. Pess, and M. Pollock. 2004. The network dynamics hypothesis: how channel networks structure riverine habitats. BioScience 54:413-427. (i)

Benda, L., M.A. Hassan, M. Church, and C.L. May. 2005. Geomorphology of steepland headwaters: the transition from hillslopes to channels. Journal of the American Water Resources Association 41:835-851. (i)

Ben-David, M., T.A. Hanley, and D.M. Schell. 1998. Fertilization of terrestrial vegetation by spawning Pacific salmon: the role of flooding and predator activity. Oikos 83:47-55. (i)

Benfield, E.F. 1997. Comparisons of litterfall input to streams. Journal of the North American Benthological Society 16:104-108. (i)

Bernhardt, E.S., M.A. Palmer, J.D. Allan, G. Alexander, K. Barnas, S. Brooks, J. Carr, S. Clayton, C. Dahm, J. Follstad-Shah, D. Galat, S. Gloss, P. Goodwin, D. Hart, B. Hassett, R. Jenkinson, S. Katz, G.M. Kondolf, P.S. Lake, R. Lave, J.L. Meyer, T.K. O'Donnell, L. Pagano, B. Powell, and E. Sudduth. 2005. Synthesizing U.S. river restoration efforts. Science 308:636-637. (i)

Bilby, R.E., R.R. Fransen, and P.A. Bisson. 1996. Incorporation of nitrogen and carbon from spawning Coho Salmon into the trophic system of small streams: evidence from stable isotopes. Canadian Journal of Fisheries and Aquatic Sciences 53:164–173. (i)

Bilby, R.E., and J.T. Heffner. 2016. Factors influencing litter delivery to streams. Forest Ecology and Management 369:29-37. (i)

Bisson, P.A., and R.E. Bilby. 1998. Organic matter and trophic dynamics. Page 373-398 *in* R.J. Naiman and R.E. Bilby, editors. River ecology and management: lessons from the Pacific Coastal Ecoregion. Springer-Verlag, New York. (i)

Bohn, H.L., B.L. McNeal, and G.A O'Connor. 1985. Soil chemistry. John Wiley and Sons, New York. (i)

Booth, D.B. 2005. Challenges and prospects for restoring urban streams: a perspective from the Pacific Northwest of North America. Journal of North American Benthological Society 24:724–737. (i)

Brooks, J.R., H. Barnard, R. Coulombe, and J.J. McDonnell. 2010. Ecohydrologic separation of water between trees and streams in a Mediterranean climate. Nature Geoscience 3:100-104. (i)

Brown G.W., A.R. Gahler, and R.B Marston. 1973. Nutrient losses after clear-cut logging and slash burning in the Oregon Coast Range. Water Resources Research 9:1450-1453. (i)

2 References are classified according to RCW 34.05.271 (see Appendix 1) denoted by a lower case roman numeral (i – viii) in parentheses at the end of the citation.

Burt, T.P., G. Pinay, F.E. Matheson, N.E. Haycock, A. Butturini, J.C. Clement, S. Danielescu, D.J. Dowrick, M.M. Hefting, A. Hillbricht-Ilkowska, and V. Maitre. 2002. Water table fluctuations in the riparian zone: comparative results from a pan-European experiment. Journal of Hydrology 265:129–148. (i)

Cardinale, B.J., M.A. Palmer, C.M. Swan, S. Brooks, and N.L. Poff. 2002. The influence of substrate heterogeneity on biofilm metabolism in a stream ecosystem. Ecology 83:412–422. (i)

Cardinale, B.J. 2011. Biodiversity improves water quality through niche partitioning. Nature 472:86-89. (i)

Carpenter, S., N.F. Caraco, D.L. Correll, R.W. Howarth, A.N. Sharpley, and V.H. Smith. 1998. Nonpoint pollution of surface waters with phosphorus and nitrogen. Issues in Ecology No. 3, Ecological Society of America, Washington, D.C. (i)

Cederholm, C.J., D.B. Houston, D.I. Cole, and W.J. Scarlett. 1989. Fate of Coho Salmon *Oncorhynchus kisutch* carcasses in spawning streams. Canadian Journal of Fisheries and Aquatic Sciences 46:1347–55. (i)

Cederholm, C.J., M.D. Kunze, T. Murota, and A. Sibatani. 1999. Pacific salmon carcasses: essential contributions of nutrients and energy for aquatic and terrestrial ecosystems. Fisheries 24:6–15. (i)

Chappell, H.N., D.W. Cole, S.P. Gessel, and R.B. Walker. 1991. Forest fertilization research and practice in the Pacific Northwest. Fertilizer Research 27:129-140. (i)

Compton, J.E., M.R. Church, S.T. Larned, and W.E. Hogsett. 2003. Nitrogen export from forested watersheds of the Oregon Coast Range: the role of N_2-fixing Red Alder. Ecosystems 6:773–85. (i)

Compton, J.E., and D.W. Cole. 1998. Phosphorus cycling and soil P fractions in Douglas-fir and Red Alder stands. Forest Ecology and Management 110:101-112. (i)

Compton, J.E., C.P. Andersen, D.L. Phillips, J.R. Brooks, M.G. Johnson, M.R. Church, W.E. Hogsett, M.A. Cairns, P.T. Rygiewicz, B.C. McComb, and C.D. Shaff. 2006. Ecological and water quality consequences of nutrient addition for salmon restoration in the Pacific Northwest. Frontiers in Ecology and the Environment 4:18–26. (i)

Cooper, C.A., P.M. Mayer, and B.R. Faulkner. 2014. Effects of road salts on groundwater and surface water dynamics of sodium and chloride in an urban restored stream. Biogeochemistry 121:149-166. (i)

Craig, L.S., M.A. Palmer, D.C Richardson, S. Filoso, E.S. Bernhardt, B.P. Bledsoe, M.W. Doyle, P.M. Groffman, B.A. Hassett, S.S. Kaushal, P.M. Mayer, S.M. Smith, and P.R. Wilcock. 2008. Stream restoration strategies for reducing river nitrogen loads. Frontiers in Ecology and the Environment 6:529-538. (i)

Dahl, M., B. Nilsson, J.H. Langhoff, and J.C. Refsgaard. 2007. Review of classification systems and new multi-scale typology of groundwater–surface water interaction. Journal of Hydrology 344:1–16. (i)

Denver, J.M., C.A. Cravotta III, S.W. Altor, and B.D. Lindsey. 2010. Contributions of phosphorus from groundwater to streams in the Piedmont, Blue Ridge, and Valley and Ridge Physiographic Provinces, Eastern United States. Scientific Investigations Report 2010–5176. U.S. Geological Survey, Reston, Virginia. (viii)

Domagalski J.L., and H. Johnson. 2012. Phosphorus and groundwater: establishing links between agricultural use and transport to streams. U.S. Geological Survey, California Water Science Center, Sacramento. (viii)

Dosskey, M.G., P. Vidon, N.P. Gurwick, C.J. Allan, T.P. Duval, and R. Lowrance. 2010. The role of riparian vegetation in protecting and improving chemical water quality in streams. Journal of the American Water Resources Association 46:261-277. (i)

Dudley-Williams, D., and N.E. Williams. 1993. The upstream/downstream movement paradox of lotic invertebrates: quantitative evidence from a Welsh mountain stream. Freshwater Biology 30:199-218. (i)

Edmonds, R.L., T.B. Thomas, and R.D. Blew. 1995. Biogeochemistry of an old-growth forested watershed, Olympic National Park, Washington. Water Resources Bulletin 31:409-419. (i)

FISRWG (Federal Interagency Stream Restoration Working Group). 1998. Stream corridor restoration: principles, processes, and practices. NEH-653. Natural Resources Conservation Service, Washington, D.C. (viii)

FEMAT (Forest Ecosystem Management Assessment Team). 1993. Forest ecosystem management: an ecological, economic and social assessment. U.S. Department of Agriculture and U.S. Department of the Interior, Portland, Oregon. (viii)

Fernald, A.G., D.H. Landers, and P.J. Wigington. 2006. Water quality changes in hyporheic flow paths between a large gravel bed river and off-channel alcoves in Oregon, USA. River Research and Applications 22:1111-24. (i)

Filoso, S., and M.A. Palmer. 2011. Assessing stream restoration effectiveness at reducing nitrogen export to downstream waters. Ecological Applications 21:1989–2006. (i)

Gellis, A.C., and G.B. Noe. 2013. Sediment source analysis in Linganore Creek watershed, Maryland, USA, using the sediment fingerprinting approach: 2008 to 2010. Journal of Soils and Sediments 13:1735–1753. (i)

Gende, S.M., R.T. Edwards, M.F. Willson, and M.S. Wipfli. 2002. Pacific salmon in aquatic and terrestrial ecosystems. BioScience 52:917-28. (i)

Giardina, C., S. Huffman, D. Binkley, and B. Caldwell. 1995. Alders increase phosphorus supply in a Douglas-fir plantation. Canadian Journal of Forest Research 25:1652-1657. (i)

Giesler, R., T. Andersson, L. Lövgren, and P. Persson. 2005. Phosphate sorption in aluminum- and iron-rich humus soils. Soil Science Society of America 69:77–86. (i)

Greathouse, E.A., J.E. Compton, and J. Van Sickle. 2014. Linking landscape characteristics and high stream nitrogen in the Oregon Coast Range: Red Alder complicates use of nutrient criteria. Journal of the American Water Resources Association 50:1383-1400. (i)

Gresh, T., J. Lichatowich, and P. Schoonmaker. 2000. An estimation of historic and current levels of salmon production in the Northeast Pacific Ecosystem: evidence of a nutrient deficit in the freshwater systems of the Pacific Northwest. Fisheries 25:15-21. (i)

Groffman, P.M., N.J. Boulware, W.C. Zipperer, R.V. Pouyat, L.E. Band, and M.F. Colosimo. 2002. Soil nitrogen cycling processes in urban riparian zones. Environmental Science & Technology 36:4547-4552. (i)

Groffman, P.M., D.J. Bain, L.E. Band, K.T. Belt, G.S. Brush, J.M. Grove, R.V. Pouyat, I.C. Yesilonis, and W.C. Zipperer. 2003. Down by the riverside: urban riparian ecology. Frontiers in Ecology and the Environment 1:315–321. (i)

Groffman, P.M., A.M. Dorsey, and P.M. Mayer. 2005. Nitrogen processing within geomorphic features in urban streams. Journal of North American Benthological Society 24:613-625. (i)

Harmon, M.E., J.F. Franklin, F.J. Swanson, P. Sollins, S.V. Gregory, J.D. Lattin, N.H. Anderson, S.P. Cline, N.G. Aumen, J.R. Sedell, G.W. Lienkaemper, K. Cromack, Jr., and K.W. Cummins, 1986. Ecology of coarse woody debris in temperate ecosystems. Advances in Ecological Research 15:133-302. (i)

Hart, S.K., D.E. Hibbs and S.S. Perakis. 2013. Riparian litter inputs to streams in the central Oregon Coast Range. Freshwater Science 32:343-358. (i)

Hedin, L.O., J.C. von Fischer, N.E. Ostrom, B.P. Kennedy, M.G. Brownand, and G.P. Robertson. 1998. Thermodynamic constraints on nitrogen transformations and other biogeochemical processes at soil-stream interfaces. Ecology 79:684-703. (i)

Hefting, M., J.C. Clement, D. Dowrick, A.C. Cosandey, S. Bernal, C. Cimpian, A. Tatur, T. P. Burt, and G. Pinay. 2004. Water table elevation controls on soil nitrogen cycling in riparian wetlands along a European climatic gradient. Biogeochemistry 67:113-134. (i)

Helfield J.M., and R. Naiman. 2001. Effects of salmon-derived nitrogen on riparian forest growth and implications for stream productivity. Ecology 82:2403-2409. (i)

Hershey, A.E., J. Pastor, B.J. Peterson, and G.W. Kling. 1993. Stable isotopes resolve the drift paradox for Baetis mayflies in an arctic river. Ecology 74:2315-2325. (i)

Hinkle, S.R., J.H. Duff, F.J. Triska, A. Laenen, E.B. Gates, K.E. Bencala, D.A. Wentz, and S.R. Silva. 2001. Linking hyporheic flow and nitrogen cycling near the Willamette River–a large river in Oregon, USA. Journal of Hydrology 244:157-80. (i)

Hinkle, S.R. 2009. Tritium/helium-3 apparent ages of shallow ground water, Portland basin, Oregon, 1997–98: Scientific Investigations Report 2009-5057. U.S. Geological Survey, Reston, Virginia. (viii)

Hoffmann, C.C., C. Kjaergaard, J. Uusi-Kämppä, H.C. Bruun, and B. Kronvang. 2009. Phosphorus retention in riparian buffers: review of their efficiency. Journal of Environmental Quality 38:1942–1955. (i)

Ice, G., and D. Binkley. 2003. Forest streamwater concentrations of nitrogen and phosphorus: comparison with EPA's proposed water quality criteria. Journal of Forestry 101:21–28. (i)

Inglett K.S., P.W. Inglett, K.R. Reddy, and T.Z. Osborne. 2012. Temperature sensitivity of greenhouse gas production in wetland soils of different vegetation. Biogeochemistry 108:77-90. (i)

Jacoby J.M., and J. Kann. 2007. The occurrence and response to toxic cyanobacteria in the Pacific Northwest, North America. Lake Reservoir Management 23:123–143. (i)

Johnson, D.W., and D.W. Cole. 1980. Anion mobility in soils: relevance to nutrient transport from forest ecosystems. Environment International 3:79-90. (i)

Jordan, S.J., J. Stoffer, and J.A. Nestlerode. 2011. Wetlands as sinks for reactive nitrogen at continental and global scales: a meta-analysis. Ecosystems 14:144-155. (i)

Kaushal, S.S., M. Pace, P. Groffman, L. Band, K. Belt, P. Mayer, and C. Welty. 2010. Land use and climate variability amplify contaminant pulses. EOS Transactions of the American Geophysical Union 91:221-222. (i)

Kaushal, S.S., and W.M. Lewis Jr. 2005. Fate and transport of dissolved organic nitrogen in minimally disturbed streams of Colorado, USA. Biogeochemistry 74:303–321. (i)

Kaushal, S.S., P.M. Mayer, P.G. Vidon, R.M. Smith, M.J. Pennino, S. Duan, T.A. Newcomer, C. Welty, and K. Belt. 2014. Land use and climate variability amplify carbon, nutrient, and contaminant pulses: a review with management implications. Journal of the American Water Resources Association 50:585-614. (i)

Lazar, J.G., A.J. Gold, K. Addy, P.M. Mayer, K.J. Forshay, and P.M. Groffman. 2014. Instream large wood: denitrification hotspots with low N_2O production. Journal of the American Water Resources Association 50:615-625.

Martin, C.W., and R.D. Harr. 1989. Logging of mature Douglas-fir in western Oregon has little effect on nutrient output budgets. Canadian Journal of Forest Research 19:35-43. (i)

Masese, F.O., K.G. Abrantes, G.M. Gettel, S. Bouillon, K. Irvine, and M.E. McClain. 2015. Are large herbivores vectors of terrestrial subsidies for riverine food webs? Ecosystems 18:686-706. (i)

Mayer, P.M., A.H. Todd, J.A. Okay, and K.A. Dwire. 2010a. Introduction to the featured collection on riparian ecosystems and buffers. Journal of the American Water Resources Association 46:207-210. (i)

Mayer, P.M., P.M. Groffman, E. Striz, and S.S. Kaushal. 2010b. Nitrogen dynamics at the groundwater-surface water interface of a degraded urban stream. Journal of Environmental Quality 39:810–823. (i)

Mayer, P.M., K.A. Dwire, J.A. Okay, and P. Vidon. 2014. Introduction to the featured collection on riparian ecosystems. Journal of the American Water Resources Association 50:529-532. (i)

Mayer, P.M., S.K. Reynolds, M.D. McMutchen, and T.J. Canfield. 2007. Meta-analysis of nitrogen removal in riparian buffers. Journal of Environmental Quality 36:1172-1180. (i)

McClain, M.E., R.E. Bilby, and F.J. Triska. 1998. Biogeochemistry of N, P, and S in Northwest rivers: natural distributions and responses to disturbance. Pages 347-372 *in* R.J Naiman and R.E. Bilby, editors. River ecology and management: lessons from the Pacific Coastal Ecoregion. Springer-Verlag, New York. (i)

McClain, M.E., E.W. Boyer, C.L. Dent, S.E. Gergel, N.B. Grimm, P.M. Groffman, S.C. Hart, J.W. Harvey, C.A. Johnston, E. Mayorga, W.H. McDowel,l and G. Pinay. 2003. Biogeochemical hot spots and hot moments at the interface of terrestrial and aquatic ecosystems. Ecosystems 6:301–312. (i)

McDowell, W.H., and G.E. Likens. 1988. Origin, composition, and flux of dissolved organic carbon in the Hubbard Brook Valley. Ecological Monographs 58:177-195. (i)

Menberg, K., P. Blum, B.L. Kurylyk, and P. Bayer. 2014. Observed groundwater temperature response to recent climate change. Hydrology and Earth System Sciences 18:4453–4466. (i)

Merritts, D., R. Walter, M. Rahnis, J. Hartranft, S. Cox, A. Gellis, N. Potter, W. Hilgartner, M. Langland, L. Manion, C. Lippincott, S. Siddiqui, Z. Rehman, C. Scheid, L. Kratz, A. Shilling, M. Jenschke, K. Datin, E. Cranmer, A. Reed, D. Matuszewski, M. Voli, E. Ohlson, A. Neugebauer, A. Ahamed, C. Neal, A. Winter, and S. Becker S. 2011. Anthropocene streams and base-level controls from historic dams in the unglaciated mid-Atlantic region, USA. Philosophical Transactions of the Royal Society A 369:976–1009. (i)

Moore, R.D., and S.M. Wondzell. 2005. Physical hydrology and the effects of forest harvesting in the Pacific Northwest: a review. Journal of the American Water Resources Association 41:763-784. (i)

Moyle, P., A. Engilis, M. Escobar, C.M. Mosser, D. Purkey, L.C., and M.L. Truan. 2009. Progress report: innovative management options to prevent loss of ecosystem services provided by Chinook Salmon in California: overcoming the effects of climate change. US EPA NCER program. Available: http://cfpub.epa.gov/ncer_abstracts/index.cfm/fuseaction/display.abstractDetail/abstract/9070/-report/2009. (January 2019). (viii).

Mulholland, P.J., E.R. Marzolf, S.P. Hendricks, R.V. Wilkerson, and A.K. Baybayan. 1995. Longitudinal patterns of nutrient cycling and periphyton characteristics in streams: a test of upstream-downstream linkage. Journal of North American Benthological Society 14:357-370. (i)

Mulholland, P.J., A.M. Helton, G.C. Poole, R.O. Hall Jr., S.K. Hamilton, B.J. Peterson, J.L. Tank, L.R. Ashkenas, L.W. Cooper, C.N. Dahm, W.K. Dodds, S.E.G. Findlay, S.V. Gregory, N.B. Grimm, S.L. Johnson, W.H. McDowell, J.L. Meyer, H.M. Valett, J.R. Webster, C.P. Arango, J.J. Beaulieu, M.J. Bernot, A.J. Burgin, C.L. Crenshaw, L.T. Johnson, B.R. Niederlehner, J.M. O'Brien, J.D. Potter, R.W. Sheibley, D.J. Sobota, and S.M. Thomas. 2008. Stream denitrification across biomes and its response to anthropogenic nitrate loading. Nature 452:202-206. (i)

Murphy, M.L. 1998. Primary productivity. Pages 144-168 *in* R.J. Naiman and R.E. Bilby, editors. River ecology and management: lessons from the Pacific Coastal Ecoregion. Springer-Verlag, New York (i)

Naiman, R.J., J.S. Bechtold, T.J. Beechie, J.J. Latterell, and R. Van Pelt. 2010. A process-based view of floodplain forest patterns in coastal river valleys of the Pacific Northwest. Ecosystems 13:1-31. (i)

Naiman, R.J., and K.H. Rogers. 1997. Large animals and system level characteristics in river corridors. BioScience 47:521–9. (i)

Naiman, R.J., C.A. Johnston, and J.C. Kelley. 1988. Alteration of North American streams by Beaver. BioScience 38:753-762. (i)

Naiman, R.J., G. Pinay, C.A. Johnson, and J. Pastor. 1994. Beaver-induced influences on the long-term biogeochemical characteristics of boreal forest drainage networks. Ecology 75:905-921. (i)

Naiman, R.J., R.E. Bilby, D.E. Schindler, and J.M. Helfield. 2002. Pacific salmon, nutrients, and the dynamics of freshwater and riparian ecosystems. Ecosystems 5:399-417. (i)

Newbold, J.D., R.V. O'Neill, J.W. Elwood, and W. Van Winkle. 1982. Nutrient spiralling in streams: implications for nutrient limitation and invertebrate activity. The American Naturalist 120:628-652. (i)

Newcomer, T.A., S.S. Kaushal, P.M. Mayer, A.R. Shields, E.A. Canuel, P.M. Groffman, and A.J. Gold. 2012. Influence of natural and novel organic carbon sources on denitrification in forested, degraded-urban, and restored streams. Ecological Monographs 82:449–466. (i)

Perakis, S.S., D.A. Maguire, T.D. Bullen, K. Cromack, R.H. Waring, and J.R. Boyle. 2006. Coupled nitrogen and calcium cycles in forests of the Oregon Coast Range. Ecosystems 9:63-74. (i)

Peterson, B.J., W.M. Wollheim, P.J. Mulholland, J.R. Webster, J.L. Meyer, J.L. Tank, E. Marti, W.B. Bowden, H.M. Valett, A.E. Hershey, W.H. McDowell, W.K. Dodds, S.K. Hamilton, S. Gregory, and D.D. Morrall. 2001. Control of nitrogen export from watersheds by headwater streams. Science 292:86-90. (i)

Peterson, C.E., and J.W. Hazard. 1990. Regional variation in growth response of coastal Douglas-fir to nitrogen fertilizer in the Pacific Northwest. Forest Science 36:625–640. (i)

Phelps, J.D. 2011. The geomorphic legacy of splash dams in the southern Oregon Coast Range. Master's thesis. University of Oregon. Eugene. (i)

Pingram M.A., K.J. Collier, D.P. Hamilton, B.O. David, and B.J. Hicks. 2012. Carbon sources supporting large river food webs: a review of ecological theories and evidence from stable isotopes. Freshwater Reviews 5:85–103. (i)

Pollock, M.M., T.J. Beechie, and C.E. Jordan. 2007. Geomorphic changes upstream of Beaver dams in Bridge Creek, an incised stream channel in the interior Columbia River basin, eastern Oregon. Earth Surface Processes and Landforms 32:1174-1185. (i)

Reddy K.R., O.A. Diaz, L.J. Scinto, and M. Agami. 1995. Phosphorus dynamics in selected wetlands and streams of the Lake Okeechobee basin. Ecological Engineering 5:183–207. (i)

Richardson, C.J., and P.E. Marshall. 1986. Processes controlling movement, storage and export of phosphorus in a fen peatland. Ecological Monographs 56:279–302. (i)

Richardson, J.S., and R.J. Danehy. 2007. A synthesis of the ecology of headwater streams and their riparian zones in temperate forests. Forest Science 53:131-147. (i)

Royer, T.V., and M.B. David. 2005. Export of dissolved organic carbon from agricultural streams in Illinois, USA. Aquatic Sciences 67:465–471. (i)

Sabater, S., H. Guasch, A. Roman, and I. Munoz. 2002. The effect of biological factors on the efficiency of river biofilms in improving water quality. Hydrobiologia 469:149-156. (i)

Sabater S., S.V. Gregory, and J.R. Sedell. 1998. Community dynamics and metabolism of benthic algae colonizing wood and rock substrata in forest stream. Journal of Phycology 34:561-567. (i)

Schechter, S.P., T.J. Canfield, and P.M. Mayer. 2013. A meta-analysis of phosphorus attenuation in best management practices (BMP) and low impact development (LID) practices in urban and agricultural areas. EPA 600/R-13/208. National Risk Management Research Laboratory, Ada, Oklahoma. (viii)

Scrivener, J.C. 1975. Water, water chemistry, and hydrochemical balance of dissolved ions in Carnation Creek watershed, Vancouver Island, July 1971 - May 1974. Technical Report 564. Canadian Fisheries and Marine Service, Vancouver, British Columbia. (viii)

Sedell, J.R., and K.J. Luchessa. 1981. Using the historical record as an aid to salmonid enhancement. Pages 210-223 *in* N.B. Armantrout, editor. Acquisition and utilization of aquatic habitat inventory information. Western Division, American Fisheries Society, Portland, Oregon. (viii)

Shen, J., L. Yuan, J. Zhang, H. Li, Z. Bai, X. Chen, W. Zhang, and F. Zhang. 2011. Phosphorus dynamics: from soil to plant. Plant Physiology 156:997-1005. (i)

Silvester, W.B. 1989. Molybdenum limitation of asymbiotic nitrogen fixation in forests of Pacific Northwest America. Soil Biology and Biochemistry 21:283-289. (i)

Sobczak, W.V., S.E.G. Findlay, and S. Dye. 2003. Relationships between DOC bioavailability and nitrate removal in an upland stream: an experimental approach. Biogeochemistry 62:309–327. (i)

Sobota, D.J., S. Johnson, S.V. Gregory, and L.R. Ashkenas, LR. 2012. A stable isotope tracer study of the influences of adjacent land use and riparian condition on fates of nitrate in streams. Ecosystems 15:1-17. (i)

Sollins, P., C.C. Grier, F.M. McCorison, K. Cromack Jr., R. Fogel, and R.L. Fredriksen. 1980. The internal element cycles of an old-growth Douglas-fir ecosystem in western Oregon. Ecological Monographs 50:261-285. (i)

Stanley, E.H., S.M. Powers, N.R. Lottig, I. Buffam, and J.T. Crawford. 2012. Contemporary changes in dissolved organic carbon (DOC) in human-dominated rivers: is there a role for DOC management? Freshwater Biology 57:26-42. (i)

Stonestrom, D.A., and J. Constantz. 2003. Heat as a tool for studying the movement of groundwater near streams. Circular 1260. U.S. Geological Survey, Denver, Colorado. (viii)

Striz, E.A., and P.M. Mayer. 2008. Assessment of near-stream groundwater-surface water interaction (GSI) of a degraded stream before restoration. EPA/600/R-07/058, National Risk Management Research Laboratory, Ada, Oklahoma. (viii)

Swain, N.R., and J.D. Reynolds. 2015. Effects of salmon-derived nutrients and habitat characteristics on population densities of stream-resident sculpins. PLOS ONE 10(6): e0116090. (i)

Sweeney, B.W., and J.D. Newbold. 2014. Streamside forest buffer width needed to protect stream water quality, habitat, and organisms: a literature review. Journal of the American Water Resources Association 50:560-584. (i)

Sweeney, B.W., T.L. Bott, J.K. Jackson, L.A. Kaplan, J.D. Newbold, L.J. Standley, W.C. Hession, and R.J. Horwitz. 2004. Riparian deforestation, stream narrowing, and loss of stream ecosystem services. Proceedings of the National Academy of Sciences 101:14132-14137. (i)

Tague, C., and G.E. Grant. 2004. A geological framework for interpreting the low-flow regimes of Cascade streams, Willamette River Basin, Oregon. Water Resources Research 40:W04303. (i)

Tarrant, R.F., L.A. Issac, and R.F. Chandler. 1951. Observations on litter fall and foliage nutrient content of some Pacific Northwest tree species. Journal of Forestry 49:914-915. (i)

Triska, F.J., J.R. Sedell, K. Cromack Jr., S.V. Gregory, and F.M. McCorison. 1984. Nitrogen budget for a small coniferous forest stream. Ecological Monographs 54:119-40. (i)

USEPA ATTAINS database. Available: http://www2.epa.gov/nutrient-policy-data/waters-assessed-impaired-due-nutrient-related-causes. (June 2015). (vi)

Vaccaro, J.J. 2011. River-aquifer exchanges in the Yakima River basin, Washington: U.S. Geological Survey Scientific Investigations Report 2011-5026. U.S. Geological Survey, Reston, Virginia. (viii)

Vannote, R.L., G.W. Minshall, K.W. Cummins, J.R. Sedell, and C.E. Cushing. 1980. The river continuum concept. Canadian Journal of Fish and Aquatic Science 37:130-137. (i)

Vidon, P., C. Allan, D. Burns, T.P. Duval, N. Gurwick, S. Inamdar, R. Lowrance, J. Okay, D. Scott, and S. Sebestyen. 2010. Hot spots and hot moments in riparian zones: potential for improved water quality. Journal of the American Water Resources Association 46:278-298. (i)

Vidon, P., P.A. Jacinthe, X. Liu, K. Fisher, and M. Baker. 2014. Hydrobiogeochemical controls on riparian nutrient and greenhouse gas dynamics: 10 Years post-restoration. Journal of the American Water Resources Association 50:639-652. (i)

Von Schiller, D., V. Acuña, D. Graeber, E. Martí, M. Ribot, S. Sabater, X. Timoner, and K. Tockner. 2011. Contraction, fragmentation and expansion dynamics determine nutrient availability in a Mediterranean forest stream. Aquatic Sciences 73:485-497. (i)

Wallace, J.B., S.L. Eggert, J.L. Meyer, and J.R. Webster. 1997. Multiple trophic levels of a forest stream linked to terrestrial litter inputs. Science 277:102-104. (i)

Walter, R.C., and D.J. Merritts. 2008. Natural streams and the legacy of water-powered mills. Science 319:299–304. (i)

Weitzman, J.N., K.J. Forshay, J.P. Kaye, P.M. Mayer, J. Koval, and R.C. Walter. 2014. Potential nitrogen and carbon processing in a landscape rich in mill-dam legacy sediments. Biogeochemistry 120:337-357. (i)

Welch, E.B., J.M. Jacoby and C.W. May. 1998. Stream quality. Pages 69-94 *in* R.J. Naiman, and R.E. Bilby, editors. River ecology and management: lessons from the Pacific Coastal Ecoregion. Springer-Verlag, New York. (i)

Wigington, P.J. Jr., T.J. Moser, and D.R. Lindeman. 2005. Stream network expansion: a riparian water quality factor. Hydrological Processes 19:1715–1721. (i)

Wigington, P.J., M.R. Church, T.C. Strickland, K.N. Eshleman, and J. Van Sickle. 1998. Autumn chemistry of Oregon Coast Range streams. Journal of the American Water Resources Association 34:1035-49. (i)

Willson, M.F., and K.C. Halupka. 1995. Anadromous fish as keystone species in vertebrate communities. Conservation Biology 9:489–97. (i)

Wilzbach, M.A., B.C. Harvey, J.L. White, and R.J. Nakamoto. 2005. Effects of riparian canopy opening and salmon carcass addition on the abundance and growth of resident salmonids. Canadian Journal of Fisheries and Aquatic Sciences 62:58–67. (i)

Wipfli, M.S. 2005. Trophic linkages between headwater forests and downstream fish habitats: implications for forest and fish management. Landscape and Urban Planning 72:205-213. (i)

Wipfli, M.S., and C.V. Baxter. 2010. Linking ecosystems, food webs, and fish production: subsidies in salmonid watersheds. Fisheries 35:373-387. (i)

Wipfli, M.S., and J. Musslewhite. 2004. Density of Red Alder (*Alnus rubra*) in headwaters influences invertebrate and detritus subsidies to downstream fish habitats in Alaska. Hydrobiologia 520:153-163.

Wise, D.R., and H.M. Johnson. 2013. Application of the SPARROW model to assess surface-water nutrient conditions and sources in the United States Pacific Northwest. Scientific Investigations Report 2013–5103. U.S. Geological Survey, Reston, Virginia. Available: **http://pubs.usgs.gov/sir/2013/5103/.** (Januray 2019) (viii)

Wise, D.R., and H.M. Johnson. 2011. Surface-water nutrient conditions and sources in the United States Pacific Northwest. Journal of the American Water Resources Association 47:1110-1135. (i)

Wohl, E.E. 2000. Mountain Rivers. The American Geophysical Union, Washington, D.C. (viii)

Wondzell, S.M. 2011. The role of the hyporheic zone across stream networks. Hydrological Processes 25:3525-3532. (i)

Xiong, S., and C. Nilsson. 1997. Dynamics of leaf litter accumulation and its effects on riparian vegetation: a review. Botanical Review 63:240–264. (i)

Yanai, R.D. 1992. Phosphorus budget of a 70-yr-old northern hardwood forest. Biogeochemistry 17:1-22. (i)

Zarnetske, J.P., R. Haggerty, S.M. Wondzell, V.A. Bokil, and R. González-Pinzón. 2012. Coupled transport and reaction kinetics control the nitrate source-sink function of hyporheic zones. Water Resources Research 48: W11508. (i)

Zarnetske, J.P., R. Haggerty, S.M. Wondzell, and M.A. Baker. 2011. Dynamics of nitrate production and removal as a function of residence time in the hyporheic zone. Journal of Geophysical Research 116:G01025. (i)

Zhang, X., X. Liu, M. Zhang, R.A. Dahlgren, and M. Eitzel. 2010. A review of vegetated buffers and a meta-analysis of their mitigation efficacy in reducing nonpoint source pollution. Journal of Environmental Quality 39:76-84. (i)

Zou, X., D. Binkley, and B.A. Caldwell. 1995. Effects of dinitrogen-fixing trees on phosphorus biogeochemical cycling in contrasting forests. Soil Science Society of America Journal 59:1452-1458. (i)



Big Creek Trail/Rachel Blomker, WDFW



Chapter 7. Riparian Areas of the Columbia Plateau

By: George F. Wilhere

This chapter is dedicated Karin Divens who passed away unexpectedly on 12 October 2017. Karin made a significant contribution to this chapter by organizing a two-day, multi-disciplinary workshop that advanced our scientific understanding of riparian areas in the Columbia Plateau Ecoregion. Karin was an effective and well-respected habitat biologist at WDFW, who brought not only science to her work but a full heart.

7.1. Introduction

The Columbia Plateau Ecoregion (sensu Omernick 1987),[1] is classified as a cold desert (Sleeter 2012), and covers about one-third of Washington State (Figure 7.1). In the driest parts of the ecoregion, a rain shadow cast by the Cascades Mountains limits precipitation to 6 to 9 in (15 to 23 cm) per year, and even wettest parts of the ecoregion, the Palouse Hills Subregion, receive only 18 to 23 in (46 to 58 cm) per year (Bryce and Omernik 1997). Uplands of the Columbia Plateau are covered by either shrub-steppe or steppe[2] vegetation (i.e., sagebrush and bunchgrass communities, respectively), and, most notably, lack trees (Franklin and Dyrness 1988). The ecoregion's desert climate confines nearly all trees to riparian areas.[3]

Seventy-five years ago Daubenmire (1942) wrote, "The vegetation of the unforested regions in the Pacific Northwest has been less thoroughly studied and is consequently less perfectly understood than is that of the forested areas." The situation has not changed. Most of what is known about riparian areas in the Pacific Northwest is based on research conducted in forested ecoregions. During my review of the scientific literature, I found far less information about the composition, structure, and functions of riparian ecosystems in unforested ecoregions, such as the Columbia Plateau, than I found for forested ecoregions. However, many of the basic principles and qualitative relationships that have emerged from research in forested ecoregions are also valid in unforested ecoregions. For instance, while there are significant quantitative differences among ecoregions in the amount of wood or shade provided by riparian areas, the physical processes of large wood recruitment and stream shading should be very nearly the same. On the other hand, processes that are strongly affected by groundwater, such as nutrient dynamics and pollutant removal, should be different. To clarify current

[1] There are several different delineations of ecoregions (e.g., USFWS 1994; Bailey 1995; Olson et al. 2001). For this report WDFW used the ecoregions of Omernick (1987). The only non-forested ecoregion in Washington is the Columbia Plateau. Forested ecoregions surrounding the Columbia Plateau in Washington are the Eastern Cascades, North Cascades, Okanogan, Northern Rockies, and Blue Mountains.

[2] Steppe is also referred to as grassland or prairie. The steppe region of southeastern Washington is called the Palouse.

[3] A notable exception is the Juniper Dunes Wilderness Area, which preserves the northernmost Western Juniper Trees *Juniperus occidentalis* in North America. This 7100-acre area contains no surface water.



The amount of rain received by the Columbia Plateau Ecoregion each year is insufficient to support trees in the uplands/Justin Haug, WDFW

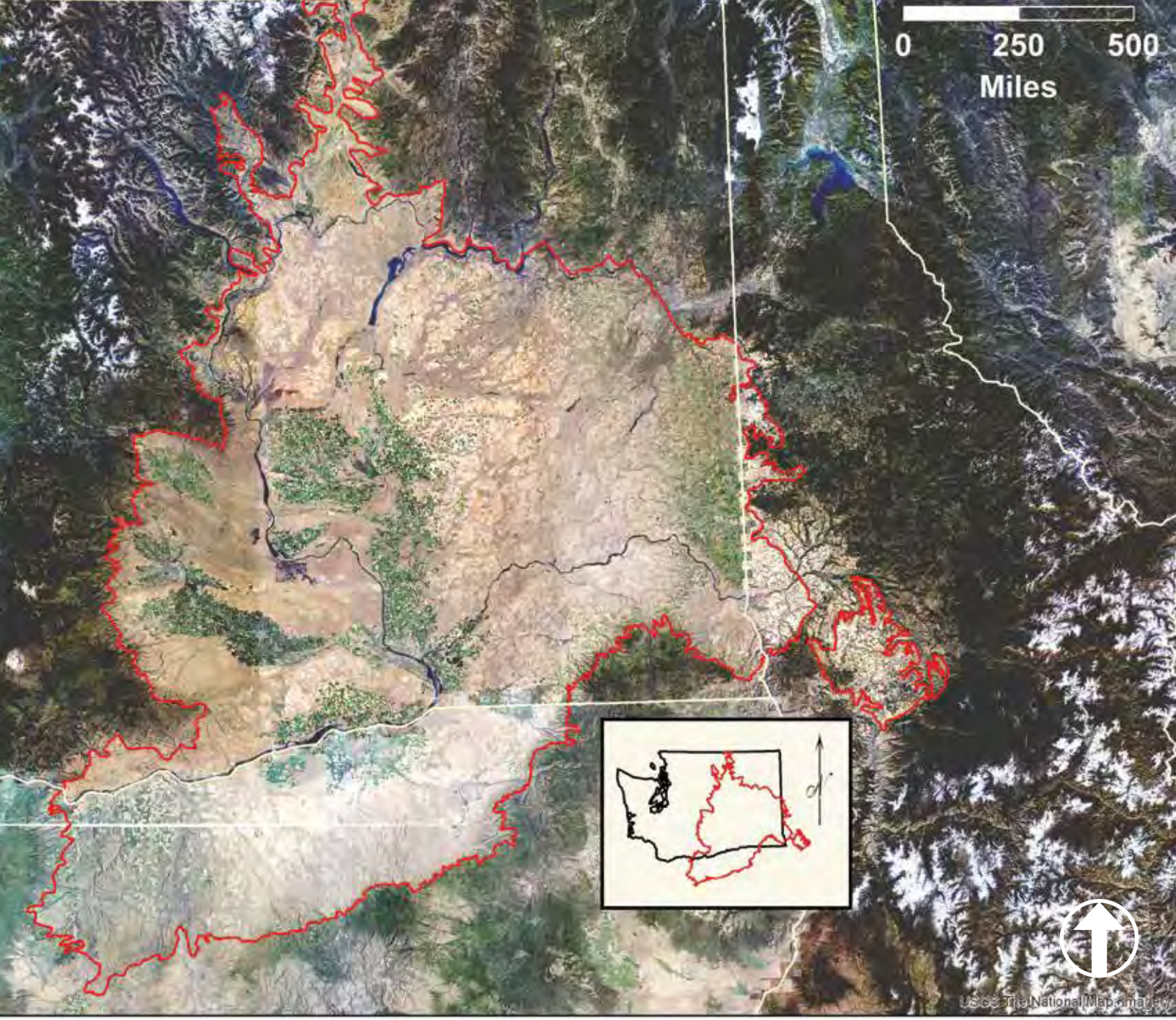


Figure 7.1. Boundary (in red) of the Columbia Plateau Ecoregion. State boundaries are white. Aerial photography for Washington State done in 2015 by the National Agriculture Imagery Program.

scientific understanding, throughout this chapter I point out differences between riparian areas in forested and unforested ecoregions.

The Columbia Plateau Ecoregion is comprised of both arid and semi-arid subregions (hereafter collectively known as drylands). Due to lack of information, I make few subregional distinctions regarding riparian areas. Most of what is known about the ecology of dryland riparian areas is based on research conducted in desert ecoregions of the southwestern United States (Patten 1998). Although these ecoregions have climate, hydrology, soils, and vegetation different from the Columbia Plateau, many of the basic principles and qualitative relationships that have emerged from research in other desert ecoregions should be valid for the Columbia Plateau.

7.1.1. Dryland Riparian Areas

Decades ago, the term "riparian" referred exclusively to areas adjacent to surface waters with moist soils that support distinctive vegetation (e.g., Thomas et al. 1979, Anderson 1987). Later definitions expanded the meaning of riparian. Sedell et al. (1989) and Naiman et al. (1992), for example, divided the "riparian ecosystem" or "riparian area" into two zones: a "riparian zone" with moist soils supporting wetland and riparian-dependent vegetation, and an upland "zone of influence" that significantly influences the exchanges of energy and matter between terrestrial and aquatic ecosystems (Figure 7.2). In forested ecoregions, the potential vegetation of both zones is commonly forest, and the ecological functions of the zones are similar. In the Columbia Plateau, vegetation within riparian ecosystems often exhibits an abrupt demarcation between the two zones. Phreatophytic[4] trees and shrubs and hydrophytic[5] herbaceous plants are confined to moist streamside areas, but the upland zone of influence may consist of sagebrush or bunchgrass communities. Consequently, the functions of the two zones may be quite different. Along some reaches, the riparian zone and zone of influence may both reside within a floodplain and exhibit similar composition and structure. For our purposes, the phrases riparian ecosystem and riparian area are synonymous.

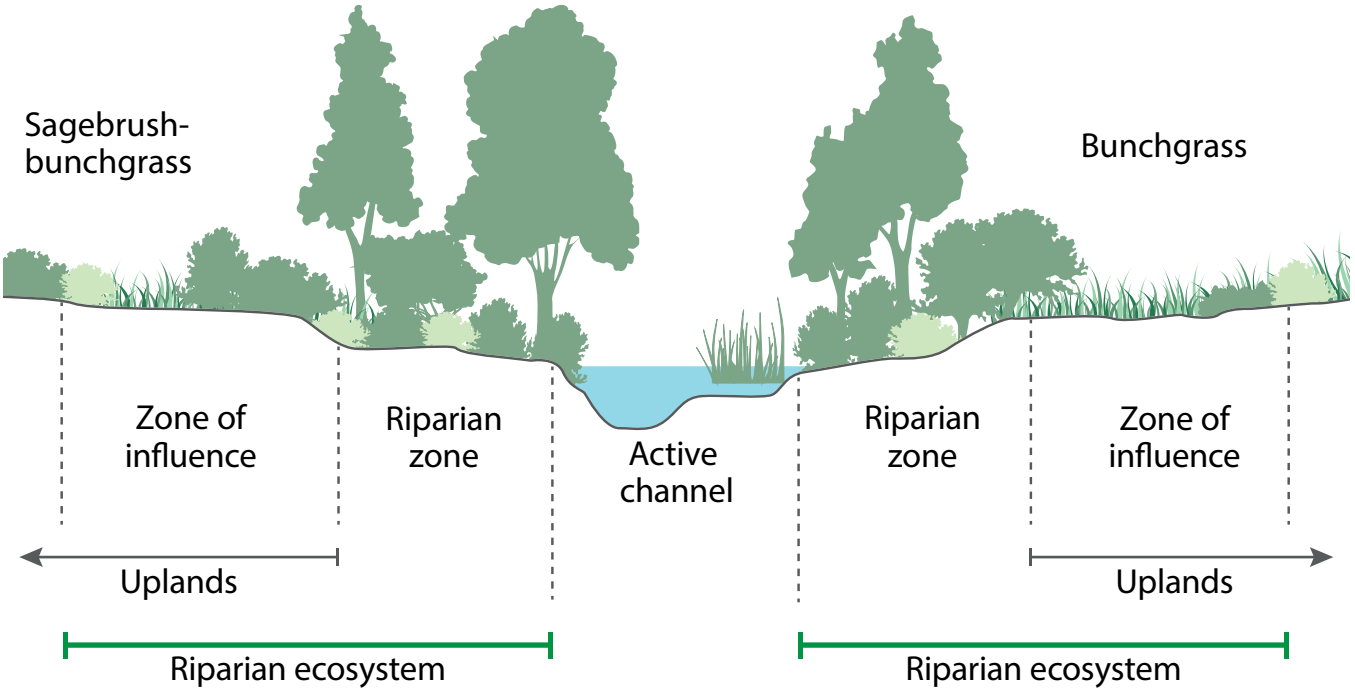


Figure 7.2. Dryland Riparian Ecosystem. The riparian ecosystem consists of two zones: riparian and zone of influence. The riparian zone extends from the edge of the active channel towards the uplands. This zone includes areas where terrestrial biota are influenced, at least periodically, by surface or subsurface waters. Beyond this is the riparian "zone of influence." This includes areas where ecological functions significantly influence the stream (diagram modified from USFS 2004).

[4] A phreatopyhtic plant is a species that obtains water from the subsurface zone of saturation either directly or through the capillary fringe (Thomas 2014).
[5] Hydrophytic plants are those that are adapted to growing conditions associated with periodically saturated soils. They include obligate wetland plants that almost always occur in wetlands under natural conditions, facultative wetland plants that usually occur in wetlands but are occasionally found in non-wetlands, and facultative plants that equally likely to occur in wetlands or non-wetlands (Lichvar et al. 2012).



In the semi-arid Columbia Plateau Ecoregion, trees are generally confined to riparian areas/Scott Fitkin, WDFW

In dryland ecoregions, riparian ecosystems are the ultimate expression of groundwater and surface-water interactions (Webb and Leake 2006). Soil moisture and water table elevation are key variables in the survival of riparian-dependent plants. Stream discharge affects soil moisture by saturating soils and recharging the alluvial aquifer during overbank flooding, and stream stage (i.e., surface elevation) directly affects water table elevation.

In dryland ecoregions, trees and dense shrubs exist only near surface water, such as a river, stream, or lake. In the Columbia Plateau, surface streamflow is highly dependent on its source. Rivers and perennial[6] streams generally originate in the adjacent mountainous ecoregions (Omernik and Gallen 1986), and their peak flows, if unaffected by dams, generally occur during fall or winter storms and/or during spring snowmelt (Reidy Liermann et al. 2012). Within the Columbia Basin, the flow source of most streams is groundwater (Reidy Liermann et al. 2012), and consequently, during the hot, dry summer, many streams originating within the ecoregion are intermittent (Daubenmire 1942; Bryce and Omernik 1997). This spatial and temporal variability in local hydrology affects the distribution, abundance, and species of plants in dryland riparian areas.

[6] A perennial stream is one which flows continuously. An ephemeral stream, or section of stream, is one that flows only in direct response to precipitation. It receives no water from springs and no long-continued supply from melting snow or other surface source. An intermittent stream is one that flows during protracted periods when it receives water from some surface or subsurface source, such as melting snow or a spring (Meinzer 1923).

The diversity[7] of riparian climax plant communities in the Columbia Plateau Ecoregion is greater than the diversity in surrounding forested ecoregions. In forested ecoregions, the potential natural vegetation of nearly all riparian areas along rivers and streams is forest. The species composition may vary, but the climax community's structure ultimately attains a closed-canopy of trees, with the upland zone of influence most often dominated by conifer species. In the Columbia Plateau, differences in hydrology and geomorphology manifest substantial site-level differences in composition and structure of riparian vegetation (Hough-Snee et al. 2015). A rudimentary classification system based on overstory conveys obvious differences in vertical structure: tall tree, short tree, tall shrub, shrub, grass-like, grass, and forb (Figure 7.3; Crawford 2003). The main tall tree types have an overstory consisting of Black Cottonwood *Populus trichocarpa*, White Alder *Alnus rhombifolia*, or Quaking Aspen *Populus tremuloides*. Short tree types have an overstory of Thinleaf Alder *Alnus incana*, Water Birch *Betula occidentalis*, or Black Hawthorn *Crataegus douglasii*.[8] Tree vegetation types are usually multi-layered with shrub and herbaceous layers under the tree canopy. Common shrubs are Redosier Dogwood *Cornus sericea*, Common Snowberry *Symphoicarpos albus*, Lewis' Mockorange *Philadelphus lewisii*, and Woods' Rose *Rosa woodsii*. Tall shrub vegetation types include those dominated by willow species (e.g., Yellow *Salix lutea*, Sandbar *S. exigua*) which can be up to 20 ft (6 m) tall.

The structural diversity of riparian vegetation in the Columbia Plateau causes differences in site-level functions. Large wood recruitment, for instance, cannot occur in all riparian areas, and the amount of stream shading will vary considerably due to site-to-site variation in vertical structure.



The most diverse and productive biological communities of the Columbia Plateau are riparian areas/Rex Crawford, WNHP



Nearly all woody vegetation in riparian areas of the Columbia Plateau consists of deciduous shrubs and trees/Scott Fitkin, WDFW

[7] Measures of biological diversity take into account two factors: species richness (i.e., the number of different types) and evenness (i.e., the relative abundance of different types). While the richness of riparian climax plant communities in forested ecoregions may be comparable to that of dryland ecoregions, the relative abundance of different riparian climax plant communities is more even in dryland ecoregions. This results in a greater diversity of types.

[8] Black Hawthorn might also be considered a tall shrub. Crawford (2003) reported Black Hawthorn in riparian areas to be 6 to 20 ft (2 to 6 m) tall, and Daubenmire (1970) found Black Hawthorn up to 27 ft (8 m) tall.

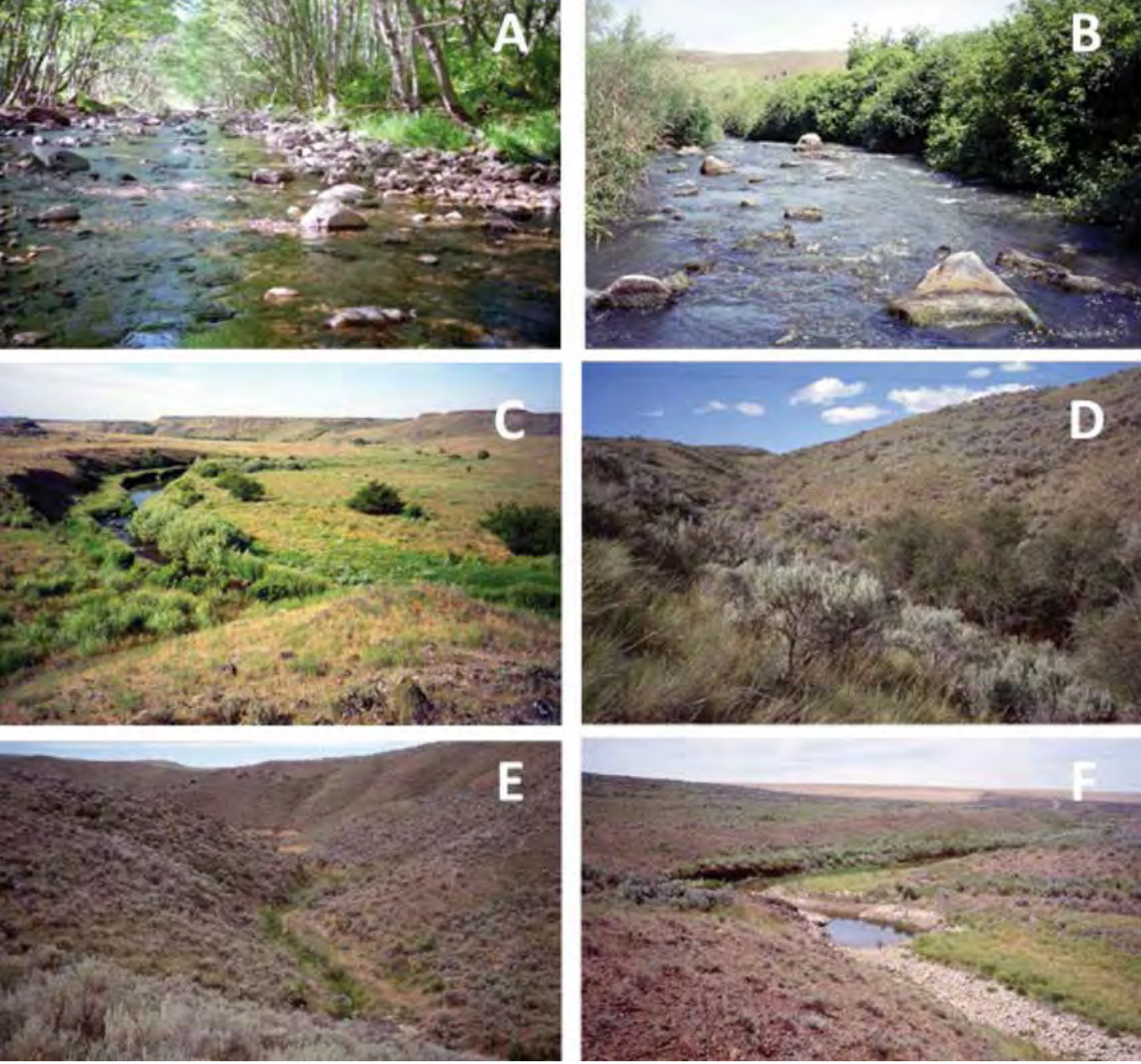


Figure 7.3. Different riparian vegetation structure types: A) tall tree, B) short tree, C) tall shrub, D) shrub on an intermittent stream, E) grass-like, F) forb/Rex Crawford, WNHP

7.2. Historical Context

Because western Washington and Oregon have a substantial amount of national park, wilderness, and roadless areas, the scientific literature contains many descriptions of unmanaged, natural riparian areas within forested ecoregions (e.g., Fonda 1974; Campbell and Franklin 1979; McKee et al. 1982; Sedell and Swanson 1984; Pabst and Spies 1999; Latterell and Naiman 2007; Fox and Bolton 2007). In the Columbia Plateau Ecoregion, however, nearly all riparian areas have been significantly impacted by human land use (grazing, intensive agriculture), resource exploitation (Beaver *Castor canadensis* trapping, timber harvest), water management (dams, diversions, reservoirs), or invasive species (Reed Canary Grass *Phalaris arundinacea*, Russian Olive *Elaeagnus angustifolia*). Daubenmire wrote in 1942, "few typical remnants of the original prairie and desert remain. These relics of the primeval vegetation likewise seem to be heading toward nearly complete extermination within a few years . . ." In short, the conditions of natural riparian areas in the Columbia Plateau Ecoregion are effectively unknown to science.

7.2.1. Beaver Trapping

The first major ecological impacts of Europeans on riparian areas in the Columbia Plateau Ecoregion were due to American Beaver (hereafter Beaver) trapping. In the early 1800s, Beaver hats were very fashionable and in high demand across Europe. The Hudson's Bay Company was determined to profit from that demand, and to obtain Beaver skins it managed a network of forts or trading posts throughout the Pacific Northwest (and throughout western North America). Several were established in and around the Columbia Plateau: Spokane House at the mouth of the Little Spokane River in 1810; Fort Okanagan at the confluence of Okanogan and Columbia rivers in 1811; a temporary post from 1812 to 1813 near confluence of Snake and Clearwater rivers; Fort Nez Perces[9] near the Walla Walla and Columbia rivers' confluence in 1818; and a temporary post at The Dalles from 1829 to 1830 (Meinig 1968). Most Beaver skins traded at these forts were obtained from the surrounding forested ecoregions.

Fort Nez Perces was situated near the center of the Columbia Plateau, and its district, which was delineated by The Dalles to the west, Priest Rapids to the north, and the Deschutes, John Day, and Grande Ronde watersheds to the south, was considered poor "fur country." Nevertheless, between 1827 and 1831 about 1,150 Beaver skins per year were traded at Fort Nez Perces (Meinig 1968). During that period, the number of Beaver skins traded per year at Fort Nez Perces dropped by 50%. Given the locations of trading posts and the high demand for Beaver skins, if Beaver could be trapped profitably in the Columbia Plateau, then they probably were. North of the Columbia Plateau, Beaver were also heavily exploited, and impacts to Beaver populations are indicated by trends in Beaver skins. The number of Beaver skins traded at the Hudson's Bay Company's Fort Colville (founded in 1825) dropped precipitously from 3600 per year in 1826 to 438 per year in 1850 (Johnson and Chance 1974).

The Hudson's Bay Company's annual Snake Country Expeditions operated out of Fort Walla Walla (formerly Fort Nez Perces). One goal of these expeditions was to create a "fur desert" which was intended to discourage America's westward expansion into lands controlled by Great Britain (Lorne 1993). George Simpson, the Hudson's Bay Company's governor at Fort Walla Walla, wrote in 1824, ". . . we have convincing proof that the country is a rich preserve of Beaver and which for

[9] In 1818 the North West Company opened a fur-trading post near the mouth of the Walla Walla River at the current location of Wallula, Washington. Originally called Fort Nez Perces, it was renamed Fort Walla Walla when the North West Company and the Hudson's Bay Company merged in 1821 (Denfeld 2011).

political reasons we should endeavor to destroy as fast as possible" (Ott 2003). In 1825 the trapper Peter Ogden and his party collected 3,577 Beaver skins in the Crooked River watershed, a semi-arid portion of the neighboring Blue Mountains Ecoregion, and on two subsequent expeditions trapped more Beaver in this area (Buckley 1993). During the 1825 expedition, Odgen noted that the Crooked River's tributaries were well lined with willows and aspen. By 1910, if not sooner, Beaver had been eliminated from some tributaries of the Crooked River, and the willow and aspen had vanished (Buckley 1993). The eradication of Beaver from dryland riparian areas is thought to have caused a cascade of adverse effects upon riparian ecosystems that I discuss in Section 7.3.

7.2.2. Open Range Grazing by Livestock

Open-range grazing by livestock was the next major ecological impact of Europeans in the Columbia Plateau Ecoregion. Around 1730, Native Americans on the Columbia Plateau acquired horses descended from those brought by Spanish explorers (Carlson 1940). In 1805, Lewis and Clark saw about 700 horses in one Indian village and thousands more in the nearby hills (Galbraith and Anderson 1971). Daubenmire (1970) believed that while most villages were on rivers, the impacts to riparian vegetation by horses were probably not extensive. A few cattle were brought to the Okanogan Valley in 1825 and to the Walla Walla Valley in 1834 (Carlson 1940). By 1855, roughly 200,000 cattle inhabited the Columbia Plateau of Washington (Daubenmire 1970). Sheep herding developed in the 1880s (Daubenmire 1970), and great numbers of sheep were brought to eastern Washington in 1892 (Galbraith and Anderson 1971). By the late 1800s, damage to rangeland from overgrazing was evident. Based on his 1893 expedition from Spokane to Steven's Pass, the botanist John Leiberg wrote, "We will never know the complete flora of these regions. Sheep and cattle are rapidly destroying the native plants and by the time private explorations reach these regions the flora will have been totally exterminated by such agencies" (as cited in Mack 1988; Weddell 2001).

Open-range management of livestock invariably results in excessive utilization of riparian areas (Ohmart 1996), and the destructive impacts of unmanaged grazing in riparian areas are well-documented (Kauffman and Krueger 1984; Ohmart 1996, Belsky et al. 1999). Riparian areas in arid and semi-arid lands of the western United States cover only 1 to 2% of land area, but produce 20% of available forage and nearly 80% of forage actually consumed by cattle (Fisher 1995). Therefore, it is reasonable to assume that the damage observed by Leiberg was greatest in riparian areas.

Restoration projects can indicate the density of woody plants that existed historically in riparian areas prior to intensive livestock grazing. For example, two years after the cessation of grazing within riparian areas in northeastern Oregon, the mean crown volume of willows and Thinleaf Alder tripled in size and that of Black Cottonwood increased nine-fold (Case and Kauffman 1997). Furthermore, shrub density increased by 50%. One possible reason for the severe impacts of grazing in the Columbia Plateau is that, unlike the Great Plains, Bison (*Bison bison*) have been rare or absent from the Columbia Plateau for close to 10,000 years (Jones 2000). According to Daubenmire (1970) and also Mack and Thompson (1982), ungulates played no significant role in the evolution of plant species in steppe and shrub-steppe communities of the Columbia Plateau, and consequently present-day vegetation cannot endure intensive grazing by livestock.

The impacts of both Beaver trapping and open-range livestock grazing may have acted synergistically to degrade riparian areas. Baker et al. (2005) suggest that Beaver and willow (*Salix* spp.) are mutualists because willow is an important food source for Beaver, and Beaver create environmental conditions suitable

as willow habitat. Baker et al. (2005) believed this relationship can persist indefinitely within a given area. They also speculated that heavy browsing by native ungulates or livestock disrupt the Beaver-willow mutualism, thus leading to degradation of the riparian ecosystem. Ohmart (1996), based on personal observation, suggested that overgrazing by livestock causes an imbalance in the Beaver-vegetation relationship that leads to collapse of riparian forests. A similar relationship has also been observed in Yellowstone National Park (Beschta and Ripple 2016) where decades of intensive grazing by Elk *Cervus canadensis* during the absence of Wolves *Canis lupus* resulted in riparian plant communities that could no longer support Beaver. The reintroduction of Wolves has led to a recovery of Beaver in Yellowstone (Beschta and Ripple 2016).

Today in the Columbia Plateau Ecoregion, the most severe impacts from grazing are caused by wild or feral horses (hereafter collectively known as wild horses). Until the mid-1900s, wild horses inhabited open rangelands in various parts of the Columbia Plateau. Today wild horses are confined to Native American reservations where the number of wild horses has fluctuated greatly over the past 140 years. The reservation of the Yakama Nation, for instance, supported roughly 16,000 horses in 1878, but a round up in 1957 left 300 horses on the reservation (Adams 2004). By 2010, the number of horses had rebounded to 12,000 (YN 2010), but the current carrying capacity of the Yakama Nation's reservation is only about 1,000 horses (Mapes 2010). Consequently, wild horses have destroyed rangelands, cultural resources, and wildlife habitats, including riparian areas (NTHC, no date). Wild horse populations also exceeded the carrying capacities of the Colville and Umatilla reservations (AP 2012; Tribal Tribune 2013). Effective management of wild horses on Native American reservations has been hampered by continual controversy regarding the most practical and ethical means of reducing their population sizes.

7.2.3. Wood Harvest and Wheat

The Donation Land Claim Act of 1850 and Homestead Act in 1862 were major impetuses for settlement of Oregon and Washington states. Settlers needed wood for fuel and construction. On the Columbia Plateau the closest source of wood, and in some places the only practical source, was riparian areas. Historians have little information on wood harvest in riparian areas by early settlers on the Columbia Plateau, however, the practices of pioneers and settlers on the Great Plains, as described by West and Ruark (2004), are likely to be similar to their practices on the Columbia Plateau. West and Ruark (2004) state that pioneers on their way west stripped virtually all trees from the Platte River valley, that riparian areas on the Great Plains were an important source of winter fuel for settlers, and that by 1900 most of the trees in riparian areas of the Great Plains had been harvested. Daubenmire (1970) speculated that Black Cottonwood, the largest tree species in the Columbia Plateau, was much more abundant before the arrival of settlers.

Impacts of Beaver trapping and open-range livestock grazing may have acted synergistically to degrade riparian areas. Baker et al. (2005) suggest that Beaver and willow are mutualists because willow is an important food source for Beaver, and Beaver create environmental conditions suitable as willow habitat.

River commerce on the Columbia and Snake rivers may have also impacted riparian areas. By 1859, steamboats were travelling upriver as far as Wallula, Washington and could reach Lewiston, Idaho at high water (Meinig 1968, cited in Evans 1989). HIstorians do not know how much wood was burned to power steamboats in the Columbia Basin, but estimates from other western watersheds suggest severe impacts to riparian forests along the Columbia and Snake. On the upper Missouri River in Montana, for instance, riparian forests along its banks were denuded of usable trees by the turn of the century (Evans 1989).

The soils and climate of the Palouse Hills subregion are suitable for dryland wheat agriculture. Consequently, the next major impact to riparian areas was converting native vegetation to wheat. The first wheat was planted in 1877, by 1895 most of the tillable land in the subregion had been plowed (Kaiser 1961), and during the 1970s industrial agriculture expedited the destruction of the last refugia for native plant communities (Black et al. 1998). Agriculture in the Palouse Hills had four major impacts on riparian areas, which were all poorly documented: 1) fields were plowed to the very edge of streambanks, thereby destroying riparian vegetation, 2) many ephemeral channels were plowed through and filled (Kaiser 1961; Bryce and Omernik 1997), 3) perennial and intermittent stream channels became deeply incised (Rockie 1939), and 4) some channels were filled with sediment from soil erosion (Rockie 1939; Bryce and Omernik 1997). Rockie (1939) reported a Nez Percé Indian telling him that some dry channels in the Palouse Hills were once perennial streams containing trout. According to Bryce and Omernik (1997), the original channel substrate, riparian vegetation, and flow regime (i.e., perennial or intermittent) are impossible to know in areas of intensive agriculture.



The least arid subregions of the Columbia Plateau support productive grasslands/Alan Bauer

7.2.4. Large-scale Irrigation Projects

Across the Columbia Plateau, the most obvious human impacts to native habitat types, including riparian areas, are those associated with irrigation projects. The U.S. Bureau of Reclamation manages two major projects on the Columbia Plateau, the Yakima and Columbia Basin, which service about 1,135,000 acres (459,318 ha) of farmland (USBR 2017a; 2017b). Another 37,000 acres (14,973 ha) are irrigated with water impounded by dams on the Snake River (USACE 2002). All 1.17 million acres (473,482 ha) of irrigated farmland were once shrub-steppe or steppe vegetation. However, these projects did not record how many acres of riparian area have been lost because ephemeral or intermittent stream channels were filled for agriculture or converted to irrigation ditches.

Construction of the Yakima Project began in 1906, and the last of 11 dams on the Yakima River or its tributaries was completed in 1939 (USBR 2017a). The Yakima Project's biggest impacts to riparian areas are along the Naches and Yakima rivers. Storage reservoirs and water diversions located upstream have truncated the rivers' natural hydrographs. This has substantially reduced river-floodplain interactions, such as inundation and lateral channel migration, which in turn have led to channel simplification and degraded aquatic and riparian habitats (Snyder and Stanford 2001; YSPB 2004).

Construction of the Columbia Basin Project began in 1933 with Grand Coulee Dam, and the first irrigation water was delivered in 1952 (USBR 2017b). The Columbia Basin Project includes a network of canals, drains, and wasteways over 5,800 miles (9,334 km) long. The reservoir behind Grand Coulee Dam, Lake Roosevelt, inundated roughly 84 miles (135 km) of riparian habitat within the Columbia Plateau Ecoregion along the Columbia, Spokane, and Sanpoil rivers.[10] Roughly 460 miles (740 km) of the Columbia River lie within the Columbia Plateau Ecoregion, but only 51 miles (82 km) of riparian habitat, the Hanford Reach, have not been inundated by reservoirs. When the dams were built, there was apparently some hope that vegetation would re-establish along new reservoir margins, but water level fluctuations appear to be too extreme for most plants to tolerate (Evans 1989). The other major impacts to riparian areas from the Columbia Basin Project are dramatic changes in hydrology. The groundwater table around lower Crab Creek, for instance, has risen between 50 and 150 ft (15 and 46 m) since 1952. Furthermore, the formerly intermittent lower Crab Creek is now perennial with four to five times the flow that occurred prior to irrigation (KWA 2004), and, as a consequence, willow species, which are adapted to the natural hydrologic regime, no longer regenerate along lower Crab Creek (Ortolano and Cushing 2000). In contrast, due to groundwater withdrawals, the groundwater table around upper Crab Creek (the Odessa subarea) has fallen 150 ft (46 m) (KWA 2004). I found no records on how the water table changes may have affected stream flow in upper Crab Creek.

Decades of hydrological alteration by dams and water diversions have altered vegetation composition and structure of riparian areas. Black Cottonwood and willow are successional pioneers that require barren sediments of disturbed alluvial floodplains for seedling germination (Patten 1998). Such conditions are produced by floods, but dams reduce peak flows and the erosive forces that scour sediments. Furthermore, the survival and growth of Black Cottonwood seedlings is highly dependent on water table elevation and its seasonal rate of change (Braatne et al. 1996). If the water table declines more rapidly than seedling root growth, then seedlings die. Braatne et al. (2007), for example, found that dams on the Yakima River created

[10] Estimated with Google Earth. Distance estimated along Spokane River comports with that reported by Ortolano and Cushing (2000).

hydrological conditions unsuitable for Black Cottonwood seedlings. They studied river reaches near Cle Elum, Union Gap, and Wapato and found: 1) no seedlings in any reaches, 2) Black Cottonwood stands less than 25 years old were extremely limited, 3) riparian areas were dominated by older age classes, and 4) altered hydrology promoted invasion of the floodplain by exotic tree species such as Silver Maple *Acer saccharinum*, Norway Maple *Acer platanoides*, and Chinese Elm *Ulmus parvifolia*. Hence, one could confidently infer that historical conditions have been altered by regulated flows. If artificial flow regimes are not changed, then as older individuals senesce and die, cottonwoods may be eliminated from some sections of the Yakima River. This would have adverse effects on multiple riparian area functions: streambank stability, shading, large wood recruitment, and detrital nutrients. Exotic tree species currently found along the Yakima River cannot provide the same ecological functions as Black Cottonwood because they cannot establish themselves in the barren, saturated sediments of recently disturbed floodplains.

Dams have also altered the flow of wood through watersheds. Historically, wood was transported from forested headwaters to dryland reaches of rivers and streams. This process is known to have occurred in other semi-arid and arid regions of the United States.

"We will never know the complete flora of these regions. Sheep and cattle are rapidly destroying the native plants and by the time private explorations reach these regions the flora will have been totally exterminated by such agencies."

- Botanist John Leiberg, 1893

Minckley and Rinne (1985) present historical evidence for the movement of large wood in desert rivers of the American southwest: wood originated in forested headwaters, moved sporadically through desert riparian areas during flood events, and was ultimately deposited at the mouth of the Colorado River in Mexico. Minckley and Rinne (1985) identified interception of large wood by dams as a major cause of large wood reduction in semi-arid and arid river basins. At artificial reservoirs in eastern Washington, such as Keechelus, Kachess, Cle Elum, Easton, Bumping, Clear, and Rimrock lakes, large wood that could potentially interfere with dam operations is removed and burned (W. Meyer, Washington Department of Fish and Wildlife, personal communication; B. Renfrow, Washington Department of Fish and Wildlife, personal communication). Large wood in dryland sections of the Wenatchee and Okanogan rivers may be effected in this way as well. How wood management at dams and smaller water diversions affects in-stream large wood in eastern Washington has not been investigated.

7.2.5. Invasive Non-native Plants

An ongoing historical anthropogenic impact is the introduction of exotic invasive plant species. After their botanical survey of the Columbia Plateau in 1893, Sandberg and Leiberg were not troubled by the meager abundance of exotic species at that time (Mack 1988), however, by 1929 about 200 exotic species were known to exist on the plateau (Mack 1988). Riparian areas in dryland landscapes are more vulnerable to invasion by exotic plant species than adjacent upland areas (Loope et al. 1988; Hood and Naiman 2000), and invasive plants in riparian areas can impact a variety of ecological processes: hydrology, sediment dynamics, nutrient dynamics, and species competition. Two invasive species of particular concern are Reed Canary Grass and Russian Olive.[11]

11 Other invasive species of concern in the Columbia Plateau Ecoregion are Crack Willow *Salix fragilis*, Yellow Flag Iris *Iris pseudacorus*, and Purple Loosestrife *Lythrum salicaria*.

Reed Canary Grass occurs as both exotic and indigenous strains (Tu 2006). The European cultivar has been present in the Pacific Northwest since the 1880s (Stannard and Crowder 2001), and, as of 2016, it is found in all Washington counties except Douglas (WSDA 2016). Reed Canary Grass forms dense stands that can exclude all other plant species, and such stands exhibit substantially higher transpiration per unit ground surface area than other species (Gebauer et al. 2015). This could alter water availability in riparian areas. Reed Canary Grass also has higher roughness values than native sedge species (Martinez and McDowell 2016). This could lead to greater sediment deposition and channel narrowing.

As of 2016, Russian Olive is found in most counties east of the Cascade crest and is most common in Grant County (WSDA 2016). In the late 1800s, it was introduced into the Pacific Northwest as an ornamental plant (Giblin 2006), but the species did not become prominent outside cultivated areas until two to five decades later, depending on location. Unlike many tree and shrub species in dryland riparian areas, Russian Olive does not require disturbed soils for germination. Hence, it can grow on sites where woody vegetation would not naturally occur (Katz and Shafroth 2003). It is also shade tolerant, and consequently, Russian Olive can establish beneath the canopy of native riparian trees or shrubs and compete with them for resources. Russian Olive exhibits about two times higher transpiration per unit basal area than cottonwood trees (Hultine and Bush 2011). This could alter water availability in riparian areas. The species is a nitrogen fixer that adds nitrogen to the soil. Tuttle et al. (2016) found that stands of Russian Olive had higher exotic plant ground cover than stands of native tree species, and they believed that the difference was due to higher available soil nitrogen that benefited fast growing exotics plants. Finally, according to Lesica and Miles (1999), Beaver foraging behavior indicates that Russian Olive is much less palatable than native cottonwood. They found that 77% of cottonwood trees along a river in Montana were damaged by Beaver but only 22% of Russian Olive trees were damaged. If Russian Olive replaces native cottonwood, then Beaver population density could be adversely affected.

7.2.6. Value of a Historical Perspective

Current scientific understanding of riparian ecosystems in the Columbia Plateau Ecoregion is mostly based on present-day conditions, which are unlikely to accurately represent historical composition and structure. History indicates that past human impacts in the Columbia Plateau may have erased fully functioning riparian ecosystems from many watersheds. For example, records of the U.S. Army cavalry at Fort Simcoe on the Yakama Indian Reservation from the 1850s describe small valleys with broad floodplains dissected by multi-threaded stream channels that are absent today. These valleys—such as the Wenas, Ahtanum, and Cowiche—historically contained a network of streams, wetlands, and Beaver ponds that supported extensive groves of willow, Redosier Dogwood, Black Cottonwood, and aspen. Cattle were said to be lost for weeks in these tangles (P. Harvester, Washington Department of Fish and Wildlife, personal communication). These same streams are now reduced to a single, incised channel with minimal riparian vegetation. The loss of riparian habitats indicated by the Fort Simcoe records is very likely to have occurred in other parts of the Columbia Plateau.

Rivers and streams of the Columbia Plateau Ecoregion have been degraded by a variety of human activities. This has adversely affected anadromous salmon—their populations are threatened with extinction and fisheries produce a small fraction of historical harvest. In response, salmon habitat restoration projects are occurring throughout the Columbia Plateau. Habitat restoration requires ecological reference information to determine site-level restoration potential, establish desired conditions, and formulate measures of success

(White and Walker 1997). Ecological reference information is generally based on historical conditions, natural areas, or minimally disturbed sites (White and Walker 1997; Stoddard et al. 2006; Higgs et al. 2014). In the Columbia Plateau Ecoregion, which lacks national parks, wilderness, or roadless areas containing natural reference sites, historical information may be the only basis for reference conditions (Wohl 2005).

Because the Columbia Plateau lacks undisturbed watersheds, even small ones, ecologists have a poor understanding of the composition, structure, and functions of natural riparian ecosystems. Historical reconstruction using journals of early explorers and naturalists, General Land Office survey notes, and historical drawings or photos (Figure 7.4) are ways to develop qualitative descriptions of riparian plant

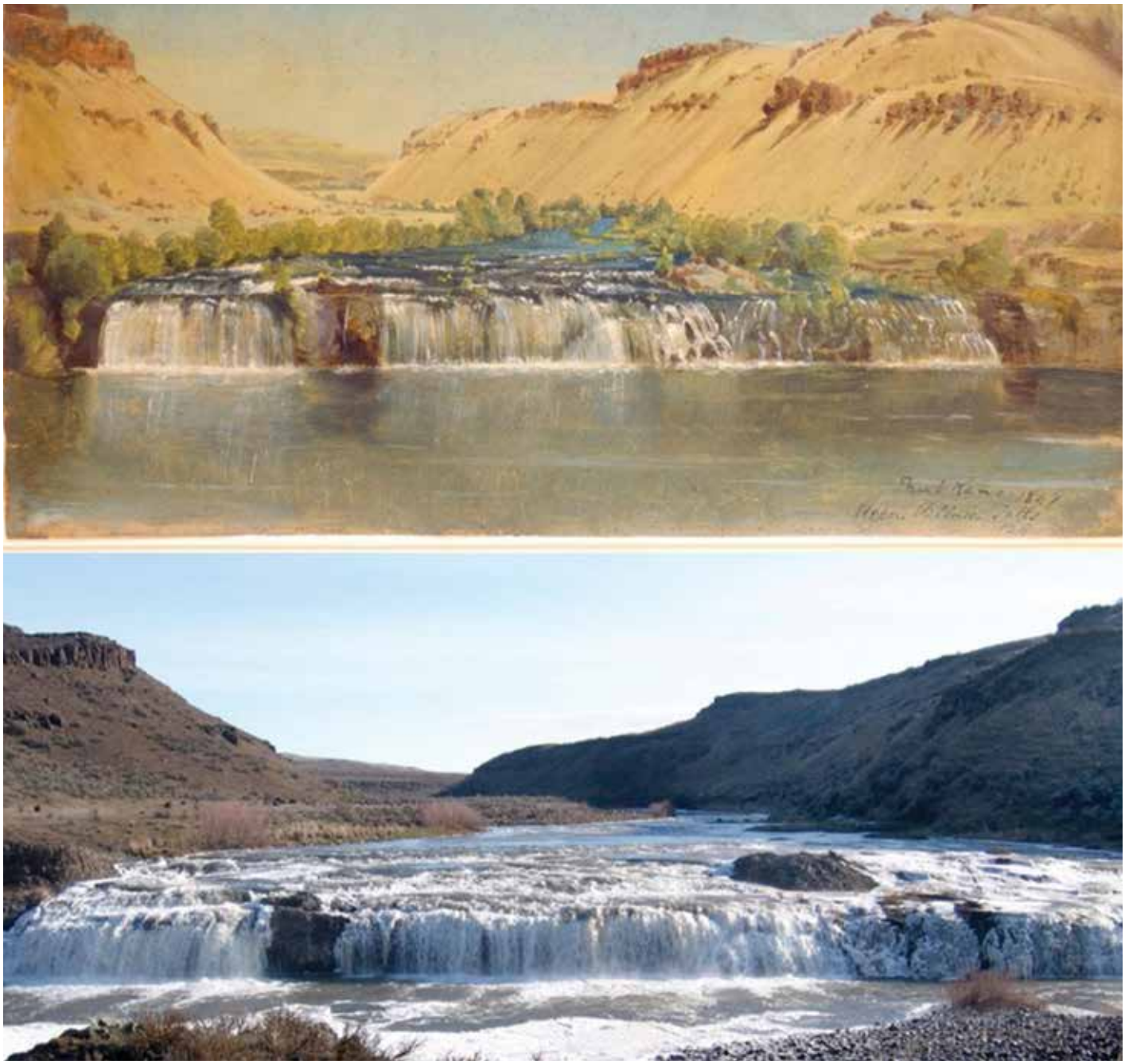


Figure 7.4. Historical drawings and paintings can provide invaluable information for riparian area restoration. A 1847 painting by Paul Kane of Upper Palouse Falls (top) shows extensive, uninterrupted small tree or tall shrub vegetation along the river banks. A recent photo by Jack Nisbet (bottom) although taken in winter, shows large gaps in small tree or tall shrub vegetation along the banks.

communities (McAllister 2008). Much work needs to be done on deducing the likely historical conditions of riparian areas in the Columbia Plateau. Studies of historical conditions in the Columbia Plateau, however, must be cognizant of one important caveat. If hydrology of a riparian area has been significantly altered by human activity, then the vegetation that site supported historically may have no relationship to the vegetation the site is capable of supporting now. Irrigation systems have altered hydrology in riparian areas throughout the Columbia Plateau, making some drier and others wetter. At such places, information on historical vegetation will often be of little value in establishing desired future conditions for restoration.

7.3. Beaver

Beaver may play an essential role in the restoration and future conservation of dryland riparian areas (Dremmer and Beschta 2008; Pollock et al. 2014). The ecosystem benefits of Beaver in dryland riparian areas have been known for over 80 years. Scheffer (1938) reported that in 1936 the Soil Conservation Service transplanted 10 Beaver to the Ahtanum Creek watershed for the purposes of increasing water storage. The Beaver constructed several large dams, one of which was 90 ft (27 m) long, 10 ft (3 m) high, and stored 5 acre-feet (6,167 m^3) of water. Scheffer (1938) implied that the dams reduced downstream flood damage and increased summer stream flows for irrigation. Finley (1937) reported the opposite situation for Silver Creek in eastern Oregon. Two trappers removed 600 Beaver in one winter. As a result, the Beaver ponds "disappeared," the water table lowered, grassy meadows "died out" and streams containing trout went dry.

The observations of Scheffer (1938) and Finley (1937) are anecdotes. More rigorous scientific research into the connections between Beaver and riparian ecosystems have found that Beaver have numerous positive effects.



Beaver viewed with night vision camera/Ned Pittman, WDFW

Beaver dams store organic nutrients and large quantities of sediment, reduce channel incision, remove excess nutrients from water, increase surface water storage and base flows, reduce peak flows, increase groundwater recharge, raise water table elevations, expand the area of riparian vegetation, and increase the salmonid habitat capacity of small streams (Naiman et al. 1988; Pollock et al. 2003; Gibson and Olden 2014). For dryland riparian areas where the extent of riparian vegetation depends on shallow groundwater, the hydrologic and geomorphic effects of Beaver dams may be necessary for the mere existence of a riparian zone at many sites. In dryland riparian areas, most ecosystem functions occur within the riparian zone.

The dramatic effects of Beaver on hydrology was shown by Westbrook et al. (2006), a multi-year study of two Beavers dams on a fourth order stream running through a dry meadow in the Rocky Mountains of Colorado. One dam diverted over half and the other diverted 70% of the stream onto the floodplain and terrace. Both dams increased substantially the area flooded by annual peak flows. One dam caused the equivalent of a 20-year flood over 30 acres (12 ha) of the valley floor during a peak flow event with a 1.6-year recurrence interval, and the other dam caused the equivalent of a 200-year flood over 21 acres (8 ha) of the valley floor during a peak flow event with a 1-year recurrence interval. One of the dams

studied by Westbrook et al. (2006) was breached by high flows. Westbrook et al. (2011) subsequently found that overbank flooding caused by that dam had deposited nutrient-rich sediments in some areas and scoured soils in other areas downstream of the dam site. These bare sediments were colonized by willow and aspen seedlings, which may eventually establish riparian plant communities.

In sagebrush steppe of Wyoming, Cooke and Zach (2008) found that the number of Beaver dams was positively associated with riparian zone width, riparian shrub height and percent cover by emergent wetland vegetation. These responses can at least partly be explained by changes in hydrology caused by Beaver dams.

Eradication of Beaver has been implicated in stream channel incision and desertification of riparian zones that has occurred throughout arid and semi-arid ecoregions of western North American (Parker et al. 1985; Pollock et al. 2003), including the Columbia Plateau (Pollock et al. 2007). According to Pollock et al. (2007), the exact mechanism that caused widespread incision of streambeds remains uncertain, however, incision almost invariably coincided with widespread trapping of Beaver and the onset of intensive livestock grazing. Channel incision, whatever the ultimate cause, occurs through an imbalance between sediment deposition and sediment mobilization. Assuming no changes in upstream sediment sources, incision is usually attributed to an increase in erosive forces or a decrease in channel resistance to erosive forces. The former can be caused by an increase in runoff, both can be caused by a decrease in channel roughness, and the latter can also be caused by loss of streamside vegetation. Therefore, channel incision can be prevented by controlling runoff caused by upstream land uses, maintaining roughness elements such as large wood, and retaining riparian vegetation. For many dryland riparian areas, Beaver are essential for the latter two. Beaver dams act as massive roughness elements that reduce flow velocities, thereby reducing hydraulic forces that cause erosion. Reducing flow velocities also results in sediment deposition, which raises the streambed elevation and creates microsites suitable for germination of riparian plants.

Several studies have suggested that reintroduction of Beaver can reverse channel incision (Pollock et al. 2007; Beechie et al. 2008), primarily by restoring sediment retention processes in the channel (Pollock et al. 2014). Sediment aggradation caused by Beaver dams fills the incision and raises the streambed elevation. As the bed elevation increases, hydrologic connectivity between the channel and former floodplain is improved both by raising the water table elevation and by reducing bank height, which allows overbank flooding to recharge the floodplain's alluvial aquifer. Increased soil moisture allows riparian plant species vegetation to re-establish. Development of a well-vegetated riparian zone provides Beaver with more food and building materials, enabling construction of more dams (Pollock et al. 2014).

The aforementioned impacts of Beaver on aquatic and riparian ecosystems are immensely beneficial to fish; however, Beaver may also have detrimental effects on fish. Sediment deposition in Beaver ponds may harm spawning beds, and Beaver dams can block upstream and downstream fish movements (Pollock et al. 2003). Water temperature in Beaver ponds can be warmer than nearby flowing waters, especially where the stream is largely under a closed canopy forest (Robison et al. 1999), but in areas with open or no canopy (such as dryland riparian areas), water temperatures tend to be similar between Beaver ponds and unimpounded reaches (Talabere 2002). Beaver ponds have also been found to provide productive habitats for non-native fish (Gibson et al. 2015) that may compete with or prey upon native fish.

7.4. Ecosystem Functions

FEMAT (1993) identified five key functions of riparian ecosystems that are important for fish habitats: streambank integrity affected by plant roots, litter fall that provides detrital nutrients, shading to limit stream temperatures, large wood recruitment, and pollution removal. Most of what is known about these key riparian functions was discovered through research conducted in forested ecoregions, in particular, the mesic forest ecoregions of the Pacific Northwest (e.g., Salo and Cundy 1987; Naiman and Bilby 1998; Richardson et al. 2005). Much of what is known about riparian areas in forested ecoregions is transferable to riparian areas in the Columbia Plateau, and therefore, where appropriate I repeat some of the knowledge and principles elucidated in chapters 1 through 6. However, as will become apparent, large gaps in knowledge remain.

In addition to FEMAT's key ecological functions, a sixth key function occurs in dryland riparian areas– alluvial water storage. Alluvial water storage occurs in riparian areas of all ecoregions, but it may be especially important in dryland ecoregions.

7.4.1. Streambank Stability

Streambank stability refers to a bank's resistance to change and its resilience after change (Bohn 1986). Streambank stability is the opposite of streambank erosion. Streambank erosion is commonly misinterpreted as a sign of adverse human impacts to riparian ecosystems, and it can be. However, a channel in dynamic equilibrium simultaneously exhibits both stable and unstable banks (Wohl et al. 2015). Streambank erosion is integral to a watershed's fluvial disturbance regime and necessary for long-term ecological sustainability (Florsheim et al. 2008) because the opposing processes of bank stability and bank erosion maintain the diversity of aquatic and riparian habitats within a watershed. Bank stability is also associated with overhanging/undercut banks which shade the water and provide cover for fish (Bohn 1986; Ohmart 1996).

The stability of streambanks is influenced by soil characteristics, groundwater, and vegetation. For the purposes of riparian area management, I focus on vegetation. Rooted vegetation is essential for streambank stability (Hupp and Osterkamp 1996; Gurnell 2014). Plants are said to provide "root strength" or "root reinforcement" along streambanks (FEMAT 1993; Pollen-Bankhead and Simon 2010). Soil is generally strong in compression, but weak in tension. Woody and herbaceous plant roots are strong in tension, but weak in compression. Consequently, the root-permeated soil of streambanks behaves as a composite material with enhanced strength (Simon and Collision 2002). Dense root networks also physically restrain or bind soil particles. Exposed roots on the bank surface increase channel roughness which dampens stream flow velocities, thereby reducing fluvial erosion (Griffin et al. 2005). Reduction of stream velocities by roots may also cause sediment deposition, which further stabilizes streambanks.

The stability provided by roots is species dependent (Polvi et al. 2014). Simon et al. (2006), for instance, found that Lemmon's Willow *Salix lemmonii* provided 10 times more root reinforcement of streambanks than Lodgepole Pine *Pinus contorta.* The difference was due to the greater root density and larger root area of Lemmon's Willow. On the southeastern slope of the Cascades Range in Washington, Liquori and Jackson (2001) found that different riparian plant communities manifested differences in bank erosion and channel form. They identified two types of riparian plant communities: a scrub-shrub community that exists within an open-canopy Ponderosa Pine *Pinus ponderosa* forest, and a dense, closed-canopy fir forest. The

Ponderosa Pine forest is maintained by regular wildfires while the fir forest was created by fire suppression. The scrub-shrub community was associated with stream channels that had less bank erosion, lower width-to-depth ratios, more pools, and more undercut banks than channels within the fir forest community. The channel morphology of scrub-shrub riparian communities also resulted in slightly lower summer stream temperatures. In the semi-arid Sierra Nevada Mountains, Micheli and Kirchner (2002) found that riparian areas comprised of sedges and/or rushes had banks five times stronger than riparian areas comprised of sagebrush and grasses, and that bank strength was correlated with the root mass to soil mass ratio. Sedges and/or rushes enabled the formation of undercut banks, and increased the width of an undercut bank by a factor of 10.

The composition and structure of riparian vegetation affects channel morphology which, in turn, affects riparian vegetation (Corenblit et al. 2007; Osterkamp and Hupp 2010). Toledo and Kauffman (2001) observed the effects of one such interactive feedback loop in semi-arid northeastern Oregon. Upland plants were found along incised channels and wetland-obligate plants (mostly sedges) were found along unincised channels, which had two times greater root biomass than incised channels. Along unincised channels, approximately 40% of root biomass was deeper than 8 in (20 cm) in the soil, but along incised channels less than 25% of root biomass was below 8 in (20 cm).

Compared to forested ecoregions, there is less large woody debris, and woody debris play a much smaller role in the fluvial processes of dryland river and streams.

Denser roots at deeper soil depths result in a larger volume of reinforced soil. According to Toledo and Kauffman (2001), the severely degraded conditions at their incised sites were caused by a positive feedback loop in which an initial channel incision led to a lower water table. The resulting reduction in soil moisture altered riparian vegetation which shifted to an upland plant community with reduced root mass. Bank erosion subsequently increased which led to channel widening and further incision.

The studies reviewed thus far have reported on the bank strength provided by hydric or wetland-obligate shrubs and herbaceous plants (sedges and rushes) in dryland riparian areas. Trees are also important for bank stability. Rood et al. (2015) studied the amount of bank erosion after major floods along Elk River in British Columbia. They found that floodplain locations occupied by grassland or small shrubs exhibited substantial erosion (>75 m of bank erosion) after major floods but locations occupied by forest, including Black Cottonwood stands, exhibited much less change (<15 m of bank erosion). Rood et al. (2015) concluded that "only big plants can resist big flows," and that other studies which demonstrated that grasses or shrubs are more erosion resistant had observed only low energy flows in smaller or shallower gradient streams.

Streambanks along incised channels of arid or semi-arid regions are particularly sensitive to changes in soil moisture. Much of the bank may be above the water table, and hence soils are unsaturated. Matric[12] suction above the water table, enhanced by transpiration of riparian vegetation, has the effect of increasing the apparent soil cohesion, and decreases in soil strength due to a loss of suction are a leading cause of bank failures in incised channels (Simon and Collison 2002).

12 Matric suction is a negative pore pressure that induces water to flow in unsaturated soil. It results from the combined effects of adsorption and capillarity of the soil matrix. Water flows from a soil with low matric suction (a wet soil) to soil with a high matric suction (a dry soil).

7.4.2. Wood

The main role of wood in aquatic ecosystems is roughness element (Bisson et al. 1987). Roughness elements are obstacles in a channel that deflect flow and change its velocity. The size, shape, and strength of large wood make it very effective at redirecting hydraulic forces and the flow of materials, such as sediment and fine organic matter. In-stream large wood increases hydraulic complexity, i.e., creates a wider range of flow velocities, which causes pool formation, streambed scour, sediment deposition, and channel migration. The net result is a diversity of aquatic habitat types.

I could find no studies conducted in the Columbia Plateau describing the density of trees or their spatial distribution in riparian areas. However, riparian areas in the Columbia Plateau certainly contain less large wood than forested ecoregions, even historically, for three reasons. First, trees are smaller in the Columbia Plateau than in forested ecoregions of Washington. Canopy dominant trees in old-growth riparian ecosystems of mesic forested ecoregions can be well over 48 in (122 cm) diameter at breast height (dbh) and over 150 ft (46 m) tall, but the maximum size of Black Cottonwood in the Columbia Plateau is much smaller (see below). Second, trees are fewer in the Columbia Plateau because in the Columbia Plateau trees inhabit the riparian zone but often do not inhabit the zone of influence. In forested ecoregions, trees inhabit both zones. Third, along some streams, particularly in the most arid subregions of the Columbia Plateau, even the riparian zone is unsuitable for tree species. At such sites, the riparian zone consists of tall shrub, shrub, grass-like, grass, and forb vegetation types. Therefore, compared to forested ecoregions, there is less large woody debris, and woody debris plays a much smaller role in the fluvial processes of dryland river and streams.

Knowledge regarding wood in aquatic and riparian ecosystems of Columbia Plateau is extremely limited at present, nevertheless, the historical abundance of woody plants in riparian areas is thought to have been much greater than it is today (Wissmar et al. 1994; Kauffman et al. 1997; Wissmar 2004). Riparian areas in the Columbia Plateau are inhabited by a variety of woody plants–Black Cottonwood, Quaking Aspen, White Alder, Thinleaf Alder, Water Birch, Black Hawthorn, and Yellow Willow (Crawford 2003). Conifer trees, including Ponderosa Pine and Douglas-fir *Pseudotsuga menziesii,* are widely scattered in eastern Washington riparian areas and were likely more common historically than at present. They are currently restricted to canyons or valleys with steep rocky walls along mid- to high-gradient streams where they are inaccessible to harvest and where microclimates are conducive to supporting trees (Evans 1989). The main causes of reduced wood are explained in Section 7.2.

The size and quantity of wood recruited to a stream depends on the size and density of woody plants, their distances from the channel, and the recruitment processes that deliver wood to the channel. Only a few tree species in riparian areas of the Columbia Plateau qualify as large wood, which is commonly defined as greater than 4 in (10 cm) in diameter and greater than 6 ft (2 m) in length.[13] Black Cottonwood is the largest riparian tree species in the Columbia Plateau Ecoregion and the largest deciduous species in western North America. The species has a typical lifespan of 100 to 200 years (Braatne et al. 1996), and can attain a dbh of about 30 to 35 in (76 to 90 cm) in the Pacific Northwest (Franklin and Dyness 1988), but sizes are smaller in the Columbia Plateau. The interior of British Columbia is less productive than the province's coastal ecoregion, and in the interior, Black Cottonwood attain an average size of 15 in (38 cm) dbh and 52 ft (16 m) tall at age 80 years, and 26 in (66 cm) dbh and 70 ft (21 m) tall at age 150 years (Roe 1958). Other tree species that might also

[13] Large wood is also known as large woody debris (LWD) or coarse woody debris. There is no universal definition of LWD. Another common definition is greater than 4 in (10 cm) in diameter and greater than 3 ft (1 m) in length. Small wood is also known as small woody debris or fine woody debris.



Large trees in riparian areas are a major source of instream large woody debris/Jim Cummins , WDFW

function as large wood are Quaking Aspen, White Alder, and Peachleaf Willow *Salix amygdaloides*. Daubenmire (1970) reported that Quaking Aspen and White Alder grow to about 8 and 23 in (10 and 58 cm) dbh, respectively, in riparian areas of the Columbia Plateau.

Substantial amounts of small wood may be recruited to and stored in stream channels through Beaver activity. Most dryland riparian areas lack large trees, but in dryland riparian areas Beaver create large roughness elements from small wood that mimic some effects of large wood (see section 7.3). In effect, Beaver convert small wood to large wood. Beaver dams consist mainly of mud and small wood. Published information on small wood sizes in dams of North American Beaver is lacking. However, Beaver most often forage on trees ranging from 1.2 to 3.2 in (3 to 8 cm) in diameter (Collen and Gibson 2001), and a large proportion of woody stems used as food are also used in dam construction (Barnes and Mallik 1996). In Maryland, Blersch and Kangas (2014) found that 98% of sticks (i.e., small wood) in a Beaver dam were less than 4 in (10 cm) in diameter and that 46% of those sticks were probably placed in the dam by Beaver. The other 54% of sticks in the dam were due to passive capture of transported wood.

Large wood recruitment processes in riparian areas of the Columbia Plateau should be very similar to those in forested ecoregions. Therefore, the main processes should be tree mortality caused by disease or senescence, bank erosion, and wind throw. Maximum recruitment distances for large wood will generally be either riparian zone width or site-potential tree height, whichever is smaller. I found no studies on recruitment mechanisms of small wood, nevertheless, the main mechanisms should be direct fall of branches into a stream channel, mobilization by overbank flooding, and Beavers. Consequently, depending on the relative distribution of small and large wood sources within a riparian area, the recruitment distance for small wood could be greater than the distance for large wood. That is, shrubs that lie farther from the stream channel than trees, could contribute small wood via flooding or Beaver.

7.4.3. Detrital Nutrients

With respect to riparian ecosystems, *detrital nutrients* most often refer to nutrients derived from terrestrial litter. Litter may consist of leaves, bark, seeds, cones, flowers, fruit, nuts, twigs, and other small plant parts (Benfield 1997). Terrestrial litter in an aquatic system is also called allochthonous nutrients.[14] Detrital nutrients are only one component of nutrient dynamics in riparian ecosystems. Riparian areas also mediate bi-directional exchange of dissolved nutrients between terrestrial and aquatic systems. Detrital nutrients in the larger context of nutrient dynamics (e.g., nitrogen cycle) are discussed in Chapter 6.

Besides research on marine derived nutrients (Naiman et al. 2002), the dynamics of macronutrients—nitrogen, phosphorus, and carbon (N, P, and C)—in riparian areas of the Pacific Northwest has been largely neglected by scientists (but see Naiman and Sedell 1980; Triska et al. 1984). I found one study related to nutrient dynamics in riparian areas that was conducted in the Columbia Plateau Ecoregion (e.g., Cushing and Wolf 1982; Cushing and Wolf 1984; Cushing 1988).

The availability of macronutrients has profound effects on the productivity, composition, and structure of ecosystems. In Washington, many streams and rivers in undisturbed watersheds are oligotrophic, i.e., exhibit low productivity associated with low N or P concentrations. Thut and Haydu reported in 1971 that roughly half of unpolluted surface waters in Washington were N-limited, and the other half were limited by P. Interestingly, N-limited waters, such as those in the Yakima River and lower Columbia River basins, most often arise from volcanic rock formations, while P-limited waters, such as those in the Okanogan River basin, flow from glacial deposits or granitic formations (Thut and Haydu 1971; Murphy 1998). Nutrient-limited waters are often sensitive to anthropogenic inputs of macronutrients, and when more N or P enters a stream than can be immediately metabolized, degradation of aquatic habitats often results. Artificial fertilizers, which are inorganic nutrients, cannot mimic the foodweb role of detrital nutrients. Artificial fertilizers are used by plants, but litter feeds heterotrophs such as macroinvertebrate detritivores (shredders and collectors), many of which are prey for salmonids. Therefore, providing adequate amounts of litter to streams is an important issue for riparian area management.

According to Xiong and Nilsson (1997), in drier and less productive grasslands, a certain amount of litter may help to conserve soil moisture and thus increase plant growth. The same effect may be obtained in dryland riparian areas. Hence, in addition to providing nutrients, litter from riparian vegetation may also retain soil moisture.

Little is known about nutrient dynamics in dryland riparian areas. Nitrogen cycling, for instance, is driven by microbes in soils, and microbial activity depends on water availability. In forested ecoregions, nitrogen cycling is rarely limited by water availability. Hence, microbial processes are active in both uplands and riparian soils, and can occur year round. In arid regions, nitrogen cycling in uplands may cease when soil moisture approaches zero. This is also true of nitrogen cycling in riparian areas, however, nitrogen dynamics are more complex in riparian areas because they are closely linked to seasonal water table elevations which are affected by site and watershed-scale hydrology (Belnap et al. 2005).

Particulate and dissolved organic carbon are important sources of energy in aquatic ecosystems. Both support organisms near the bottom of the food web. In forested ecoregions, productivity of headwater streams is typically light-limited by a closed canopy (Conners and Naiman 1984; Murphy 1998), and consequently, the main source of energy is allochthonous chemical energy

[14] Allochthonous means originating or formed in a place other than where found. In contrast, autochthonous means originating or formed in the place where found.

from riparian areas. In arid and semi-arid regions, the canopy over headwater streams tends to be more open, which allows more light to reach the aquatic ecosystem. Cushing and Wolf (1982) found that chemical energy for a small spring-fed stream in central Washington, Rattlesnake Springs, was predominantly autochthonous, i.e., produced within the stream by Watercress *Rorippa nasturtium-aquatica,*[15] Cattail *Typha latifolia*, and algae. Direct allochthonous inputs contributed 11% of total energy inputs, and all of it was consumed. Consequently, Cushing and Wolf (1982) concluded that the aquatic community exhibited both autotrophic and heterotrophic traits.

The amount of allochthonous carbon produced by dryland riparian areas varies considerably. The input rates of allochthonous organic matter (specifically, leaf litter from shrubs) in two dryland riparian areas were 1.1 oz/ft^2/yr (350 g/m^2/yr) at Rattlesnake Springs and 0.54 oz/ft^2/yr (165 g/m^2/yr) at Snively Springs (Fisher 1995). The former is about 1.2 to 2.1 times greater than the amount of leaf litter produced by riparian areas in mesic forests (Gregory et al. 1991; cited in Fisher 1995).

Nearly all N in lotic ecosystems in forested ecoregions of the Pacific Northwest is derived from allochthonous sources. Headwater streams in the western Cascades of Oregon, for instance, obtain more than 90% of annual nitrogen inputs from biotic processes in the adjacent forest (Triska et al. 1984). An important source of N in forests of western Oregon and Washington is N_2-fixing Red Alder *Alnus rubra*, which contributes both litter and dissolved organic N to streams (Compton et al. 2003). Small streams in the Columbia Plateau Ecoregion must also obtain N from allochthonous sources. The overstory of some riparian plant communities in that ecoregion consists of N_2-fixing White Alder *Alnus rhombifolia* or Thinleaf Alder *Alnus incana*. Evidence suggests that Black Cottonwood and willow species contain mutualistic organisms that fix nitrogen (Doty et al. 2009, Wuehlissch 2011). This helps to explain how these species can survive and grow on recently disturbed, barren, floodplain sediments. Litter from these pioneering plants also provides nitrogen for other plant species in subsequent successional stages and deliver allochthonous nitrogen to the aquatic ecosystem.

The only study I could find on litter source distances was conducted in mature conifer forest in western Washington. Bilby and Heffner (2016) found that about 95% of litter delivered to streams comes from distances between 39 and 54% of mean tree height, depending upon forest type, topography, and wind. For Snively Springs, a spring-fed small stream with a riparian area comprised of dense willow and wild rose in central Washington, Cushing (1988) found that roughly 40% of litter fell directly into the stream from overhanging vegetation and 60% was blown laterally from plants some distance from the streambank. He did not measure distances. These proportions were affected by factors that influence wind, such as vegetation density and topography.

7.4.4. Shade

For an in-depth discussion of shade and water temperature refer to Chapter 4.

Numerous studies in dryland riparian areas have shown that salmonid species abundance is negatively correlated with stream temperature (Platts and Nelson 1989; Li et al. 1994; Ebersole et al. 2003a; Zoellick 2004). Even when primary and secondary production increase in response to reduced shading, salmonid populations often respond negatively to high temperatures (Tait et al. 1994). Shade is important because it directly affects stream temperatures. Other factors can significantly affect stream temperature, such as topographic shading, channel azimuth, channel form, groundwater flow, and hyporheic exchange, but for the purposes of riparian area management, I focus on shade provided by vegetation. Vegetation also affects local air temperature,

15 Watercress (*Rorippa nasturtium-aquaticum*) is an exotic plant in Washington State.



In the Columbia Plateau, some stream reaches have no shade from vegetation/Alan Bauer

humidity, and air movement, which all affect stream temperature (Cristea and Janisch 2007).

Shading of a stream is affected by the vegetation's height and foliage density and by the stand's depth (or width) and stem density. In general, a taller, denser, or wider strip of vegetation will shade a larger proportion of a channel for a longer time, at both daily and annual time scales. Riparian vegetation also enables the formation of undercut banks, which provide shade along streambanks that has been shown to lower water temperatures of individual pools (Ebersole et al. 2003a; Ebersole et al. 2003b).

The classification system based on overstory underscores the substantial differences in shading provided by riparian vegetation types: tall tree, short tree, tall shrub, shrub, grass-like, grass, and forb (Crawford 2003). The obvious implication of these vegetation types is that some stream channels in the Columbia Plateau receive little or no shade from vegetation, even historically. However, the actual historical condition of many riparian areas is unknown. Studies show that restoration of riparian areas, especially restoration of incised channels, can alter vegetation type, increase shading, and reduce water temperatures. How spatial variation in vegetation type and consequent shading currently affects salmonid habitat regionally is also unknown. Ecologists lack a map of current and potential riparian vegetation types across the Columbia Plateau that would enable managers to assess impacts on fish-bearing streams from insolation (see Macfarlane et al. 2017 for a first approximation).

7.4.5. Pollutant Removal

For an in-depth discussion of pollutant removal by riparian areas refer to Chapter 5.

The capability of riparian areas to remove certain pollutants from runoff is well documented (Barling and Moore 1994; Hickey and Doran 2004; Polyakov et al. 2005; Dosskey et al. 2010). Management of riparian areas for pollutant removal differs from the other ecological functions discussed in this document in that the primary focus is on mitigating activities occurring outside the riparian area. The pollutant removal function is unique in that it only exists in the presence of human activities that generate polluted runoff, and it is only necessary when runoff from upland activities threatens to degrade in-stream water quality. Major nonpoint-source pollutants removed with riparian "buffers"[16] are sediments, excess nutrients (nitrogen or phosphorus), pesticides, and pathogens.

16 Riparian buffers are also known as riparian management zones (RMZs). "Buffer" refers to its purpose, which is to reduce or prevent adverse impacts to water quality, fisheries, and aquatic biodiversity from human activities occurring upslope of the buffer. Riparian buffers managed specifically for pollutant removal may also be called vegetated filter strips.

The processes in riparian areas affecting pollutant transport and fate are complex and often interrelated. Riparian areas can slow surface runoff and increase infiltration of water into the soil, thereby enhancing both deposition of solids and filtration of water-borne pollutants. Riparian areas also intercept and act on contaminants in subsurface flow through dilution, sorption, physical transformation, chemical degradation by various biogeochemical processes, and through uptake and assimilation by plants, fungi, and microbes. Hydrology, soils, and vegetation all affect pollutant transport and fate, but for the purposes of riparian area management I focus on vegetation.

Research on pollutant removal by riparian buffers conducted in arid or semi-arid ecoregions is very limited (Hook 2003). I could locate only three such studies (Tate et al. 2000; Fasching and Bauder 2001; Hook 2003), but all three have significant shortcomings. Hook (2003), for instance, simulated sediment-laden run-off from rangeland in western Montana. He reported that 20 ft (6 m) buffers removed at least 94% of sediment regardless of vegetation type in the buffer, but whether these simulations are realistic is unknown because he did not compare his run-off flow volumes and sediment concentrations to values from actual rangeland. Fasching and Bauder (2001), simulated sediment-laden run-off from tilled, bare cropland in central Montana. They found that 40 ft (12 m) wide buffers removed 75 to 80% of sediment during a simulated 50-year 24-hour storm event. However, while the buffer was 40 ft (12 m) wide, the bare cropland was only 15 ft (3 m) wide, which is certainly an unrealistic size for cropland. Tate et al. (2000) measured nitrate-nitrogen, total phosphorus, and suspended solids in run-off from irrigated pastures in the Central Valley of California. They reported that 33 ft (10 m) wide buffers did not significantly reduce nitrate-nitrogen concentration, total phosphorus concentration, or total suspended solid load. However, the strength of their inferences was compromised by extreme variability. Some buffered plots yielded higher concentrations of all three pollutants than unbuffered plots, which they attributed to differences in soil and microtopography among plots.

Despite the large quantity of research conducted around the world, no widely accepted recommendations have emerged on minimum buffer widths needed to protect water quality. The lack of agreement amongst scientists is due, in part, to the surprising complexity of the biogeochemical processes that remove pollutants from surface and subsurface flows, the many different environmental conditions among research sites, the variety of methods used to study pollutant removal, and the shortcomings of some research (as described above). One way to cut through this variability and develop quantitative relationships between buffer width and pollutant removal efficacy is meta-analysis.[17] I found five such meta-analyses in the literature (Mayer et al. 2007; Liu et al. 2008; Yuan et al. 2009; Zhang et al. 2010; Sweeney and Newbold 2014).

The number of studies in the five meta-analyses ranged from to 52 to 88. I could determine the geographic locations of all studies included in four of the meta-analyses; only one study was conducted in an arid or semi-arid region (i.e., Tate et al. 2000, cited in Zhang et al. 2010). Four meta-analyses analyzed sediment studies, three meta-analyses analyzed nitrogen studies, and 1 one meta-analysis (Zhang et al. 2010) analyzed phosphorus and pesticide studies. All meta-analyses show that: 1) removal efficacy increases as buffer width increases, 2) removal efficacy varies among pollutants, and 3) relationships between buffer width and removal efficacy follow a nonlinear law of diminishing returns. In other words, the marginal removal efficacy decreases as buffer width increases. Comparing the four pollutants, buffer width that resulted in 90% removal was narrowest for sediment and widest for nitrogen (surface and subsurface combined). See Chapter 5 for a complete summary of their results.

17 Meta-analysis refers to various approaches for drawing statistical inferences from many separate but similar experiments (Mann 1990).

Only one study from arid or semi-arid ecoregions was included in the meta-analyses. Therefore, actual removal efficacy versus buffer width relationships may be quite different for riparian buffers in the Columbia Plateau. Differences in soil, hydrology, and vegetation between arid or semi-arid ecoregions and other ecoregions are significant, and are likely to affect pollutant removal. Because soils in arid ecoregions with biological crusts may be less permeable (Warren 2014) and vegetation tends to be less dense, especially in the upland zone of influence, the meta-analyses may underestimate buffer widths needed for a given level of removal efficacy. This issue can only be resolved through research on pollutant removal by dryland riparian areas.

7.4.6. Alluvial Water Storage

Alluvial water storage, also known as bank storage, is an ecological function of riparian areas that is thought to be especially important for small streams in dryland ecoregions (Pollock et al. 2003). However, the idea that alluvium can supply enough water to maintain base flows is controversial because empirical data to support it are lacking (S. Wondzell, U.S. Forest Service, personal communication).

Alluvial water storage is thought to be part of a cyclic process. During annual floods, stream stage exceeds water table elevation, and surface waters flow into shallow alluvial aquifers (Winter et al. 1998). During the dry season, as stream stage declines, water flow reverses from aquifers to surface water, and the released water may comprise a substantial portion of the stream's base flow (Brunke and Gonser 1997; Whiting and Pomerants 1997). By absorbing some floodwaters, alluvial aquifers may also reduce the impacts of flood events (Whiting and Pomerants 1997). The water volume in bank storage depends on the duration of flooding, the area of inundated floodplain, hydraulic gradients between surface water and the aquifer, soil infiltration rate, the permeability and porosity of alluvial sediments, floodplain width, and thickness of the bank storage layer (Whiting and Pomerants 1997; Chen and Chen 2003).



Autumn foliage, brown grass, and low flows annually coincide in Columbia Plateau Ecoregion/Scott Fitkin, WDFW



Alluvial fans, such as these emanating from side canyons, store water from spring snow melt that contributes to a river's base flow during the dry season/Scott Fitkin, WDFW

On the semi-arid plains of Alberta, Meyboom (1961) found that groundwater released from bank storage is a substantial portion of dry-season stream flow in the Elbow River. Bank storage was 73% of total groundwater discharge during normal base-flow recession, and during late summer, discharge from bank storage comprised 50 to 70% of the river's daily mean discharge. On the eastern edge of the Great Plains in central Iowa, Kunkle (1968) determined that base flow characteristics of Four Mile Creek were related mainly to the adjacent alluvial sand reservoir. Bank storage discharge accounted for 37 to 42% of the annual base flow.

Hydrological studies in the Yakima River basin (Synder and Stanford 2001, and studies cited therein) have suggested that prior to irrigation projects extensive exchange between surface and ground waters occurred in riparian areas and floodplains. Annual inundation of floodplains, including riparian areas, would recharge shallow surficial aquifers, including the alluvial aquifer. Synder and Stanford (2001) asserted for the Yakima River, "Based on fundamental hydrologic principles, there is no question that groundwater recharge of this nature would not only have maintained base flows, but would have provided areas of cooler thermal refugia." A salient characteristic of alluvial water

storage is residence time, which can vary from days to years, depending upon floodplain width and hydraulic connectivity of alluvial sediments (Whiting and Pomereants 1997). The historical hydrology of rivers in the Columbia Plateau was water entered alluvial aquifers during spring peak flows and exited the aquifer weeks later during the low flows of late summer and fall of that same year (Synder and Stanford 2001). The historical timing and magnitudes of aquifer recharge and discharge may have been altered by dams, diversions, and levees.

Riparian and floodplain vegetation affect alluvial water storage in four ways. First, vegetation may reduce water storage through evapotranspiration. In fact, removing riparian vegetation can increase annual water yield from a watershed (Salemi et al. 2012). However, the timing of the additional surface water may not coincide with annual low flows when it is most needed. Second, through root growth and decay, vegetation creates soil macropores that increase soil permeability (Fisher and Binkley 2000) and thus enhance infiltration of floodwaters. Third, vegetation increases the residence time of floodwaters in floodplains by increasing surface roughness (Thomas and Nisbet 2007). The increased residence time provides more time for floodwaters to percolate through soils and into the alluvial aquifer. Vegetation increases surface roughness through stems, organic litter, large woody debris, and by altering micro-topography. Fourth, riparian vegetation helps to maintain cooler temperatures of shallow groundwater. Heat conduction from the soil surface into groundwater affects groundwater temperatures. Consequently, shallow groundwater temperatures are cooler in winter and warmer in summer. During the summer, shade from riparian vegetation and the riparian microclimate, which is cooler than adjacent uplands, may result in cooler groundwater. Stanford et al. (2002), for example, collected data suggesting that intact riparian forest moderated the rate of increase in groundwater temperatures along several reaches of the Yakima River.

Alluvial aquifers typically underlie floodplains (Vaccaro 2011), including riparian areas. The alluvial water storage function of floodplains has been degraded by dams that reduce flood magnitudes, levees that reduce the area of flooding, and the channelization or loss of distributary channels across alluvial fans. To replace natural recharge pathways, water managers are trying artificial recharge of shallow alluvial aquifers (USBR & WDOE 2012; WWBWC 2013). While artificial recharge may replace the aquifer recharge function of floods, it cannot replace the fluvial disturbances caused by flooding that are needed to maintain riparian vegetation and aquatic habitats.

7.5. Conclusions

The goal for riparian areas of the Columbia Plateau Ecoregion is the same as the goal for forested ecoregions—maintain or restore key ecological functions. However, management to achieve that goal is more complicated in dryland riparian areas for three reasons. First, there is a greater diversity of plant communities within riparian ecosystems of the Columbia Plateau than in the surrounding forested ecoregions—the vegetation heights of dryland riparian ecosystems range from sedges to tall trees. Several key ecological functions of riparian areas—namely, shade, wood, and detrital nutrients for aquatic habitats—are dependent on vegetation height. The other three functions—bank stability, pollutant removal, and alluvial water storage—are largely dependent on processes occurring at or below the soil surface. In forested ecoregions, the total capacity of a riparian area to provide five of the key functions typically occurs within a site-potential tree height (FEMAT 1993). In other words, with respect to aquatic habitats, full function for five of the key riparian ecological functions is typically provided by an area that is one site-potential tree height wide.[18]

[18] Site-potential" is a concept related to forest productivity. A site's productivity is often expressed as the height a particular tree species growing on that site is expected to attain by a specified age. FEMAT (1993) defined site-potential tree height as the average maximum height of the tallest dominant trees (200 years old or greater).

In dryland ecoregions, the width of the riparian ecosystem is based on the ecological function that creates the widest zone of influence. At most sites, this will be either the wood (large and small) or pollutant removal functions. For grass, herb, shrub, and small tree vegetation types, the zone of influence based on wood, which depends on vegetation height, will be narrower than the zone of influence based on pollutant removal. Therefore, if pollutants, including sediments due to ground disturbance, are a concern at a particular site, then riparian ecosystem width should be based on the desired removal efficacy for pollutants created at that site. If, for instance, surface run-off containing excess nitrogen is a concern and a 95% removal is desired, then the zone of influence is 170 ft (52 m) wide, measured from the active channel, see Table 5.4. If pollutant removal is not a concern, then riparian ecosystem width should be based on site-potential vegetation height (i.e., trees or shrubs), which should provide maximum wood and shade for aquatic habitats.



Some trees (Pinus ponderosa) *have all the luck/Scott Fitkin, WDFW*

The second reason management of riparian ecosystems is more complicated in the Columbia Plateau Ecoregion is water. The existence of dryland riparian areas depends on soil moisture and water table elevations. Many dryland riparian plant communities evolved under an annual hydrological cycle of flooding followed by gradual recession of stream flows. This cycle has been disrupted by dams and water diversions. The consequences of water management on riparian areas were documented by Braatne et al. (2007) who found an unsustainable age-class distribution of cottonwoods along the Yakima River. Two long-term impacts for these reaches of the Yakima could be reductions in shade and large wood for aquatic habitats. Water management is likely to have caused adverse changes to riparian plant communities along other rivers and streams in the Columbia Plateau. Under state law (RCW 90.03), in-stream flows are managed only to maintain flows above a specified minimum flow. Little consideration is given to mimicking the natural seasonal hydrograph for the sake of riparian ecosystems. To restore riparian ecosystems and aquatic habitats in the Columbia Plateau, that may need to change.

Third, management will be more complicated because many riparian areas in the Columbia Plateau have been highly altered by human activities, and ecologists do not know their historical or "properly functioning" conditions. Lacking such information will hamper the success of site-scale riparian restoration projects and regional restoration plans. An initial step toward grappling with this issue might be a subregional or WRIA-level mapping of potential riparian vegetation types. The mapping could include the capacity to support Beaver (e.g., Macfarlane et al. 2017) and the vegetation that would develop in the presence of Beaver. The map would serve three purposes: 1) a vegetation guide for riparian restoration projects, 2) a historical baseline for fish habitat conditions in the Columbia Plateau, and 3) habitat restoration objectives for the recovery of salmon and other aquatic species.

Historical information on riparian areas will serve three other purposes. First, knowledge of historical conditions will enable an accounting of lost ecosystem services. The losses incurred by fisheries are well recognized, but losses of wildlife, both game and nongame species, due to altered riparian areas have not been rigorously evaluated. Another major ecosystem service is the contribution to perennial stream flow from short-term storage of water in shallow alluvial aquifers that lie beneath floodplains (USBR & WDOE 2012; WWBWC 2013). Losses of this ecosystem service caused by disconnecting floodplains from streams also have not been rigorously evaluated. Second, knowledge of historical conditions may enable an estimate of the past quantity and quality of salmon habitats. Historical knowledge of past salmon habitats can be used in salmon recovery plans to establish habitat restoration objectives and priorities. The third purpose is partly political. Knowledge of past habitat loss can influence policy decisions to conserve remaining habitats or to restore habitats where practicable.

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7.7. Literature Cited[19]

Adam, S. 2004. Appendix E *in* B.E. Jamison and M.F. Livingston. Sage-Grouse habitat evaluation in the shrub-steppe ecosystem of the Yakama Reservation. Project final report. Wildlife, Range & Vegetation Resources Management Program, Confederated Tribes and Bands of the Yakama Nation, Toppenish, Washington. (vii)

AP (Associated Press). 2012. Umatilla tribes hope to trim wild horse numbers without slaughtering any. Available: http://www.oregonlive.com/pacific-northwest-news/index.ssf/2012/10/umatilla_tribes_hope_to_trim_w.html. (February 2018). (vii)

Anderson, E.W. 1987. Riparian area definition – a viewpoint. Rangelands 9(2):70. (i)

Bailey, R.G. 1995. Description of the ecoregions of the United States (2nd ed.). Misc. Pub. No. 1391. U.S. Forest Service, Washington, D.C. (viii)

Baker, B.W., H.C. Ducharme, D.C.S. Mitchell, T.R. Stanley, and H.R. Peinetti. 2005. Interaction of Beaver and Elk herbivory reduces standing crop of willow. Ecological Applications 15:110–118. (i)

Barling, R.D., and I.D. Moore. 1994. Role of buffer strips in management of waterway pollution: a review. Environmental Management 18:543-558. (i)

Barnes, D.M., and A.U. Mallik. 1996. Use of woody plants in construction of Beaver dams in northern Ontario. Canadian Journal of Zoology 74:1781-1786. (i)

Beechie, T.J., M.M. Pollock, and S. Baker. 2008. Channel incision, evolution and potential recovery in the Walla Walla and Tucannon River basins, northwestern USA. Earth Surface Processes and Landforms 33:784–800. (i)

Belnap, J., J.R. Welter, N.B. Grimm, N.N. Barger, and J.A. Ludwig. 2005. Linkages between microbial and hydrologic processes in arid and semi-arid watersheds. Ecology 86:298–307. (i)

Belsky, A.J., A. Matzkem, and S. Uselman. 1999. Survey of livestock influences on stream and riparian ecosystems in the western United States. Journal of Soil and Water Conservation 54:419-431. (i)

Benfield, E.F. 1997. Comparisons of litterfall input to streams. Journal of the North American Benthological Society 16:104-108. (i)

Beschta, R.L., and W.J. Ripple. 2016. Riparian vegetation recovery in Yellowstone: the first two decades after Wolf reintroduction. Biological Conservation 198:93-103. (i)

Bilby, R.E., and J.T. Heffner. 2016. Factors influencing litter delivery to streams. Forest Ecology and Management 369:29-37. (i)

Bisson, P.A., R.E. Bilby, M.D. Bryant, C.A. Dollof, G.B. Grette, R.A. House, M.L. Murphy, K.V. Koski, and J.R. Sedell. 1987. Large woody debris in forested streams in the Pacific Northwest: past, present, and future. Pages 143-190 *in* E.O. Salo and T.W. Cundy, editors. Streamside management: forestry and fishery interactions. Contribution No. 57. Institute of Forest Resources, University of Washington, Seattle. (i)

Black, A.E., E. Strand, P. Morgan, J.M. Scott, R.G. Wright, and E. Watson. 1998. Biodiversity and land-use history of the Palouse bioregion: pre-European to present. Pages 85-99 *in* T.D. Sisk, editor. Perspectives on the land use history of North America: a context for understanding our changing environment. Biological Science Report USGS/BRD/BSR-1998-0003. U.S. Geological Survey, Reston, Virginia. (viii)

Blersch, D.M., and P.C. Kangas. 2014. Signatures of self-assembly in size distributions of wood members in dam structures of *Castor Canadensis*. Global Ecology and Conservation 2:204-213. (i)

Bohn, C. 1986. Biological importance of streambank stability. Rangelands 8(2):55-56. (i)

Braatne, J.H., R. Jamieson, K.M. Gill, and S.B. Rood. 2007. Instream flows and the decline of riparian cottonwoods along the Yakima River, Washington, USA. River Research and Applications 23:247–267. (i)

[19] References are classified according to RCW 34.05.271 (see Appendix 1) denoted by a lower case roman numeral (i – viii) in parentheses at the end of the citation.

Braatne, J.H., S.B. Rood, and R.E. Heilman. 1996. Life history, ecology and conservation of riparian cottonwoods in North America. Pages 57-85 *in* R.F. Stettler, H.D. Bradshaw, P.E. Heilman, and T.M. Hinckley, editors. Biology of *Populus* and its implications for management and conservation. NRC Research Press, Ottawa, Ontario. (i)

Brunke. M., and T. Gonser. 1997. The ecological significance of exchange processes between rivers and groundwater. Freshwater Biology 37:1-33. (i)

Bryce, S.A., and J.M. Omernik. 1997. Level IV ecoregions of the Columbia Plateau Ecoregion of Oregon, Washington, and Idaho. Pages 11-22 *in* S.E. Clark and S.A. Bryce, editors. Hierarchical subdivisions of the Columbia Plateau and Blue Mountains ecoregions. PNW-GTR-395. U.S. Forest Service, Pacific Northwest Forest Station, Portland, Oregon. (viii)

Buckley, G.L. 1993. Desertification of the Camp Creek drainage in central Oregon. Yearbook of the Association of Pacific Coast Geographers 55:91-126. (i)

Campbell, A.G., and J.F. Franklin. 1979. Riparian vegetation in Oregon's western Cascade Mountains: composition, biomass, and autumn phenology. Bulletin No. 14. Coniferous Forest Biome Ecosystem Analysis Studies, University of Washington, Seattle. (i)

Carlson, N.K. 1940. The history of grazing and livestock development in the Pacific Northwest. Range Division, Region 9, Soil Conservation Service. (viii)

Case, T.L., and J.B. Kauffman. 1997. Wild ungulate influence on the recovery of willows, Black Cottonwood, and Thin-Leaf Alder following cessation of cattle grazing in northeastern Oregon. Northwest Science 71:115-126. (i)

Chen, X., and X. Chen. 2003. Stream water infiltration, bank storage, and storage zone changes due to stream fluctuations. Journal of Hydrology 280:246-264. (i)

Collen, P., and R.J. Gibson. 2001. The general ecology of beavers (*Castor* spp.), as related to their influence in stream ecosystems and riparian habitats, and the subsequent effects on fish – a review. Reviews in Fish Biology and Fisheries 10:439–461. (i)

Compton, J.E., M.R. Church, S.T. Larned, and W.E. Hogsett. 2003. Nitrogen export from forested watersheds of the Oregon Coast Range: the role of N_2-fixing Red Alder. Ecosystems 6:773–85. (i)

Conners, M.E., and R.J. Naiman. 1984. Particulate allochthonous inputs: Relationships with stream size in an undisturbed watershed. Canadian Journal of Fisheries and Aquatic Sciences 41:1473–1488. (i)

Cooke, H.A., and S. Zack. 2008. Influence of Beaver dam density on riparian areas and riparian birds in shrubsteppe of Wyoming. Western North American Naturalist 68:365-373. (i)

Corenblit, D., E. Tabacchi, J. Steiger, and A.M. Gurnell. 2007. Reciprocal interactions and adjustments between fluvial landforms and vegetation dynamics in river corridors: a review of complementary approaches. Earth-Science Reviews 84: 56-86. (i)

Crawford, R.C. 2003. Riparian vegetation classification of the Columbia Basin, Washington. Natural Heritage Program Report 2003-03. Washington Department Natural Resources. Olympia, Washington. (viii)

Cristea, N., and J. Janisch. 2007. Modeling the effects of riparian buffer width on effective shade and stream temperature. Ecology Publication No. 07-03-028. Environmental Assessment Program, Washington State Department of Ecology, Olympia, Washington. (viii)

Cushing, C.E. 1988. Allochthonous detritus inputs to a small, cold desert spring-stream. Vereinigung fur Theoretische und Angewandte Limnologie 23:1107-1113. (i)

Cushing, C.E., and E.G. Wolf. 1982. Organic energy budget of Rattlesnake Springs, Washington. American Midland Naturalist 107:404-407. (i)

Cushing, C.E., and E.G. Wolf. 1984. Primary production on Rattlesnake Springs, a cold desert spring-stream. Hydrobiologica 114:229-236. (i)

Daubenmire, R.F. 1942. An ecological study of the vegetation of southeastern Washington and adjacent Idaho. Ecological Monographs 12:53-79. (i)

Daubenmire, R.F. 1970. Steppe vegetation of Washington. Washington State Experimental Station Technical Bulletin 62. Washington State University Cooperative Extension, Pullman, Washington. (viii)

Denfeld, D.C. 2011. Fort Walla Walla. Essay 9649, HistoryLink.org. Available: http://www.historylink.org/File/9649. (January 2019). (viii)

Dosskey, M.G., P. Vidon, N.P. Gurwick, C.J. Allan, T.P. Duval, and R. Lowrance. 2010. The role of riparian vegetation in protecting and improving chemical water quality in streams. Journal of the American Water Resources Association 46:261-277. (i)

Doty, S.L., B. Oakley, G. Xin, J.W. Kang, G.L. Singleton, Z. Khan, A. Vajzovic, and J.T. Staley. 2009. Diazotrophic endophytes of native Black Cottonwood and willow. Symbiosis 47:23–33. (i)

Dremmer, R., and R.L. Beschta. 2008. Recent history (1988-2004) of Beaver dams along Bridge Creek in central Oregon. Northwest Science 82:309-318. (i)

Ebersole, J. L., W.J. Liss, and C.A. Frissell. 2003a. Thermal heterogeneity, stream channel morphology, and salmonid abundance in northeastern Oregon streams. Canadian Journal of Fisheries and Aquatic Sciences 60:1266-1280. (i)

Ebersole, J. L., W.J. Liss, and C.A. Frissell. 2003b. Cold water patches in warm streams: physicochemical characteristics and the influence of shading. Journal of the American Water Resources Association 39:355-368. (i)

Evans, S. 1989. Provisional riparian and aquatic wetland plant communities on the Columbia Plateau. Report prepared under contract No. C0089098. Report to Washington Department of Ecology. Natural Heritage Program, Washington Department of Natural Resources, Olympia, Washington. (viii)

Fasching, R.A., and J.W. Bauder. 2001. Evaluation of agricultural sediment load reductions using vegetative filter strips of cool season grasses. Water Environment Research 73:590-596.

FEMAT (Forest Ecosystem Management Assessment Team). 1993. Forest ecosystem management: an ecological, economic, and social assessment. United States Department of Agriculture and United States Department of Interior, Portland, Oregon. (viii)

Finley, W.L. 1937. The Beaver – conserver of soil and water. Pages 295-297 *in* Transactions of the Second North American Wildlife Conference. American Wildlife Institute, Washington, D.C. (viii)

Fisher, S.G. 1995. Stream ecosystems of the western United States. Pages 61-87 *in* C.E. Cushing, K.W. Cummins, and G.W. Minshall, editors. River and stream ecosystems of the world. University of California Press, Berkley, California. (i)

Fisher, R.F., and D. Binkley. 2000. Ecology and management of forest soils. Wiley, New York.

Florsheim, J.L., J.F. Mount, and A. Chin. 2008. Bank erosion as a desirable attribute of rivers. BioScience 58:519-529. (i)

Fonda, R.W. 1974. Forest succession in relation to river terrace development in Olympic National Park, Washington. Ecology 55:927-942. (i)

Fox, M., and S. Bolton. 2007. A regional and geomorphic reference for quantities and volumes of instream wood in unmanaged forested basins of Washington State. North American Journal of Fisheries Management 27:342-359. (i)

Franklin, J.F., and C.T. Dyrness. 1988. Natural vegetation of Oregon and Washington. Oregon State University Press, Corvallis, Oregon. (i)

Galbraith, W.A., and E.W. Anderson. 1971. Grazing history of the Northwest. Journal of Rangeland Management 24:6-12. (i)

Gebauer, A.D., R. Brown, S. Schwab, C. Nezat, and C. McNeely. 2015. Effects of an invasive grass (*Phalaris Arundinacea*) on water availability in semi-arid riparian zones. Wetlands 36:59–72. (i)

Giblin, D. 2006. Russian Olive, *Elaeagnus angustifolia*. Pages 78–79 *in* P.D. Boersma, S.H. Reichard, and

A.V. van Buren, editors. Invasive species in the Pacific Northwest. University of Washington Press, Seattle. (i)

Gibson, P.P., and J.D. Olden. 2014. Ecology, management, and conservation implications of North American Beaver (*Castor canadensis*) in dryland streams. Aquatic Conservation: Marine and Freshwater Ecosystems 24:391-409. (i)

Gibson, P.P., J.D. Olden, and M.W. O'Neill. 2015. Beaver dams shift desert fish assemblages toward dominance by non-native species (Verde River, Arizona, USA). Ecology of Freshwater Fish 24:355–372. (i)

Gregory, S.V., F.J. Swanson, W.A. McKee, and K.W. Cummins. 1991. An ecosystem perspective of riparian zones. Bioscience 41: 540–551. (i)

Griffin, E., J. Kean, K. Vincent, J. Smith, and J. Friedman. 2005. Modeling effects of bank friction and woody bank vegetation on channel flow and boundary shear stress in the Rio Puerco, New Mexico. Journal of Geophysical Research 110:F04023. (i)

Gurnell, A. 2014. Plants as river system engineers. Earth Surface Processes and Landforms 39:4-25. (i)

Hickey, M.B., and B. Doran. 2004. A review of efficiency of buffer strips for the maintenance and enhancement of riparian ecosystems. Water Quality Research Journal of Canada 39:311-317. (i)

Higgs, E., D.A. Falk, A. Guerrini, M. Hall, J. Harris, R.J. Hobbs, S.T. Jackson, J.M. Rhemtulla, and W. Throop. 2014. The changing role of history in restoration ecology. Frontiers in Ecology and the Environment 12:499–506. (i)

Hood, W.G., and R.J. Naiman. 2000. Vulnerability of riparian zones to invasion by exotic vascular plants. Plant Ecology 148:105-114. (i)

Hook, P.B. 2003. Sediment retention in rangeland riparian buffers. Journal of Environmental Quality 32:1130-1137. (i)

Hough-Snee, N., B.B. Roper, J.M. Wheaton, and R.L. Lokteff. 2015. Riparian vegetation communities of the American Pacific Northwest are tied to multi-scale environmental filters. River Research and Applications 31:1151-1165. (i)

Hultine, K.R., and S.E. Bush. 2011. Ecohydrological consequences of non-native riparian vegetation in the southwestern United States: A review from an ecophysiological perspective. Water Resources Research 47: W07542. (i)

Hupp, C.R., and W.R. Osterkamp. 1996. Riparian vegetation and fluvial geomorphic processes. Geomorphology 14:277-295. (i)

Johnson, D.R., and D.H. Chance. 1974. Presettlement overharvest of upper Columbia River Beaver populations. Canadian Journal of Zoology 52:1519-1521. (i)

Jones, A. 2000. Effects of cattle grazing on North American arid ecosystems: a quantitative review. Western North American Naturalist 60:155-164. (i)

Kaiser, V.G. 1961. Historical land use and erosion in the Palouse – a reappraisal. Northwest Science 35:139-153. (i)

Katz, G.L., and P.B. Shafroth. 2003. Biology, ecology and management of *Elaeagnus angustifolia* L. (Russian Olive) in western North America. Wetlands 23:763-777. (i)

Kauffman, J.B., R.L. Beschta, N. Otting, and D. Lytjen. 1997. An ecological perspective of riparian and stream restoration in the western United States. Fisheries 22:12-24. (i)

Kauffman, J.B., and W.C. Krueger. 1984. Livestock impacts on riparian ecosystems and streamside management implications: a review. Journal of Range Management 37:430-438. (i)

Kunkle, G.R. 1968. A hydrogeologic study of the ground-water reservoirs contributing base runoff to Four Mile Creek, east-central Iowa. Geological Survey Water-Supply Paper 1839-O. U.S. Geological Survey, Washington, D.C. (i)

KWA. 2004. Crab Creek subbasin plan. KWA Ecological Sciences Inc., Duvall, Washington. (viii)

Latterell, J.J., and R.J. Naiman. 2007. Sources and dynamics of large logs in a temperate floodplain river. Ecological Applications 17:1127-1141. (i)

Lesica, P., and S. Miles. 1999. Russian olive invasion into cottonwood forests along a regulated river in north-central Montana. Canadian Journal of Botany 77: 1077-1083. (i)

Li, H.W., G.A. Lamberti, T.N. Pearsons, C.K. Tait, and J.L. Li. 1994. Cumulative effects of riparian disturbance along high desert trout streams of the John Day Basin, Oregon. Transactions of the American Fisheries Society 123:627-640. (i)

Lichvar, R.W., N.C. Melvin, M.L. Butterwick, and W.N. Kirchner. 2012. National wetland plant list indicator rating definitions. ERDC/CRREL TN-12-1. U.S. Army Corps of Engineers, Washington, D.C. (viii)

Liu, X., X. Zhan, and M. Zhang. 2008. Majors factors influencing the efficacy of vegetated buffers on sediment trapping: a review and analysis. Journal of Environmental Quality 37:1667-1674. (i)

Liquori, M., and C.R. Jackson. 2001. Channel response from shrub dominated riparian communities and associated effects on salmonid habitat. Journal of the American Water Resources Association 37:1639-1651. (i)

Loope, L.L., P.G. Sanchez, P.W. Tarr, W.L. Loope, and R.L. Anderson. 1988. Biological invasions of arid land nature reserves. Biological Conservation 44:95-118. (i)

Lorne, L. 1993. Marketing wildlife: the Hudson's Bay Company and the Pacific Northwest, 1821-1849. Forest & Conservation History 37(January):14-24. (i)

Macfarlane, W.W., J.T. Gilbert, M.L. Jensen, J.D. Gilbert, N. Hough-Snee, P.A. McHugh, J.M. Wheaton, and S.N. Bennett. 2017. Riparian vegetation as an indicator of riparian condition: detecting departures from historic condition across the North American West. Journal of Environmental Management 202:447-460. (i)

Macfarlane, W.W., J.M. Wheaton, N. Bouwes, M.L. Jensen, J.T. Gilbert, N. Hough-Snee, and J.A. Shivik. 2017. Modeling the capacity of riverscapes to support Beaver dams. Geomorphology 277:72-99. (i)

Mack, R.N. 1988. First comprehensive botanical survey of the Columbia Plateau, Washington: the Sandberg and Leiberg Expedition of 1893. Northwest Science 62:118-128. (i)

Mack, R.N., and J.N. Thompson. 1982. Evolution in steppe with few large, hooved mammals. American Naturalist 119:757-773. (i)

Mann, C. 1990. Meta-analysis in the breech. Science 249:476-480. (i)

Mapes, L.V. 2010. Northwest tribes seek solutions to unwanted horses. The Seattle Times. Available: **https://www.seattletimes.com/seattle-news/northwest-tribes-seek-solutions-to-unwanted-horses/**. (February 2018). (viii)

Martinez, A.E., and P.F. McDowell. 2016. Invasive Reed Canarygrass (*Phalaris arundinacea*) and native vegetation roughness. Invasive Plant Science and Management 9:12-21. (i)

Mayer, P.M., S.K. Reynolds, M.D. Marshall, D. McCutchen, and T.J. Canfield. 2007. Meta-analysis of nitrogen removal in riparian buffers. Journal of Environmental Quality 36:1172-1180. (i)

McAllister, L.S. 2008. Reconstructing historical riparian conditions for two river basins in eastern Oregon, USA. Environmental Management 42:412-425. (i)

McKee, A., G. LaRoi, and J.F. Franklin. 1982. Structure, composition, and reproductive behavior of terrace forests, South Fork Hoh River, Olympic National Park. Pages 22-29 *in* E.E. Starkey, J.F. Franklin, and J.W. Matthews, technical coordinators. Ecological Research in National Parks of the Pacific Northwest. Oregon State University Research Laboratory Publication, Corvallis, Oregon. (i)

Meinig, D.W. 1968. The great Columbia Plain: a historical geography. University of Washington Press, Seattle, Washington. (i)

Meinzer, O.E. 1923. Outline of ground-water hydrology. Water Supply Paper 494. U.S. Geological Survey, Washington, D.C. (i)

Meyboom, P. 1961. Estimating ground-water recharge from stream hydrographs. Journal of Geophysical Research 66:1203-1214. (i)

Micheli, E.R., and J.W. Kirchner. 2002. Effects of wet meadow riparian vegetation on streambank erosion. 2. Measurements of vegetated bank strength and consequences for failure mechanics. Earth Surface Processes and Landforms 27:687–697. (i)

Minckley, W.L., and J.N. Rinne. 1985. Large woody debris in hot-desert streams: an historical overview. Desert Plants 7(3):142-153. (i)

Murphy, M.L. 1998. Primary productivity. Pages 144-168 *in* R.J. Naiman and R.E. Bilby, editors. River ecology and management: lessons from the Pacific Coastal Ecoregion. Springer-Verlag, New York. (i)

Naiman, R.J., and R.E. Bilby, editors. 1998. River ecology and management: lessons from the Pacific Coastal Ecoregion. Springer-Verlag, New York. (i)

Naiman, R.J., R.E. Bilby, D.E. Schindler, and J.M. Helfield. 2002. Pacific salmon, nutrients, and the dynamics of freshwater and riparian ecosystems. Ecosystems 5:399-417. (i)

Naiman, R.J., T.J. Beechie, L.E. Benda, D.R. Berg, P.A. Bisson, L.H. MacDonald, M.D. O'Conner, P.L. Olsen, and E.A. Steel. 1992. Fundamental elements of ecologically healthy watersheds in the Pacific Northwest Coastal Ecoregion. Pages 127-188 *in* R.J. Naiman, editor. Watershed management: balancing sustainability and environmental change. Springer, New York. (i)

Naiman, R.J., C.A. Johnston, and J.C. Kelley. 1988. Alteration of North American streams by Beaver. BioScience 38:753-762. (i)

Naiman, R.J., and J.R. Sedell. 1980. Relationships between metabolic parameters and stream order in Oregon. Canadian Journal of Fisheries and Aquatic Sciences 37:834-847. (i)

NTHC (Northwest Tribal Horse Coalition). no date. Managing excess feral horses in the Inland Northwest. Available: **https://www.ynwildlife.org/Wildhorsecoalition.php.** (February 2018). (viii)

Ohmart, R.D. 1996. Historical and present impacts of livestock grazing on fish and wildlife resources in western riparian habitats. Pages 245-279 in P.R. Krausman, editor. Rangeland wildlife. Society for Range Management, Denver, Colorado. (i)

Olson, D.M., E. Dinerstein, E.D. Wikramanayake, N.D. Burgess, G.V.N. Powell, E.C. Underwood, J.A. D'Amico, H.E. Strand, J.C. Morrison, C.J. Loucks, T.F. Allnutt, J.F. Lamoreux, T.H. Ricketts, I. Itoua, W.W. Wettengel, Y. Kura, P. Hedao, and K. Kassem. 2001. Terrestrial ecoregions of the world: A new map of life on Earth. BioScience 51:933-938. (i)

Omernik, J.M. 1987. Ecoregions of the conterminous United States. Annals of the Association of American Geographers 77(1):118-125. (i)

Omernik, J.M. and A.L. Gallant. 1986. Ecoregions of the Pacific Northwest. EPA/600/3-86/033. U.S. Environmental Protection Agency, Corvallis, Oregon. (i)

Ortolano, L.K., K. Cushing, and contributing authors. 2000. Grand Coulee Dam and the Columbia Basin Project, USA. World Commission on Dams, Cape Town, South Africa. (viii)

Osterkamp, W.R., and C.R. Hupp. 2010. Fluvial processes and vegetation – glimpses of the past, the present, and perhaps the future. Geomorphology 116:274-285. (i)

Ott, J. 2003. "Ruining" the rivers in the Snake country. Oregon Historical Quarterly 104(2):166-195. (i)

Pabst, R.J., and T.A. Spies. 1999. Structure and composition of unmanaged riparian forests in the coastal mountains of Oregon, USA. Canadian Journal of Forest Research 29:1557-1573. (i)

Parker, M., F.J. Wood, B.H. Smith, and R.G. Elder. 1985. Erosional downcutting in lower order riparian ecosystems: have historical changes been caused by the removal of Beaver? Pages 35-38 in R.R. Johnson, C.D. Ziebell, D.R. Patton, P.F. Ffolliott, R.H. Hamre, editors. Riparian ecosystems and their management: reconciling conflicting uses. RMRS-GTR-RM-120. U.S. Forest Service, Rocky Mountain Forest and Range Experimental Station, Fort Collins, Colorado. (viii)

Patten, D.T. 1998. Riparian ecosystems of semi-arid North America: diversity and human impacts. Wetlands 18:498–512. (i)

Platts, W.S., and R.L. Nelson. 1989. Stream canopy and its relationship to salmonid biomass in the intermountain west. North American Journal of Fisheries Management 9:446-457. (i)

Pollen-Bankhead, N., and A. Simon. 2010. Hydrologic and hydraulic effects of riparian root networks on streambank stability: Is mechanical root-reinforcement the whole story? Geomorphology 116:353-362. (i)

Pollock, M.M., T.J. Beechie, and C.E. Jordan. 2007. Geomorphic changes upstream of Beaver dams in Bridge Creek, an incised stream channel in the interior Columbia River basin, eastern Oregon. Earth Surface Processes and Landforms 32:1174-1185. (i)

Pollock, M.M., T.J. Beechie, J.M. Wheaton, C.E. Jordan, N.Bouwes. N. Weber, and C. Volk. 2014. Using Beaver dams to restore incised stream ecosystems. Bioscience 64:279-290. (i)

Pollock, M.M., M. Heim, and D. Werner. 2003. Hydrological and geomorphic effects of Beaver dams and their influence on fishes. Pages 213-233 in S.V. Gregory, K.L. Boyer, and A.M. Gurnell, editors. The ecology and management of wood in world rivers. American Fisheries Society, Bethesda, Maryland. (i)

Polvi, L.E., E.E. Wohl, and D.M. Merritt. 2014. Modeling the functional influence of vegetation type on streambank cohesion. Earth Surface Processes and Landforms 39:1245-1258. (i)

Polyakov, V., A. Fares, and M.H. Ryder. 2005. Precision riparian buffers for the control of nonpoint source pollutant loading into surface water: a review. Environmental Reviews 13:129-144. (i)

Reidy Liermann, C.A., J.D. Olden, T.J. Beechie, M.J. Kennard, P.B. Skidmore, C.P. Konrad, and H. Imaki. 2012. Hydrogeomorphic classification of Washington state rivers to support emerging environmental flow management strategies. River Research and Applications 28:1340–1358. (i)

Richardson, J.S., R.J. Naiman, F.J. Swanson, and D.E. Hibbs. 2005. Riparian communities associated with Pacific Northwest headwater streams: assemblages, processes, and uniqueness. Journal of the American Water Resources Association 41:935-947.

Robison, G.E., J. Runyon, and C. Andrus. 1999. Cooperative stream temperature monitoring: project completion report for 1994–1995. Forest Practices Technical Report 2, Oregon Department of Forestry, Salem, Oregon. (viii)

Rockie, W.A. 1939. Man's effects on the Palouse. The Geographical Review 29(1):34-45. (i)

Roe, A.L. 1958. Silvics of Black Cottonwood. Miscellaneous Publication 17. U.S. Forest Service, Intermountain Forest and Range Experiment Station, Ogden, Utah. (viii)

Rood, S.B., S.G. Bigelow, M.L. Polzin, K.M. Gill, and C.A. Coburn. 2015. Biological bank protection: trees are more effective than grasses at resisting erosion from major river floods. Ecohydrology 8:772-779. (i)

Salemi, L.F., J.D. Groppo, R. Trevisan, J.M. de Moraes, W. de Paula Lima, and L.A. Martinelli. 2012. Riparian vegetation and water yield: a synthesis. Journal of Hydrology 454–455:195–202. (i)

Salo, E.O., and T.W. Cundy, editors. 1987. Streamside management: forestry and fishery interactions. Contribution No. 57. Institute of Forest Resources, University of Washington, Seattle. (viii)

Scheffer, P.M. 1938. The Beaver as an upstream engineer. Soil Conservation 3:178-181. (i)

Sedell, J.R., F.H. Everest, and D.R. Gibbons. 1989. Streamside vegetation management for aquatic habitat. Pages 115-125 in Proceedings of the National Silviculture Workshop: silviculture for all resources. U.S. Forest Service, Washington, D.C. (i)

Sedell, J.R., and F.J. Swanson. 1984. Ecological characteristics of streams in old-growth forest of the Pacific Northwest. Pages 9-16 in W.R. Meehan, T.R. Merrell, and T.A. Hanley, editors. Fish and wildlife relationships in old-growth forests. American Institute of Fishery Research Biologists. (i)

Simon, A., and A.J.C. Collison. 2002. Quantifying the mechanical and hydrologic effects of riparian vegetation on streambank stability. Earth Surface Processes and Landforms 27:527–546. (i)

Simon, A., N. Pollen, and E. Langendoen. 2006. Influence of two woody riparian species on critical conditions for streambank stability: upper Truckee River, California. Journal of the American Water Resources Association 42:99-113. (i)

Sleeter, B.M. 2012. Columbia Plateau Ecoregion. Pages 299- 236 in B.M. Sleeter, T.S. Wilson, and W. Acevedo, editors. Status and trends of land change in the Western United States – 1973 to 2000: U.S. Geological Survey Professional Paper 1794–A. U.S. Geological Survey, Reston, Virginia.

Stannard, M., and W. Crowder. 2001. Biology, history, and suppression of Reed Canarygrass (Phalaris arundinacea L.). Technical Note Plant Materials No. 40. Natural Resources Conservation Service, Boise, Idaho. (viii)

Stanford, J.A., E.B. Snyder, M.N. Lorang, D.C. Whited, P.L. Matson, and J.L. Chaffin. 2002. The reaches project: ecological and geomorphic studies supporting normative flows in the Yakima River basin, Washington. Flathead Lake Biological Station, Polson, Montana. (viii)

Stoddard, J.L., D.P. Larsen, C.P. Hawkins, R.K. Johnson, and R.H. Norris. 2006. Setting expectations for the ecological condition of streams: the concept of reference condition. Ecological Applications 16:1267–1276. (i)

Snyder, E.B., and J.A. Stanford. 2001. Review and synthesis of river ecological studies in the Yakima River, Washington, with emphasis on flow and salmon habitat interactions. Flathead Lake Biological Station, Polson, Montana. (viii)

Sweeney, B.W., and J.D. Newbold. 2014. Streamside buffer width needed to protect stream water quality, habitat, and organisms: a literature review. Journal of the American Water Resources Association 50:560-584. (i)

Talabere, A.G. 2002. Influence of water temperature and Beaver ponds on Lahontan Cutthroat Trout in a high-desert stream, southeastern Oregon. Master's thesis. Oregon State University, Corvallis. (i)

Tait, C.K., J.L. Li, G.A. Lamberti, T.N. Pearsons, and H.W. Li. 1994. Relationships between riparian cover and the community structure of high desert streams. Journal of the North American Benthological Society 13:45-56. (i)

Tate, K., G. Nader, and D. Lewis. 2000. Evaluation of buffers to improve the quality of runoff from irrigated pastures. Journal of Soil and Water Conservation 55:473–478. (i)

Thomas, F.M. 2014. Ecology of phreatophytes. Progress in Botany 75:335-375. (i)

Thomas, J.W., C. Maser, and J. E. Rodiek. 1979. Wildlife habitats in managed rangelands – the Great Basin of southeastern Oregon: riparian zones. GTR-PNW-80. U.S. Forest Service, Pacific Northwest Experimental Station, Portland, Oregon. (viii)

Thomas, H., and T.R. Nisbet. 2007. An assessment of the impact of floodplain woodland on flood flows. Water and Environment Journal 21:114-126. (i)

Thut, R.N., and E.P. Haydu. 1971. Effects of forest chemicals on aquatic life. Pages 159-171 in J.T. Krygier and J.D. Hall, editors. A symposium on forest land uses and the stream environment. Continuing Education Publications, Oregon State University, Corvallis. (i)

Toledo, Z.O., and J.B Kauffman. 2001. Root biomass in relation to channel morphology of headwater streams. Journal of the American Water Resources Association 37:1653-1663. (i)

Tribal Tribune. 2013. Horses on the landscape. Available: http://www.tribaltribune.com/news/article_3abf8d87-e606-54b1-9e42-5ef6c0fb1036.html. (February 2018). (viii)

Triska, F.J., J.R. Sedell, K. Cromack Jr, S.V. Gregory, and F.M. McCorison. 1984. Nitrogen budget for a small coniferous forest stream. Ecological Monographs 54:119-40. (i)

Tu, M. 2006. Reed Canarygrass, *Phalaris arundinacea*. Pages 12–13 *in* P.D. Boersma, S.H. Reichard, and A.V. van Buren, editors. Invasive species in the Pacific Northwest. University of Washington Press, Seattle. (i)

Tuttle, G.M., G.L. Katz, J.M. Friedman, and A.P. Norton. 2016. Local environmental context conditions the impact of Russian Olive in a heterogeneous riparian ecosystem. Invasive Plant Science and Management 9:272-289. (i)

USACE (U.S. Army Corps of Engineers). 2002. Final Lower Snake River juvenile salmon migration feasibility report/environmental impact statement, Appendix I: Economics. Walla Walla District, Washington. (i)

USBR (U.S. Bureau of Reclamation). 2017a. Yakima Project. Available: https://www.usbr.gov/projects/index.php?id=400. (September 2018). (viii)

USBR (U.S. Bureau of Reclamation). 2017b. Columbia Basin Project. Available: https://www.usbr.gov/projects/index.php?id=438. (September 2018). (viii)

USBR & WDOE (U.S. Bureau of Reclamation and Washington Department of Ecology). 2012. Final programmatic environmental impact statement Yakima River basin integrated water resource management plan. Yakima, Washington. (viii)

USFS (U.S. Forest Service). 2004. Riparian restoration. 0423 1201–SDTDC. Technology & Development Program, San Dimas, California. (viii)

USFWS (U.S. Fish and Wildlife Service). 1994. An ecosystem approach to fish and wildlife conservation. Washington, D.C. (viii)

Vaccaro, J.J. 2011. River-aquifer exchanges in the Yakima River basin, Washington. U.S. Geological Survey, Reston, Virginia. (viii)

Warren, S.D. 2014. Role of biological soil crusts in desert hydrology and geomorphology: implications for military training operations. Reviews in Engineering Geology 22:177-186. (i)

Webb, R.H., and S.A. Leake. 2006. Ground-water and surface-water interactions and long-term change in riverine riparian vegetation in the southwestern United States. Journal of Hydrology 320:302-323. (i)

Weddell, B.J. 2001. Changing perspectives in nineteenth century written descriptions of Palouse and canyon grasslands. Technical Bulletin No. 01-13. Bureau of Land Management, Cottonwood District, Cottonwood, Idaho. (viii)

West, E., and G. Ruark. 2004. A long, long time ago: historical evidence of riparian forests in the Great Plains and how that knowledge can aid with restoration and management. Journal of Soil and Water Conservation 59:105A-110A. (i)

Westbrook, C.J., D.J. Cooper, and B.W. Baker. 2006. Beaver dams and overbank floods influence groundwater-surface water interactions of a Rocky Mountain riparian area. Water Resources Journal 42:W06404. (i)

Westbrook, C.J., D.J. Cooper, and B.W. Baker. 2011. Beaver assisted river valley formation. River Research and Applications 27:247–256. (i)

White, P., and J.L. Walker. 1997. Approximating nature's variation: selecting and using reference information in restoration ecology. Restoration Ecology 5:338-349. (i)

Whiting, P.J., and M. Pomerants. 1997. A numerical study of bank storage and its contribution to streamflow. Journal of Hydrology 202:121-136. (i)

Winter, T.C., J.W. Harvey, O.L. Franke, and W.M. Alley. 1998. Ground water and surface water: a single resource. Circular 1139. U.S. Geological Survey, Denver, Colorado. (viii)

Wissmar, R.C. 2004. Riparian corridors of eastern Oregon and Washington: functions and sustainability along lowland-arid to mountain gradients. Aquatic Sciences 66:373-387. (i)

Wissmar, R.C., J.E. Smith, B.A. McIntosh, H.W. Li, and G.H. Reeves. 1994. A history of resource use and disturbance in riverine basins of eastern Oregon and Washington (early 1800s-1990s). Northwest Science 68 (special issue):1-35. (i)

Wohl, E. 2005. Compromised rivers: understanding historical human impacts on rivers in the context of restoration. Ecology and Society 10(2):2. (i)

Wohl, E., B.P. Bledsoe, R.B. Jacobson, N.L. Poff, S.L. Rathburn, D.M. Walters, and A.C. Wilcox. 2015. The natural sediment regime in rivers: broadening the foundation for ecosystem management. Bioscience 65:358-371. (i)

WSDA (Washington State Department of Agriculture). 2016. Washington State noxious weed general distribution maps. Olympia, Washington. Available: https://agr.wa.gov/washington-agriculture/maps/weed-distribution. (January 2020). (viii)

Wuehlisch, G.V. 2011. Evidence for nitrogen-fixation in the Salicaceae family. Tree Planter Notes 54(2):38-41. (i)

WWBWC (Walla Walla Basin Watershed Council). 2013. Walla Walla basin aquifer recharge strategic plan. Milton-Freewater, Oregon. (viii)

Xiong, S., and C. Nilsson. 1997. Dynamics of leaf litter accumulation and its effects on riparian vegetation: a review. Botanical review 63:240–264. (i)

YN (Yakama Nation). 2010. Wild Horse (K'u-See) Project. Wildlife, Range & Vegetation Resources Management Program, Confederated Tribes and Bands of the Yakama Nation, Toppenish, Washington. Available: https://www.ynwildlife.org/wildhorseprogram.php. (February 2018) (viii)

YSPB (Yakima Subbasin Planning Board). 2004. Yakima subbasin plan. Yakima Subbasin Fish and Wildlife Planning Board, Benton and Yakima counties, Washington. (viii)

Yuan, Y., R.L. Bingner, and M.A. Locke. 2009. A review of effectiveness of vegetative buffers on sediment trapping in agricultural areas. Ecohydrology 2:321-336. (i)

Zhang, X., X. Liu, M. Zhang, and R.A. Dahlgren. 2010. A review of vegetated buffers and a meta-analysis of their mitigation efficacy in reducing nonpoint source pollution. Journal of Environmental Quality 39:76-84. (i)

Zoellick, B.W. 2004. Density and biomass of redband trout relative to stream shading and temperature in southwestern Idaho. Western North American Naturalist 64:18-26. (i)

Chapter 8. Watersheds

By: Derek B. Booth

8.1. Introduction

This chapter on watershed-scale processes and management looks beyond the typical site-by-site perspective at which riparian management and stream protection is normally applied. This chapter also considers the interactions between site-specific treatments, whose collective effects may be greater (or less) than anticipated by the individual actions themselves, and it uses these insights to offer a broader approach to riparian management for the protection of aquatic systems. Given this expanded focus, the conditions and influences discussed here may lie outside the framework of normal guidance and regulatory mandates, but they nonetheless affect the health and productivity of riparian areas and their associated aquatic systems. Thus, the conceptual framework provided here should be useful when considering the likely effects of riparian management policies or practices.

The purpose of this chapter is to explore the relationship (and the importance) of watershed-scale management to achieving the goal of abundant, self-sustaining fish and wildlife populations. It assumes that a broader watershed-scale perspective on aquatic ecosystems will ultimately enhance the beneficial effects of management applied at all scales.

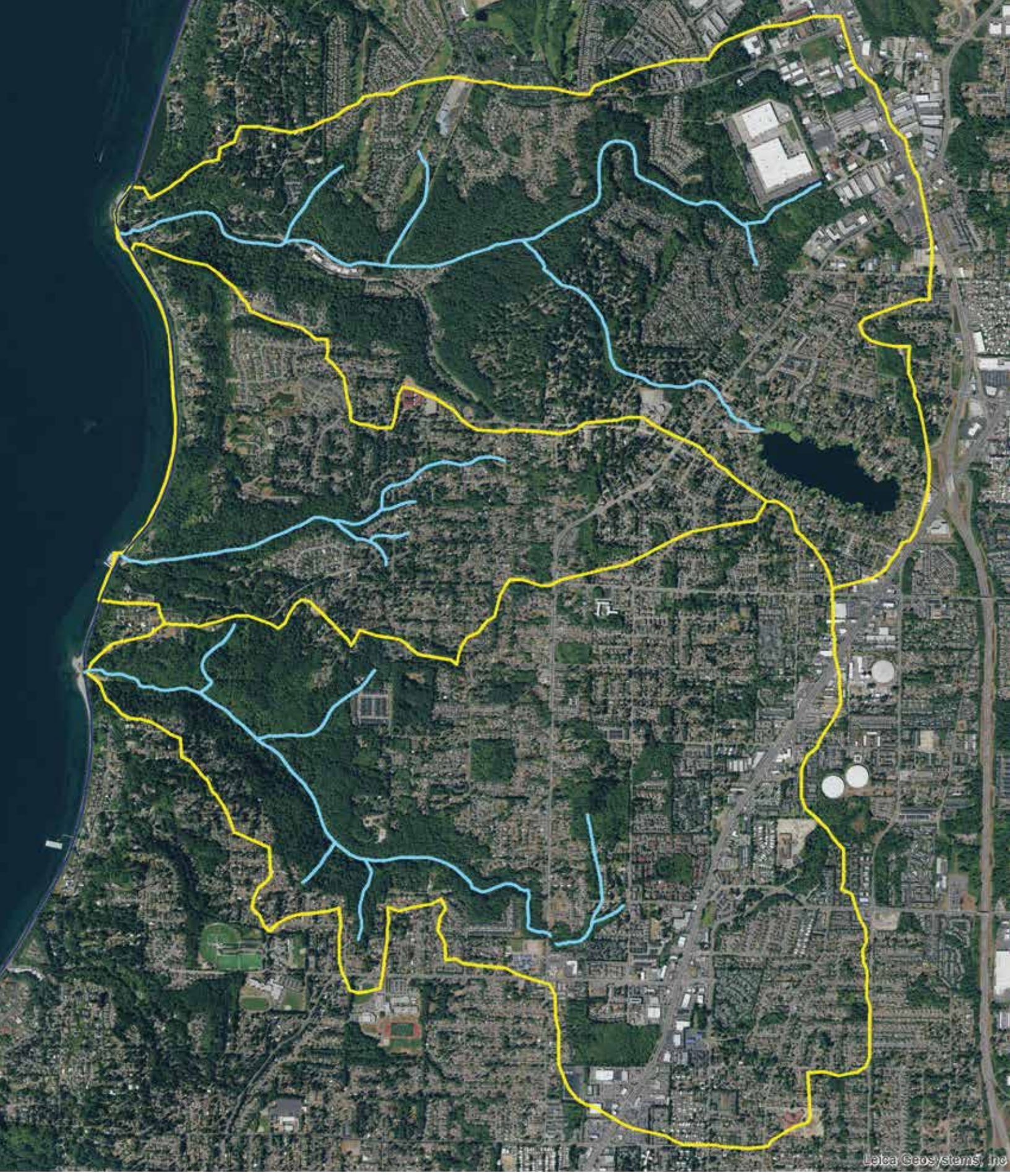
The chapter is divided into four primary sections:

1. A conceptual framework that identifies the key watershed processes and their primary influences on riparian ecosystems and their watercourses, a perspective with a long history in the scientific literature. However, advances in the discipline of landscape ecology over the past two decades—particularly the recognized importance of interrelationships between landscape elements in both spatial (e.g., connectivity and discontinuities) and temporal (e.g., disturbances and recovery) domains—have changed how biological and physical scientists view aquatic ecosystems and the riverine landscape that they occupy.

2. A discussion of how riparian management at the site scale, the emphasis of the other chapters in this document, can best support ecological functions and improve habitat conditions for fish and wildlife, even if a complementary set of watershed-scale management actions (e.g., land use at the watershed scale) cannot be implemented.

3. A description of how individual site-scale management actions, and their recognized site-scale benefits, relate to one another across a channel network and/or landscape. In other words, how do the consequences and overall value/benefit of isolated actions integrate along a channel network? Are the effects of individual actions simply additive, or are there synergistic effects that are revealed by a landscape ecology perspective?

4. Guidance, developed from an understanding of watershed processes and the perspective of landscape ecology, for improving the management of riparian ecosystems. This goal is complicated by the fact that most watersheds are managed under diverse and often uncoordinated responsibility: different landowners and managers have different goals and objectives. Furthermore, many of these managers have neither responsibility nor a process by which to coordinate their



Three watersheds (outlined in yellow) in urban areas of north Seattle/Terry Johnson, WDFW

actions, especially over the long durations necessary for riparian management actions to achieve their greatest effects. This chapter offers no prescription for resolving these challenges, but it proceeds under the belief that greater awareness of these interactions will ultimately lead to more successful protection of riparian systems, streams, and their biota.

8.2. Conceptual Framework

This chapter seeks to integrate the functions of riparian ecosystems into the overall landscape in which they interact–the riverine landscape or *riverscape*. This riverine landscape differs from the contributing watershed of the river or stream: although the flux of water and water-borne biota respect the drainage divides of a watershed almost exactly, other components do not. In particular, mobile organisms (e.g., birds, and large mammals such as American Beaver *Castor canadensis*, and bear (*Ursus* spp.), wind-borne seeds, and wildfire all have the potential to affect and be affected by landscape elements both within and beyond the boundaries of any given watershed, and so they must be included in any comprehensive conceptual framework (Figure 8.1). Despite these watershed-crossing elements, the lotic (flowing-water) environment itself is strongly organized by the unidirectional flow of water, a property that is distinct from terrestrial environments, and so rivers commonly display systematic patterns in the downstream direction (e.g., the "river continuum" of Vannote 1980.) They also display systematic cross-stream patterns, notably the spatial, physical, and ecological relationships between the channel and its adjacent floodplain; and to a less visible but still significant degree in the vertical dimension as well, particularly the interaction of shallow groundwater with stream water in the hyporheic zone (Boulton et al. 1998).

Landscape ecology is the scientific discipline best suited to this larger perspective of the riverine landscape: "...we perceive a need to conceptualize rivers not as sampling points, lines, or gradients, but as spatially continuous longitudinal and lateral mosaics. As such, heterogeneity in the river landscape, or riverscape, becomes the focus of study" (Fausch et al. 2002:485) (Figure 8.2). The foundational premise of landscape ecology is that both biotic and abiotic elements of the landscape interact with one another, and those interactions are spatially mediated (Malanson 1995).

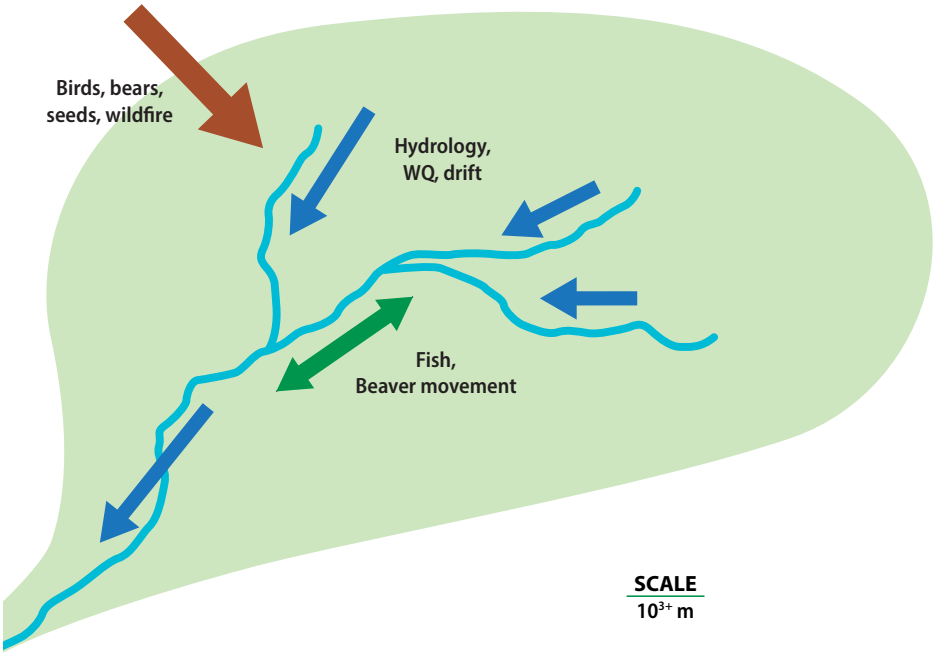


Figure 8.1. Movement of water and biota at the whole-watershed scale. WQ refers to water quality, and drift refers to the downstream transport of bottom-dwelling invertebrates by flowing water.



Figure 8.2. An example of landscape heterogeneity at multiple scales in an aerial view that includes the urban centers of Renton (west edge, labeled a) and Issaquah (northeast corner, b); suburban development throughout the south-central and northwest parts of the image (c); agriculture and rural-residential development, particularly in the valleys of May Creek and McDonald Creek trending NW across the center of the image (d); and extensive forest lands of Cougar, Squak, and Tiger Mountains (e) in the north-central and east parts. At finer spatial scales within the largely undeveloped areas in the eastern part of the image, fragmentation is nonetheless widespread from roads, utility lines, and clearing for residential lots and subdivisions (f).

This perspective emphasizes the importance of spatial heterogeneity; it also acknowledges the key role of episodic disturbances in determining the flux of energy and materials, the movement of organisms, and the creation of unique dynamics within the watershed (Wiens 2002).

At a finer spatial scale, water and biota interact across the permeable and dynamic boundary between riparian areas and a watershed's uplands (Figure 8.3, left panel). These areas comprise multiple components. Within riparian areas, these components include surface waters, in-channel bars and islands, floodplains, marshes, wet meadows, alluvial forests, and woody debris. For the uplands, these components might include unstable slopes, aquifer recharge areas, wetlands, seeps, forests, and areas of intensive human modification. Both areas also include the vast variety of organisms that occupy one or more of these habitats.



River running through rural residential area/Jane Atha, WDFW

Riparian areas occupy a particularly dynamic and disturbance-prone region (Figure 8.3, right panel) that can experience decadal, annual, or even more frequent flood events that locally alter, rearrange, or obliterate its components altogether.

> *In the natural state, riverine landscapes exemplify the* new paradigm in ecology *(sensu Talbot 1996), in which ecological systems are widely recognized as non-deterministic, open systems in continual states of flux, rather than internally regulated, homeostatic systems exhibiting equilibrium conditions. Yet, despite their highly dynamic nature, riverine landscapes provide predictable ecological conditions. Although individual landscape components exhibit high turnover, largely as a function of interactions between fluvial dynamics and successional phenomena, their relative abundances in the river corridor as a whole tend to remain constant over ecological time. [From Ward et al. 2002:518.]*

So, for example, a flood may scour a gravel bar at one location in a river and deposit sediment in another; but along any given channel reach the relative frequency of pools and bars may not vary substantially over time. The resulting transience and diversity of habitats provide a variety of habitats that, although ideally always present in aggregate, are not necessarily static in place or time (Robinson et al. 2002). Thus, managers should recognize this dynamic equilibrium as the key attribute of a truly functional riparian–aquatic ecosystem and make the protection of its dynamic *behavior* (rather than any specific *feature*) the overarching goal of riparian management.

Existing policies, however, generally do not facilitate management for dynamic conditions:

> *Policies setting underlying riparian goals that are essentially static and homogenous have become an integral part of many of the management guidelines that drive the goals for riparian management on federal, state and private lands in western Washington. Discussions [at a statewide forest management symposium] did not indicate that current management and policy guidelines necessarily preclude practices that might produce dynamic and heterogeneous riparian conditions. Because they promote uniform conditions over large areas, however, current policy and management guides do little to encourage treatments that would lead to ecologically diverse landscapes that could maintain critical functions that were formerly produced by natural disturbance regimes... [From Ryan and Calhoun 2010:viii-ix].*

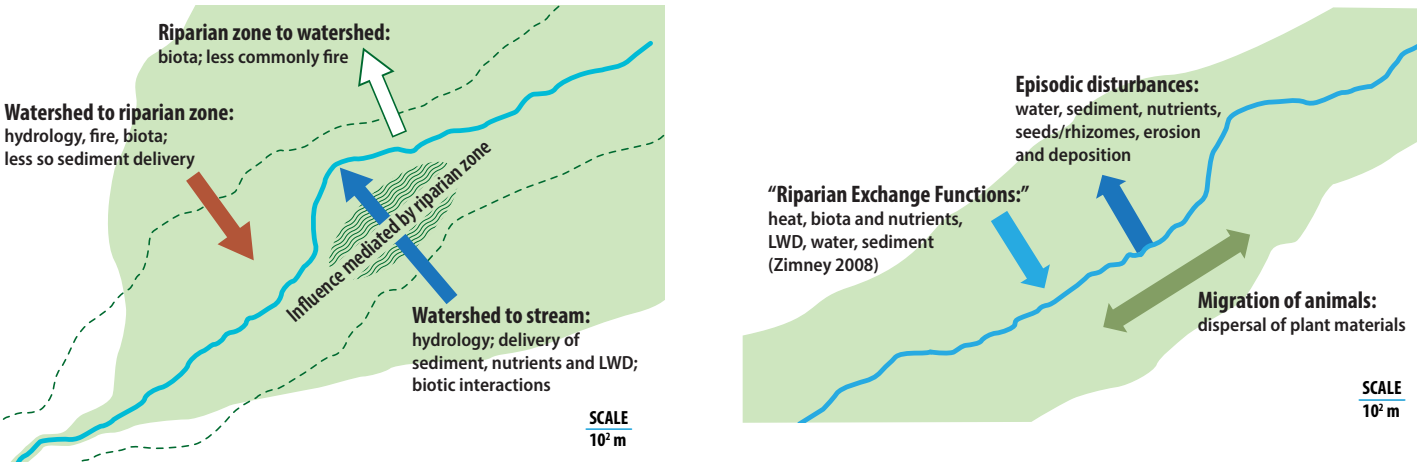


Figure 8.3. Movement of water, biota, and other elements of the aquatic system from the watershed into and through riparian areas (left) and between riparian areas and the stream (right).

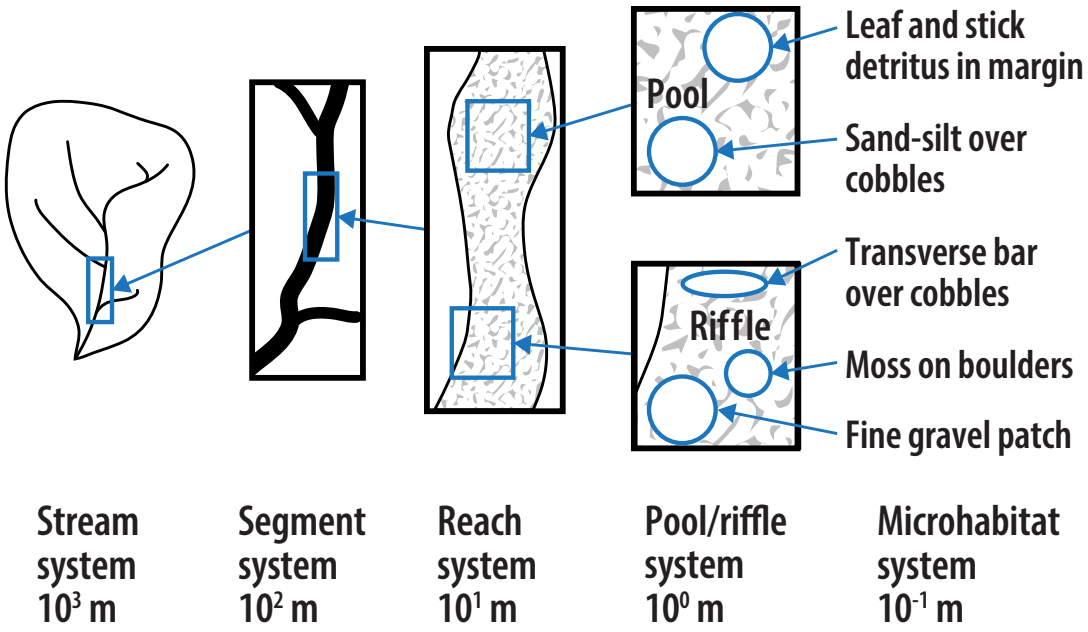


Figure 8.4. Hierarchical spatial organization of a watershed and its aquatic habitats. Approximate spatial scale, appropriate to second or third-order mountain stream (modified from Frissell et al. 1986).

On the other hand, riparian areas have experienced high levels of anthropogenic disturbance, both directly (e.g., harvest, road building) and indirectly (e.g., windthrow, landslides, and forest fire) due to forest management, which also compromises the dynamic equilibrium in riparian-aquatic ecosystems. In response, policy makers have reduced forest management-related disturbances in riparian areas, with the intent of passively reestablishing underrepresented late-seral classes (such as mature forest) which should improve riparian ecological functions, and conserve fish and wildlife species dependent on older forest. Such policies are all likely necessary parts of a successful riparian management strategy. However, because they do not address watershed-scale processes, these policies by themselves are almost surely insufficient to achieve desired riparian and aquatic ecosystem outcomes.

8.2.1. What are Watershed Processes?

Although the immediate goal of riparian management is the protection of species and their habitats, Frissell et al. (1986:199) suggested that "[w]e begin with the assumption that structure, operation, and other aspects of the organization and development of stream communities are largely determined by the organization, structure, and dynamics of the physical stream habitat." (Using the terminology elsewhere in this document, these terms correspond to the structure, composition, and functions of physical habitat). If so, "the problem becomes one of understanding these physical patterns across time and space. This requires a broad, integrative framework that places streams, their habitats, and their

communities in wider geographic context" (Frissell et al. 1986:200). Frissell et al. (1986) developed this wider context by describing a spatial hierarchy that recognizes the influence of larger scale conditions and processes acting primarily (but not exclusively) unidirectionally on smaller scales (Figure 8.4). Factors that are best characterized over the largest extents, and that exert their influence over longest time frames, can be thought of as the ultimate "drivers" of the conditions and processes at lower levels in the hierarchy.

Three overarching process drivers—climate, geology, and topography—structure the suite of landscape-forming processes that are distributed over a landscape and that, in turn, govern watershed characteristics and processes (paraphrasing the framework of Montgomery 1999). At management time scales (i.e., years to decades), these process drivers are invariant and immutable—they are the "givens" under which a watershed evolves. The physical habitat features of any watershed do not simply arise from these process drivers directly, however; instead, they are created and continuously modified by the fluxes of materials (particularly water and sediment) and energy that arise from these process drivers and are widely termed watershed processes. Watershed processes are defined as "[t]he dynamic physical and chemical interactions that form and maintain the landscape and ecosystems on a geographic scale of watershed to basins (i.e., hundreds to thousands of square miles)" (Stanley et al. 2011:8).

To this simple, unidirectional, physical model of watershed influences must be added a few complications of lesser but still critical importance. First, the flow of influence is not always one-way: although topography exerts the dominant influence on the flow of water, over time the erosion by that flowing water will alter the topography to some degree (which, over geologic time scales, may be sufficient to change the very boundaries of the watershed). Second, biota are not always passive respondents to the presence and changes of physical habitat, but instead can also influence that physical habitat in ways that are only slowly being recognized (see Moore 2006 for an overview of such effects). Robinson et al. (2002) emphasizes the role of fauna as ecosystem engineers of riverine landscapes, for which the modification of stream substrates by spawning salmon (Montgomery et al. 1996) or the rearrangement of floodplain dynamics by Beaver (Pollock et al. 2003) are two widely recognized examples. Biological conditions and processes are also of fundamental importance to the expression of some watershed processes: the flux of nutrients may not alter the physical habitat but is key to the health of the ecosystem; the character and extent of vegetative cover will greatly mediate the effects of topography, climate, and geology on the movement of runoff, the downslope transport of sediment, and the potential for dramatic, process-altering wildfire. Finally, the effects of people and human activities cannot be ignored in any useful conceptual framework applied to the modern landscape. Although direct modification of habitat and streams is an obvious impact with a long historical legacy in the Pacific Northwest (and beyond), the aggregate effects of human activities across whole watersheds can be even more consequential to instream resources, to the extent that land use, in many settings, becomes no less of a process driver (i.e., a determinant in a watershed) than is topography or climate.

These concepts are integrated into Figure 8.5, which emphasizes the unidirectional, hierarchical flow of influence from the large-scale process drivers onto the watershed processes that, in turn, give rise to the instream physical and ecological conditions and responses. This representation is not intended to deny the *upstream* influences that also occur (see Beechie et al. 2010, Figure 1 as an alternative representation), but it sacrifices completeness for clarity in acknowledging the overriding importance of this unidirectional perspective. This conceptual model also articulates the variety of processes that are embraced within each of the major watershed processes we

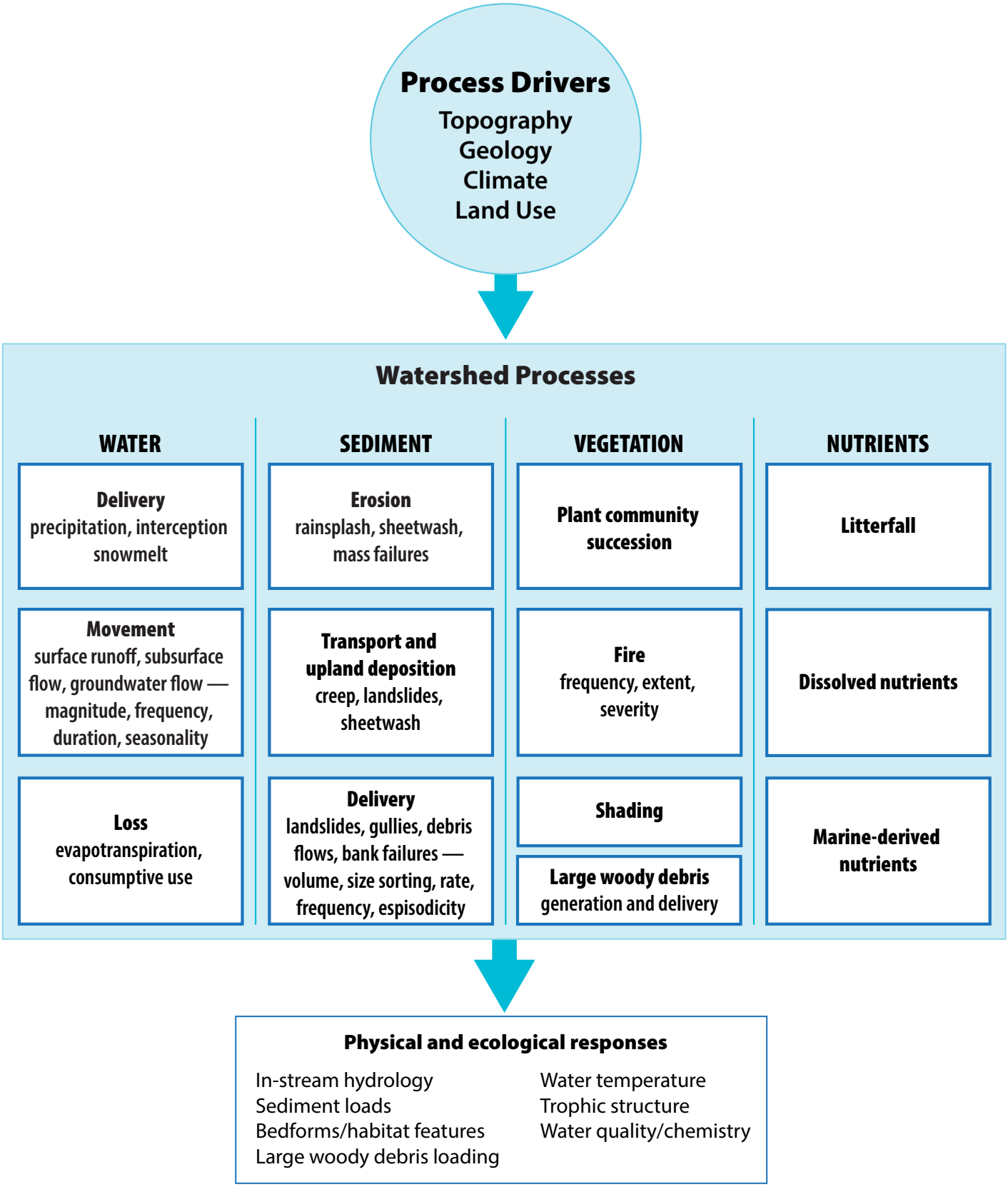


Figure 8.5. Conceptual framework for the hierarchical relationship of invariant, large-scale process drivers, the suite of watershed processes that are determined by these drivers, and the instream physical and biological responses to those processes. Multiple additional interactions between elements and levels are not shown on this diagram to emphasize the primary influences; but in any given setting, one or more of these secondary interactions may temporarily achieve equivalent importance. This framework embraces the definition of watershed processes from Stanley et al. (2011:8): "[t]he dynamic physical and chemical interactions that form and maintain the landscape and ecosystems."

recognize (water, sediment, vegetation, and nutrients), and it reminds us of the major instream responses to these dynamic watershed processes.

8.2.2. How Does the Watershed Affect Instream Conditions?

The direct effects (both physical and biological) of watershed processes on the stream channel are most commonly understood as the delivery of material from the watershed, with or without some attenuation or other modifications as they pass through the riparian ecosystem: water, sediment, nutrients, pollutants, and large wood. These materials are delivered primarily by surface water flow, subsurface flow, landslides and debris flows (Figure 8.6). These fluxes of material and energy from the broader riverine landscape interact with those arising from the riparian corridor itself, to different degrees and over different time scales, with a resulting complexity that defies our current efforts to quantitatively predict their expression in the physical form or biological condition of a stream.

The complexity of these interactions is highlighted by relatively weak correlations reported between various instream features and landscape predictors, regardless of the spatial scale being evaluated (e.g., whole-watershed vs. riparian areas). For example, Anlauf et al. (2011) evaluated the correlation between eleven instream habitat features with landscape variables characterizing both process drivers (e.g., watershed gradient, rainfall) and management-influenced factors (e.g., forest cover, disturbance history, road density) across 121 coastal Oregon streams. The strongest relationships showed unexceptional correlations between particular habitat features and the suite of landscape variables (active channel width, R^2 = 0.72; percentage of fine sediments, R^2 = 0.48). Other habitat features expressed essentially no relationship (percentage gravel, R^2 = 0.05; pools per 328 ft (100 m), R^2 = 0.11; percentage secondary channel area, R^2 = 0.12). Including management-influenced predictors increased adjusted R^2 values only modestly (by up to 16%). Many of the strongest relationships followed intuitive expectations, such as: "Wood volume was associated with several landscape predictors reflecting wood availability (% non-forest, % small trees, and % remnant forests), whereas pools per 328 ft (100 m) were associated with disturbances affecting pool retention (cow density, road density) and pool formation (% small trees)" (Anlauf et al. 2011:708). However, no relationship was sufficiently strong to suggest that either deterministic understanding or statistical correlations are sufficient to precisely characterize the influence of watershed-scale processes on a stream.

Our inability to predict instream conditions from watershed processes and riparian conditions with any useful degree of accuracy is widely recognized. In part, this inability is because the riparian corridor itself has significant, complex effects on the stream (see other chapters in this document). In addition, all of these influences—at every spatial scale—occur within a time-dependent framework mediated by rates of vegetation growth and decay, seasonal variations in flow, and episodic disturbances from floods, and even less frequent but potentially long-lasting channel impacts from fire or landslides (Lake 2000; Roper et al. 2007; Luce et al. 2012; Jellyman et al. 2013).

> ***[E]mpirical associations between land use and stream response only varyingly succeed in implicating pathways of influence. This is the case for a number of reasons, including (a) covariation of anthropogenic and natural gradients in the landscape; (b) the existence of multiple, scale-dependent mechanisms; (c) nonlinear responses; and (d) the difficulties of separating present-day from historical influences. [From Allan 2004:257.]***

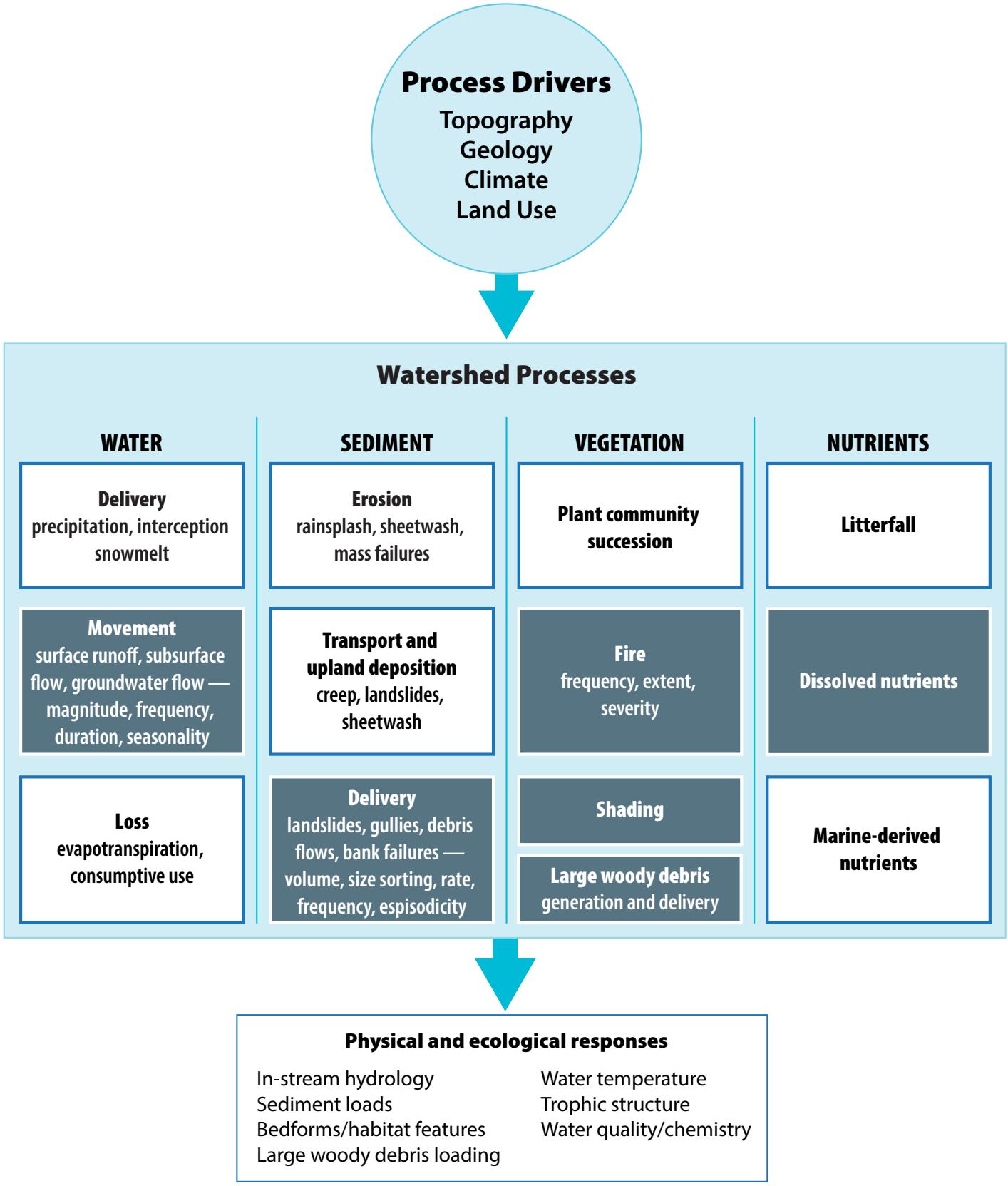


Figure 8.6. The conceptual framework of Figure 8.4, highlighting the subset of watershed processes (dark shaded boxes) that most directly affect instream conditions.



Clearcut harvest in a managed forest landscape/Jane Atha, WDFW

Regardless of our present inability to make reliable predictions of instream conditions from watershed processes, watershed processes do create and maintain instream habitat, and so the determinants of those processes are of indirect, but ultimately critical importance, to the understanding and the management of aquatic resources. Because the nature and intensity of these processes are strongly influenced by prevailing (and past) watershed land use(s), the effects of the dominant land use activities of the Pacific Northwest are discussed individually.

Forestry

The effects of watershed-scale forestry on instream conditions have been a primary focus of scientific research and forest practice regulations for many decades. Most of the attention has been paid to several discrete problems: increased stream temperature from loss of riparian vegetation, the degree to which large-scale loss of forest canopy alters the hydrologic regime, whether the creation of new roads has a discernible impact on both hydrology and sediment delivery to the channel network, and whether forest practices increase the frequency and intensity of debris flows and other forms of mass failure that reach the stream.

The potential for hydrologic alteration in logged watersheds focuses on two major mechanisms: 1) the loss of forest canopy, which should increase total water yield by reducing interception and evapotranspiration, and increase accumulation of snow on canopy-less ground, which increases the total volume of water available during subsequent rain-on-snow events, and 2) more rapid drainage of surface runoff to stream channels from a newly created road network. The review article of Andréassian (2004:12) provides a convenient summary of much of the voluminous literature on this topic, concluding that "deforestation could definitely increase both flood volumes and flood peaks. However, this effect is much more variable than the effect on total flow and may even be inverted in some years or in some

seasons." The underlying causes for such increases are associated not only with the loss of forest canopy but also (and, perhaps, primarily) the consequences of soil compaction and development of the road network.

Increased sediment delivery to streams from watersheds is an anticipated outcome of both the direct and indirect effects of logging. Direct consequences result from the loss of canopy cover, increasing the potential for rainsplash and sheetwash erosion in areas of intrinsically low infiltration capacity, and the eventual loss of soil cohesion in areas of steep slopes. Indirect effects result from the construction of roads, for which inappropriate siting can result in sheetwash erosion and a greater incidence of landslides and debris flows from either concentrated road runoff or failure of the road prism itself. A variety of case studies making use of detailed field mapping, radionuclide tracers, and suspended sediment measurements have implicated various landscape features and erosive processes in post-logging watersheds, such as skid trails and landings, promoting surface runoff and erosion (Wallbrink et al. 2002), enhanced gully erosion (Reid et al. 2010), and road-initiated debris flows (May 2002).

Nutrient dynamics across the watershed are also affected by forest practices, with potential effects throughout the ecosystem (including the channel network and its riparian corridor). Richardson et al. (2005) offered a well-focused and detailed evaluation of the consequences of watershed disturbance, including logging, on the delivery and retention of organic matter in small streams of the Pacific Northwest. He noted that the replacement of coniferous with deciduous trees in recently logged areas can increase the delivery of nutrients, but that more rapid breakdown of delivered material and the accompanying reduction in both large wood and channel complexity, commonly expressed throughout the channel network of logged watersheds, "could produce a substantial reduction in stored organic matter." (Richardson et al. 2005:930).

Agriculture

Cultivated agriculture normally occupies a comparatively narrow range of low-gradient settings in a watershed. Thus, processes associated with steep slopes—particularly landslides and debris flows—found in logged watersheds are nearly absent here. However, the working of the agricultural land surface is far more intensive where it does occur, and a wider range of water-borne contaminants are potentially introduced. As with forestry, hydrology, sediment delivery, and nutrient dynamics are all affected by agricultural land use, but the nature and severity of its impacts on instream resources can be quite different. Runoff from agricultural watersheds, notably its load of nutrients and pesticides, were the historical impetus for the use of riparian buffers under an assumption of surface-runoff filtration (Osborne and Kovacic 1993). Brown et al. (2009) found that the legacy of prior agricultural land use, even in areas presently undergoing urbanization, is one of the strongest determinants of instream conditions in their nine study areas nationwide.

Grazing is a second, broad category of agricultural activities with significant impacts to streams, primarily as a result of direct encroachment into riparian areas and the channel itself. Belsky et al. (1999:2) reviewed dozens of mid- to late-20th century evaluations of grazing throughout arid lands of the American West that evaluated impacts to water quality and temperature, hydrology, channel geomorphology,

Watershed processes help create and maintain instream habitat. Thus the determinants of those processes are indirect but critically important to the understanding and the management of aquatic systems.

wildlife, and instream and riparian-zone vegetation. Their conclusion was that "[n]o positive environmental impacts were found" as a result of grazing, and they advocate complete cessation of grazing as the only sure course for recovery of riparian areas. More recent work (e.g., Agouridis et al. 2005; Raymond and Vondracek 2011) suggest that various strategies of rangeland management may have local success at reducing the magnitude of such impacts; but the large spatial extent over which grazing occurs in certain areas of the Pacific Northwest continues to make this a regionally significant impact to streams and riparian areas.

Urbanization

Urbanization is widely recognized to be the most intensive land use affecting watershed processes. It is also typically the most permanent, insofar as urban developments are rarely returned to anything approaching a natural state, a transition that is not precluded by agriculture and is quite practical in commercially managed forests. As a pervasive, near-total conversion of the land surface, urbanization has the ability to alter each of the dominant watershed processes wherever it occurs: hydrology (both surface and groundwater); the delivery of sediment, nutrients, pollutants, and sunlight; and the interaction of upland/terrestrial biota with the stream channel (Booth et al. 2004; Walsh et al. 2005). Nearly all of these alterations stem from the same fundamental change: the conversation of the land surface, with its vegetative cover and natural soils, to a variety of impervious and near-impervious surfaces. Undisturbed riparian corridors are widely recognized as useful protective measures for streams in urban areas, but all multi-scale evaluations of urban land cover and instream quality affirm the shared importance of not only riparian areas but also upland urbanization in ultimately determining instream conditions (e.g., Wang et al. 2001; Morley and Karr 2002). These watershed-level effects are significant at even low levels of urbanization (e.g., Vietz et al. 2014), and to date they have proven virtually impossible to control under typical riparian-management policies, highlighting the continuing challenge of achieving meaningful aquatic-system protection in an urbanizing watershed.

8.2.3. How Does the Watershed Affect Riparian Areas?

Changes to an upland watershed and watershed processes can also affect the conditions and functions of riparian areas directly (Figure 8.7). Although a riparian area is commonly defined in terms of its relationship to the stream, it also has a relationship to the uplands that surround it. Water from the stream channel will commonly be the riparian area's dominant source of both overland flow (during floods) and groundwater, but adjacent upland water sources can support riparian hydrology during periods of low flow. Much of the sediment that originates from the uplands is transported directly to the streams via channeled flow, but some fraction of that load will deposit before ever reaching the main channel, particularly if the riparian area includes a broad, low-gradient floodplain or if delivery occurs via episodic and channel-overtopping debris flows. Upland vegetation "buffers" riparian areas, providing

More important than simply protecting the habitat itself is protecting the processes that create and sustain that habitat. For this strategy to be successful, however, space in which that habitat can be expressed must also be protected.

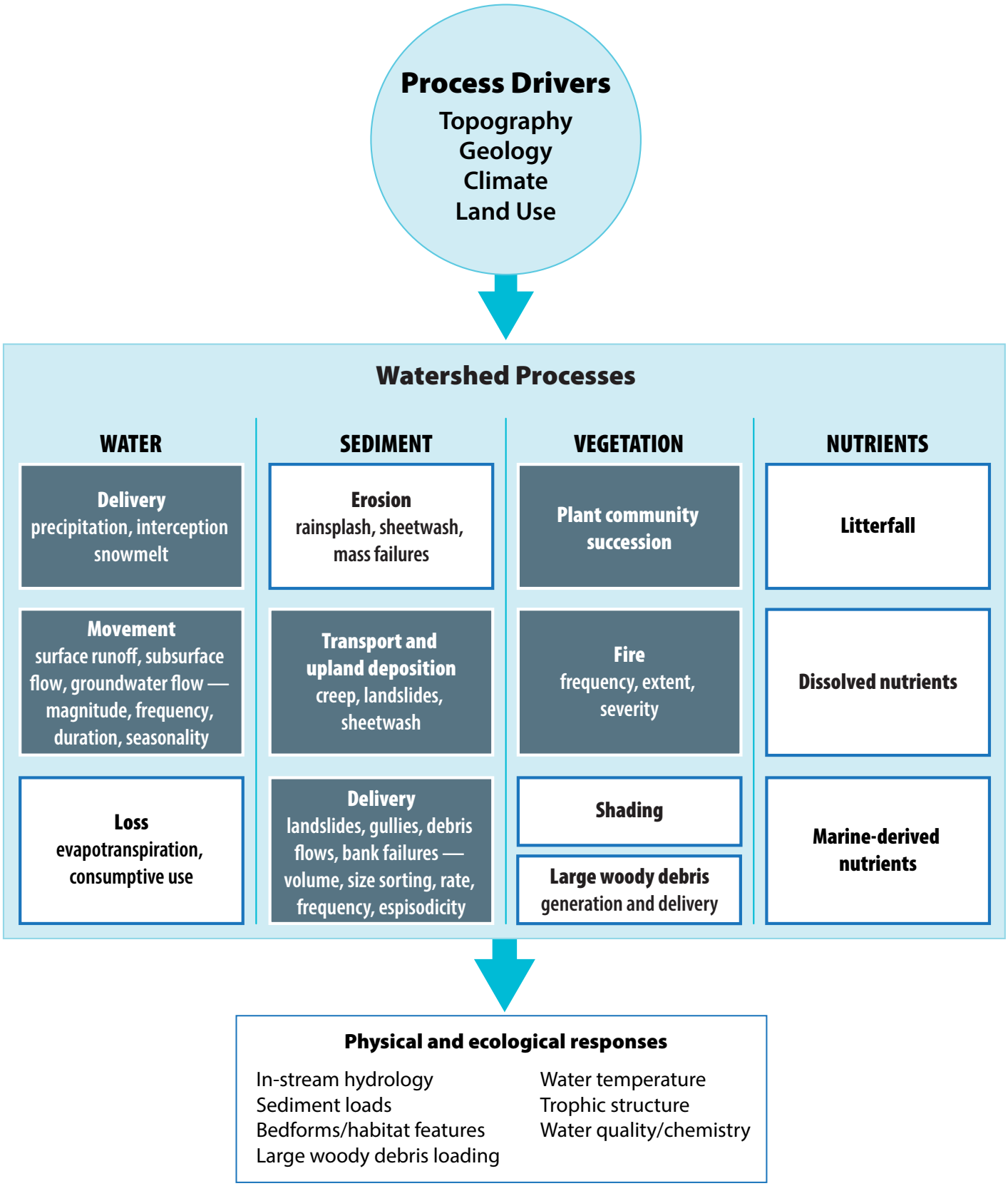


Figure 8.7. The conceptual framework of Figure 8.4, highlighting the subset of watershed processes (dark shaded boxes) that most directly affect conditions in riparian areas.

ecological connectivity between upland plant and animal communities with their riparian counterparts, and providing protection from mechanical disturbances, such as windthrow. Uplands also constitute a broader environment that either supports or suppresses wildfires that may freely cross the upland/riparian boundary.

Various land uses are relatively consistent with respect to their particular impacts to riparian ecosystems. That is, all three of the primary types (forestry, agriculture, urban) physically remove native vegetation, with differences only in the degree of impact. The loss of upland vegetation will consistently affect ecological connectivity and the risks of windthrow and fire regardless of the specific upland land use.

The interactions between uplands, riparian areas, and instream conditions are particularly complex with respect to wildfire. Arkle et al. (2010:299) found that "increasing riparian burn severity and extent were associated with greater year-to-year variation, rather than a perennial increase, in sediment loads, organic debris, large woody debris (LWD) and undercut bank structure." They emphasized a decrease in the stability of physical habitat and high variability in macroinvertebrate communities, which they attributed to annually fluctuating loadings of sediment, large wood and other organic material. They did not recognize any tendency for the macroinvertebrate community to become more like those of relatively undisturbed, reference streams over time, suggesting that changes to wildfire regime can result in permanent changes to stream ecosystems, and that these changes are a result not only of direct influence of burned areas on the stream but also of a permanently altered structure of the riparian corridor. With greater human disturbance, invasive species with high flammability (including those that have begun transforming riparian areas from fire breaks to fire-prone areas of a landscape; Coffman et al. 2010) become more common, as does the greater overall frequency of wildfire in modern human-dominated landscapes (Keeley et al. 2009). Thus this process driver, operating largely independent of typical considerations of riparian area management, can have a profound influence on instream resources (Pausas and Keeley 2014).



Wildfire in Methow River valley, 2018/ Scott Fitkin, WDFW

8.3. The Role and Limitations of Site-Scale Riparian Area Management

Whereas large-scale watershed processes govern the interactions and delivery of water, sediment, organic material, and nutrients to the stream over long distances, the effects of riparian vegetation on physical and ecological processes occur over much shorter distances with complex, direct, time-dependent interactions. These effects are expressed along river corridors "by influencing temperature and light regimes; producing organic detritus (leaf litter, woody debris); by routing water and sediment; by structuring the physical habitat at several scales; by providing a substrate for biological activity and habitat/cover for aquatic, amphibious and terrestrial animals" (Ward et al. 2002:524). For this reason, particular management attention to riparian areas is warranted, insofar as this part of a watershed has a unique, intimate interaction with the stream channel and its biota. Previous chapters explore these specific interactions in detail.

In addition to spatial relationships, temporal interactions are fundamental attributes of aquatic and riparian habitats. These habitats can be created by disturbances and also are episodically affected by them—streams are not static. Just as the influence of process drivers is not uniform across a watershed, so also is the influence of disturbances. In the case of floods, the most common and obvious of disturbances in rivers, this variability is primarily temporal and can be expressed through flood frequency, duration, seasonality (i.e., when in the year they occur), magnitude, and the predictability of occurrence (Lytle and Poff 2004).

The expression of these drivers, their interactions within a watershed and in individual streams, and their variability over time creates and maintains a dynamic mosaic of habitats. These interactions among drivers are complex and intertwined even in the absence of anthropogenic disturbances. Therefore, scientists have had difficulty separating the effects of the different drivers independently and in assessing how any species (even well studied salmon species) respond to this mosaic (Fausch et al. 2002). Adding to this complexity is the fact that habitats are species-specific; what constitutes habitat for one species may be mostly unrelated to what constitutes habitat for another aquatic species in the same river.

Thus, if riparian areas are managed with the objective of maintaining high-quality habitats for aquatic species, managers must ensure that riparian areas contribute what they can (i.e., separate from, but in combination with, watershed processes or drivers) to the long-term maintenance of the temporally variable spatial mosaic of habitat conditions. The mere presence of these habitats, however, is not sufficient: they must exist in configurations that are advantageous to aquatic species, with sufficient variety to support multiple life stages, adequate size and number to support a population, sufficiently proximate to be accessible from one to another, and yet sufficiently distal to not be subject to the same deleterious disturbances.

This, then, defines the fundamental challenge of watershed and riparian ecosystem management: given a system of great diversity and complexity, with attributes that can vary greatly and unpredictably in their influence over time, and biological communities that depend on both the diversity and interconnections between habitats, what fundamental principles should guide management to perpetuate fish and wildlife? We return to this question in the last section of this chapter.

8.4. Integrated Effects of Site-Scale Riparian Areas Management

"Connectivity" is the term most often used to describe whether organisms can move from one habitat to another (Taylor et al. 1993). It comprises two parts: structural connectivity, the physical relationships among habitat patches without regard for the behavior or organisms; and functional connectivity, the degree of movement of organisms through the landscape (Taylor et al. 2006; Kadoya 2009). The two are obviously related in all landscapes, but lotic systems impose some characteristic influences. First, there is a strong (though not universal) downstream bias on functional connectivity, insofar as most organisms and all inert constituents move in the direction of water flow. Second, impediments to flow can impose partial barriers to both structural and functional connectivity, but to very different degrees. For example, a culvert may allow most or all discharges to pass unimpeded but nevertheless present a barrier to migrating salmon (e.g., Davis and Davis 2011).

Concern over longitudinal barriers along a channel network typically focuses on the effects of instream physical barriers, particularly dams, culverts, and road crossings, rather than the consequences of longitudinal disturbances to riparian areas more broadly. Instream connectivity and riparian connectivity are related, however, even if they are not direct surrogates. Some types of discontinuity (e.g., a road running perpendicular to the stream) will affect the longitudinal connectivity (both structural and functional) of both; but others (e.g., an impassible migration barrier in the stream) will affect the movement of aquatic and terrestrial organisms quite differently. Most importantly from the perspective of riparian management, alterations that are limited to riparian areas can nonetheless affect instream (functional) connectivity. For example, loss of shading from riparian area disturbance (Chapter 4) can create unfavorable instream temperatures that impact the movement or outright survival of migrating salmonids (e.g., Thorstad et al. 2008; Martins et al. 2012). Other direct and indirect actions, such as channelization, removal of large wood, or bank failures from vegetation loss can affect connectivity for migratory fish and among other aquatic species, and alter the flow of material and nutrients through the stream network.

These impacts have been explored in a variety of studies at multiple scales. Flitcroft et al. (2012:288) reported that "…[spatial] network variables perform better at explaining juvenile Coho Salmon *Oncorhynchus kisutch* density than instream habitat variables. Moreover, analysis of network distances among seasonal habitats indicates that juvenile Coho Salmon density may be higher where the distance between critical seasonal habitats is short." Perkin and Gido (2012:2183) found lower species richness in fish communities in stream networks fragmented by road crossings across multiple spatial scales. "Our findings support network connectivity as a mediator of ecological processes occurring within complex dendritic ecosystems and promote the need for improved connectivity to enhance conservation of metacommunity dynamics and biodiversity in dendritic ecological networks." Similarly, Favaro et al. (2014:1815) interpreted their findings on the influence of culverts in a channel network to demonstrate that "…fragmentation of habitats and populations acted on a whole stream scale rather than being restricted to within-stream differences that related to position."

These findings speak to the importance of recognizing the channel as part of the riparian ecosystem, that is, they form an interconnected system, both laterally and longitudinally. The degree to which seemingly isolated discontinuities affect either of these elements directly can ultimately impact the entire ecological network. Prescriptive management is challenging, however,

because the ecological functions of any given site or habitat patch along a channel network depend on its context and interconnection with other such sites. Furthermore, not all habitats have the same value for all species:

> ***The relationship between species richness and connectivity is therefore determined by complex relationships among several interacting variables. In addition, species richness maxima for different faunal and floral elements occur at different positions along the connectivity gradient (Tockner et al. 1998). Fish diversity, for example, may peak in highly connected habitats, whereas amphibian diversity tends to be highest in habitats with low connectivity. Other groups attain maximum species richness between these two extremes. The resulting pattern is a series of overlapping species diversity peaks along the connectivity gradient, suggesting that habitats collectively traversing a broad range of connectivity will optimise community diversity in riverine landscapes. [From Ward et al. 2002:535.]***



Chum Salmon Oncorhynchus keta *need connected habitat to reach spawning grounds/Alex Biswas, WDFW*

Although such studies emphasize the importance of connectivity along the channel corridor, they offer little guidance for managing these barriers and discontinuities beyond *less is better.* The impacts of road crossings, in particular, have been evaluated in several studies in Pacific Northwest lowland streams, comparing measures of biological conditions with the frequency of crossings that describe a negative, monotonic relationship (May et al. 1997; McBride and Booth 2005). Unfortunately, these studies do not suggest a consistent, discrete threshold of impacts that might serve as a management objective. For example, the study of McBride and Booth (2005) showed correlations between biological health (as characterized by a multi-metric index of benthic macroinvertebrates) and road crossings with more than three crossings per km, whereas the biological differences reported by Perkin and Gido (2012) occurred on fragmented streams with as few as one road crossing over a stream segment length of one to many kilometers.

The overarching message from these studies is that any given implementation of site-scale riparian area management does not occur in a vacuum: "protecting a site" has ecological meaning only within the context of the entire channel network. Although existing computational tools can characterize the degree of fragmentation from discontinuities or the spatial coherence of a riparian corridor of varying width, the existing literature suggests that we lack clear deterministic linkages between alternative riparian management strategies and the resulting response of instream organisms, particularly the identification of thresholds of disturbance that impact fish mobility. However, any management action that results in frequent interruptions to riparian areas, or riparian corridors where blockage of terrestrial and aquatic organisms is not fully mitigated, is sure to have deleterious impacts to aquatic and terrestrial system health.

8.5. Managing Riparian Areas From a Watershed Perspective

The perspective of riparian area management developed in this chapter has been intentionally expanded, in both space and time, beyond that normally applied (and most feasibly implemented) in the Pacific Northwest. It relies heavily on the active research in the field of landscape ecology, which is organized around a few themes of particular relevance to riparian area management: 1) patches differ in quality, 2) patch boundaries affect flows, 3) patch context matters, 4) connectivity is critical, 5) organisms are important, and 6) scale is important (Wiens 2002:501). We will explore each of these in turn with an eye towards how management of riparian areas might be improved with respect to perpetuating fish and wildlife.

8.5.1. Patches Differ in Quality

Not every location along a stream is equally influential on the physical processes or ecological functions of the riparian-aquatic ecosystem. This generalization is complicated, however, by the fact that different perspectives may not assign the same level of "influence" to every location. For example, bedrock-bound channels have very limited capacity for response (Montgomery and Buffington 1997), despite the potential for highly variable, episodic inputs of water and sediment. Thus, from a geomorphological perspective they might be considered less sensitive and so "less critical" for riparian area protection. However, such channels commonly occupy headwater, high-elevation positions in their watersheds that host potentially critical habitat(s) for a variety of non-fish species. A general treatment of the topic such as this cannot resolve the multiplicity of such complex phenomena across the diversity of landscapes in the Pacific Northwest, but this brief discussion suggests the importance of recognizing the range of riparian functions that must be served, and the improbability that they are all of equivalent importance throughout a channel network.

8.5.2. Patch Boundaries Affect Flows

In general, riparian regulations rarely consider the nature of the transition from riparian to upland (i.e., from regulated to unregulated) areas. This theme provides a reminder that the character of those transitions can affect each of the patches through the flux of material, energy, and organisms across their shared boundary. So, for example, when what was once a part of a forest interior becomes the exposed edge of a buffer strip, adjacent to recently cleared uplands, windthrow can greatly increase (and so compromise the riparian management area itself). Direct adjacency of a riparian area to urban development can invite substantial human intrusion (e.g., invasive species, excess nutrients, pesticides) into the riparian area, reaching all the way to the nominally protected stream because attention is not given to the relationship of upland development to the riparian area, nor to the "porosity" of the boundary between them.

8.5.3. Patch Context Matters

Riparian areas within separate watersheds containing different land uses (e.g., forestry, agricultural, urban) provide very different ecological functions depending on the adjacent land uses. The impacts to a stream from watershed urbanization, for example, span the range

from pervasive hydrologic changes (for which buffers are typically irrelevant) to pesticide-laden run-off (for which the pollutant removal that a buffer provides may be somewhat to highly effective). In a forestry dominated watershed, primary concerns may be the potential for unnaturally high delivery of sediment from increased rates of mass wasting; or potential losses of streambank integrity, habitat complexity, shading, large wood, and allochthonous inputs of organic matter.

According to Hansen et al. (2015:54):

> ***Our review demonstrated that greater widths were required to achieve objectives when adjacent land use intensity was high, or when the objective of management was improving terrestrial biodiversity (particularly fauna). This becomes problematic when intense land use practices occur on small properties, reducing the amount of riparian land that can economically be protected or targeted for management…For example, if we apply the evidence summarized here to a streamside property used for dairying in the lower Hunter River, New South Wales, a riparian zone width of 40 m may achieve ≥75% reduction of nitrogen inputs to the river and reduce streambank erosion, contributing to improved downstream water quality. However, the same investment in riparian set-aside in the upper reaches of the Hunter catchment may provide additional improvements to stream nutrient processing (Lowe and Likens 2005), aquatic biodiversity (Chessman et al. 1997) and bird diversity (Bennett et al. 2014).***

8.5.4. Connectivity is Critical

Connectivity in riparian areas occurs not only parallel to the stream (previous section), but also orthogonally to the channel in a lateral dimension – from the stream through the riparian area into uplands–and the vertical dimension in the hyporheic zone. Typical riparian area regulations are generally successful at maintaining connectivity in the longitudinal dimension at some minimum width, although the consequences of limited interruptions to longitudinal connectivity (e.g., bridges, utility crossings) are commonly dismissed, a consequence of viewing riparian areas only from the perspective of lateral width rather than a recognition of the importance of stream network connectivity.

Longitudinal connectivity is especially important for the movement of sediment, large wood, and other organic matter. Fox (2003), for instance, found that the condition of riparian areas was a reasonable predictor for the quantity of large wood key pieces in adjacent stream channels; however, upstream basin characteristics and processes were likely responsible for most of the large wood in larger channels. Therefore, land managers should not base site-level objectives for in-stream large wood on the condition of adjacent riparian areas alone, but should also manage riparian areas at the watershed scale to provide adequate in-stream large wood throughout a watershed's stream network.



Issaquah Creek is a tributary to Lake Sammamish in King County/ Derek Booth

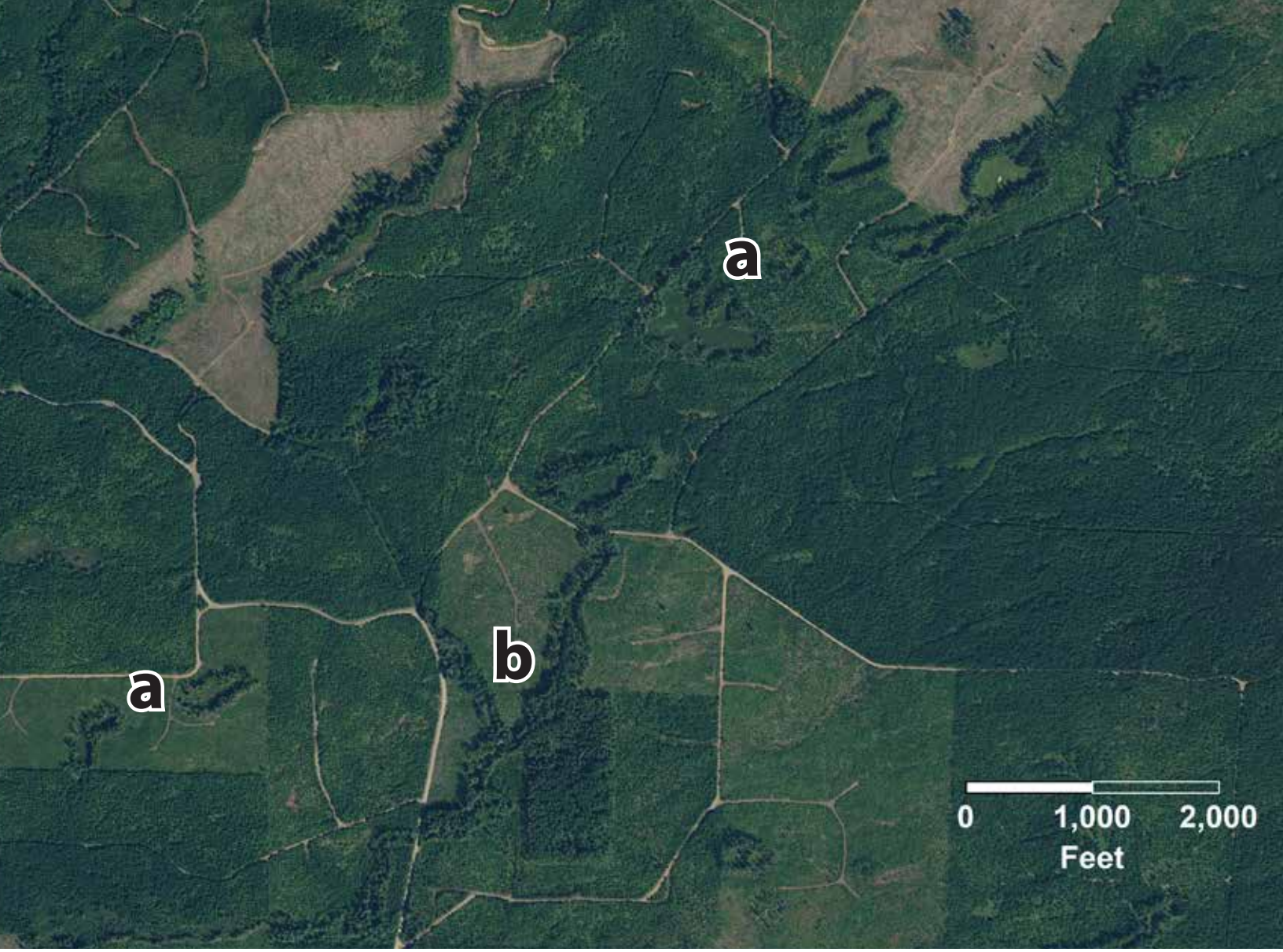


Figure 8.8. View of isolated wetlands (a) and riparian management zones (b) in a commercially logged portion of southwest Washington, providing some degree of local, structural connectivity within each buffer but no functional connectivity between them. Forested buffers in this image are approximately 50 feet (15 meters) wide.

Lateral connectivity, particularly between the riparian area and the adjacent uplands, is a more complex relationship, because improving this connectivity simultaneously enhances ecosystem protection but can also compromise the protection of a stream from upland activities. Continuity of a protected riparian area with uplands that are protected as well provides a range of key habitats for mobile species that depend on both upland and riparian environments for different needs or at different life stages. Separated patches with relatively porous boundaries may achieve only a modest fraction of these benefits, however, and truly isolated riparian–upland patches may be no better than an absence of such habitats altogether (at least for many terrestrial species of concern) (Figure 8.8). Porous boundaries also run the risk of compromising some of the primary goals of a riparian management area, and so the nature of connectivity does not universally result in beneficial outcomes (see 8.5.2 above).

Vertical connectivity occurs at the ecotone between stream water and deeper groundwater. This ecotone, known as the hyporheic zone, is comprised of coarse sediments, and the vertical connectivity occurring there is more commonly referred to as hyporheic exchange (Boultan et al. 1998). Hyporheic exchange includes

water, dissolved solutes, fine sediments, fine organic matter, and small organisms. The size of the hyporheic zone is enlarged by structures such as large wood and boulders that store sediment. Hyporheic exchange is enhanced by structures such as large wood or boulders that redirect flow into the streambed and by undulations in channel morphology (e.g., meanders, pool-riffle beds) that intercept the flow of water.

In summary, the importance of connectivity is broadly recognized:

> ***Restoration of important ecological processes often implies improving connectivity of the stream. For example, longitudinal and lateral connectivity can be enhanced by restoring fluvial dynamics on flood-suppressed rivers and by increasing water availability in rivers subject to water diversion or withdrawal, thereby increasing habitat and species diversity. Restoring links between surface and ground water flow enhances vertical connectivity and communities associated with the hyporheic zone. [From Jansson et al. 2007:589.]***

However, tangible recommendations for how best to manage for this outcome in typical regulatory settings are more elusive.

8.5.5. Organisms are Important

Although not strictly an issue of spatial or temporal relationships between landscape elements, the recognition of organisms as key elements of riverine composition, structure, and functions is a valuable contribution of landscape ecology to watershed management. Some of these influences have been long-appreciated: the importance of large wood to stream structure and salmonid habitat, the role of root strength in mediating bank erosion, and indeed the entire construct of conserving riparian areas of native



Black Bear Ursus Americanus *feeding on grass/Scott Fitkin, WDFW*

vegetation to maintain ecosystem health. However, this perspective has broadened our appreciation of the multiple ways in which biota interact with the physical environment and each other to support the full range of watershed processes and thus the systems that depend on them (Beavers, bears, and marine nutrients, etc.). Management of riparian areas thus must include not only some awareness of the watershed in which that riparian area exists but also the biota that inhabit this environment (and, in some cases, move beyond its boundaries), and the ways in which those biota support the integrity of the aquatic ecosystem (Robinson et al. 2002).

8.5.6. Scale is Important

The goals and application of riparian management actions are generally limited in both space (i.e., the site) and time (i.e., the present). In a system as interconnected and disturbance-prone as a stream channel network, however, the site-scale management of a riparian area is *necessary*, but not *sufficient*, to ensure the desired composition, structure, and functions

of riparian and aquatic habitats. Of all locations on a natural or human-dominated landscape, river channels are probably the least stable in time, experiencing (and depending on) both gradual changes and episodic disturbance that structure their habitats and the organisms that utilize them. They also are subject to a spatial hierarchy of influences, not only those of the immediately adjacent riparian area itself (such as shade) but also those of the upstream watershed (delivering water and sediment to the channel) and the landscape even beyond its drainage boundaries. "Conditions far from stream banks affect the distribution of key instream habitat characteristics. Amount of instream wood, percentage of gravel, and pool frequency, which are essential to healthy salmon habitat, are particularly sensitive to land use" (O'Callaghan 2012:2). At even larger scales, the mobility of large terrestrial animals, the ability of salmon to return to headwater streams from the ocean, and the episodic disturbance from wildfire can exert equivalent (or greater) influences.

8.6. Conclusions

The perspective provided by landscape ecology emphasizes the temporally and spatially varying nature of habitats, and it suggests that achieving genuine habitat protection (and thus species conservation) is crippled by management that is limited to only narrow riparian corridors. To perpetuate fish and wildlife in the long term, three principles need to become integrated into the current paradigm for protecting aquatic ecosystems:

1. More important than simply protecting habitats is protecting the processes that create and sustain habitats. For this strategy to be successful, however, space in which that habitat can be expressed must also be protected. So, for example, instream and riparian area protection is indeed necessary, but it is not sufficient—the watershed and local-scale processes that create habitats within these areas must also be maintained. Current paradigms that focus on site-level management of riparian areas will not successfully support the dynamic processes that maintain diverse, productive fluvial ecosystems.

2. Habitats have not only spatial but also temporal dimensions to their creation and maintenance, and they cannot retain their functions if they remain static. The historical frequencies, durations, and magnitudes of natural disturbances (flood and fire being the most common) need to be better understood and then emulated to the greatest extent that surrounding land uses can tolerate.

3. Spatial connectivity between habitats is critical, particularly for species (such as salmon) with a variety of habitat requirements at different life stages. Isolated key habitats for mobile species are scant improvement over no habitat at all.

Integration of these principles into the management of aquatic systems will be challenging under existing regulatory frameworks. However, even an awareness of their relevance to sustaining healthy ecosystems may reveal opportunities for their application in regulatory and non-regulatory settings alike. The following key points are offered in support of such opportunities:



Decaying salmon carcass/Ned Pitmann, WDFW

8.6.1. Manage the Riverine Landscape

The riverine landscape is the proper construct for understanding and managing aquatic systems. Although riparian areas are disproportionately important for fish and wildlife relative to their area on a landscape, they are not exclusively important. Although riparian areas affect many critical instream conditions, including temperature, nutrient input, bank stability, and large wood, while also filtering sediment and other pollutants from adjacent upland areas, the watershed outside of the riparian area is no less influential on the ultimate state of instream conditions, particularly with respect to its control of hydrology and sediment delivery. From even beyond a watershed's boundaries, influences on the stream can be carried by wind, mobile biota, and wildfire.

8.6.2. Manage at Multiple Scales

Effective and efficient conservation of fish and wildlife habitats requires management at multiple spatial and temporal scales. Just as the influences on streams arise from within and beyond the riparian area, management must find vehicles to embrace these multiple spatial scales as well. Treatments must also embrace the ever-changing temporal patterns of stability and disturbance, which not only result in constantly shifting physical habitats but also create the ecological template necessary for healthy, resilient biological communities (Ryan and Calhoun 2010). This will require approaches that allow sufficient space and for the expression of key habitat-forming processes (Beechie et al. 2010) rather than simply the creation or protection of static habitat features.

8.6.3. Connect Individual Actions

Particularly in rivers, longitudinal connectivity of individual locations is a defining feature of these systems and their biota, and so maintaining this connectivity is an essential consideration of aquatic ecosystem protection. We increase our chances of maintaining connectivity with coordinated actions across all riparian sites, and even more so by considering the entire riverine landscape as the focus of conservation efforts. However, connectivity is only as strong as its weakest link, and so even a single ill-executed action can preclude achieving this goal altogether.

8.6.4. Engage the Challenge of Implementing Effective Management

Adhering to these key points for achieving genuine riparian ecosystem protection, particularly in the face of continued human impacts, may not be presently attainable. Even if specific beneficial actions are neither everywhere known nor universally feasible to implement, our current understanding can support a positive trajectory. "Landscape conditions far from the river's edge may have strong impacts on instream conditions. Understanding the effects of natural processes and human activities across entire drainage basins is key to researching, monitoring, and restoring aquatic resources." (O'Callaghan 2012:5). Progress will require not only an appreciation of the most effective riparian management strategies but also a broadened perspective on the scope of necessary actions, actions that must extend far beyond the river itself and its adjacent riparian ecosystem.

8.7. Literature Cited[1]

Agouridis, C.T., S.R. Workman, R.C. Warner, and G.D. Jennings. 2005. Livestock grazing management impacts on stream water quality: a review. Journal of the American Water Resources Association 41:591-606. (i)

Allan, J.D. 2004. Landscapes and riverscapes: the influence of land use on stream ecosystems. Annual Review of Ecology, Evolution, and Systematics 35:257-284. (i)

Andréassian, V. 2004. Waters and forests: from historical controversy to scientific debate. Journal of Hydrology 291:1-27. (i)

Anlauf, K.J., D.W. Jensen, K.M. Burnett, E.A. Steel, K. Christiansen, J.C. Firman, B.E. Feist, and D.P. Larsen. 2011. Explaining spatial variability in stream habitats using both natural and management-influenced landscape predictors. Aquatic Conservation: Marine and Freshwater Ecosystems 21:704-714. (i)

Arkle, R.S., D.S. Pilliod, and K. Strickler. 2010. Fire, flow and dynamic equilibrium in stream macroinvertebrate communities. Freshwater Biology 55:299-314. (i)

Beechie, T.J., D.A. Sear, J.D. Olden, G.R. Pess, J.M. Buffington, H. Moir, P. Roni, and M.M. Pollock. 2010. Process-based principles for restoring river ecosystems. BioScience 60:209-222. (i)

Belsky, A.J., A. Matzke, and S. Uselman. 1999. Survey of livestock influences on stream and riparian ecosystems in the western United States. Journal of Soil and Water Conservation 54:419-431. (i)

Bennett A.F., D.G. Nimmo, and J.Q. Radford. 2014. Riparian vegetation has disproportionate benefits for landscape-scale conservation of woodland birds in highly modified environments. Journal of Applied Ecology 51:514-523. (i)

Booth, D.B., J.R. Karr, S. Schauman, C.P. Konrad, S.A. Morley, M.G. Larson, and S.J. Burges. 2004. Reviving urban streams: land use, hydrology, biology, and human behavior. Journal of the American Water Resources Association 40:1351-1364. (i)

Boulton, A.J., S. Findlay, P. Marmonier, E.H. Stanley, and H.M. Valett. 1998. The functional significance of the hyporheic zone in streams and rivers. Annual Review of Ecology and Systematics 29:59-81. (i)

Brown, L.R., T.F. Cuffney, J.F. Coles, F. Fitzpatrick, G. McMahon, J. Steuer, A.H. Bell, and J.T. May. 2009. Urban streams across the USA: lessons learned from studies in 9 metropolitan areas. Journal of the North American Benthological Society 28:1051-1069. (i)

Chessman B.C., J.E. Growns, and A.R. Kotlash. 1997. Objective derivation of macroinvertebrate family sensitivity grade numbers for the SIGNAL biotic index: application to the Hunter River system, New South Wales. Marine and Freshwater Research 48:159-172. (i)

Coffman, G.C., R.F. Ambrose, and P.W. Rundel. 2010. Wildfire promotes dominance of invasive Giant Reed (*Arundo donax*) in riparian ecosystems. Biological Invasions 12:2723-2734. (i)

Davis, J.C., and G.A. Davis. 2011. The influence of stream-crossing structures on the distribution of rearing juvenile Pacific salmon. Journal of the North American Benthological Society 30:1117-1128. (i)

Fausch, K.D., C.E. Torgersen, C.V. Baxter, and L.W. Li. 2002. Landscapes to riverscapes: bridging the gap between research and conservation of stream fishes. BioScience 52:483-498. (i)

Favaro, C., J.W. Moore, J.D. Reynolds, and M.P. Beakes. 2014. Potential loss and rehabilitation of stream longitudinal connectivity: fish populations in urban streams with culverts. Canadian Journal of Fisheries and Aquatic Sciences 71:1805-1816. (i)

[1] References are classified according to RCW 34.05.271 (see Appendix 1) denoted by a lower case roman numeral (i – viii) in parentheses at the end of the citation.

Flitcroft, R.L., K.M. Burnett, G.H. Reeves, and L.M. Ganio. 2012. Do network relationships matter? Comparing network and instream habitat variables to explain densities of juvenile Coho Salmon (*Oncorhynchus kisutch*) in mid-coastal Oregon, USA. Aquatic Conservation: Marine and Freshwater Ecosystems 22:288-302. (i)

Fox, M.J. 2003. Spatial organization, position, and source characteristics of large woody debris in natural systems. Doctoral dissertation. University of Washington, Seattle. (i)

Frissell, C.A., W.J. Liss, C.E. Warren, and H.D. Hurley. 1986. A hierarchical framework for stream habitat classification: viewing streams in a watershed context. Environmental Management 10:199-214. (i)

Hansen, B.D., P. Reich, T.R. Cavagnaro, and P.S. Lake. 2015. Challenges in applying scientific evidence to width recommendations for riparian management in agricultural Australia. Ecological Management and Restoration 16:50-57. (i)

Jansson, R., C. Nilsson, and B. Malmqvist. 2007. Restoring freshwater ecosystems in riverine landscapes: the roles of connectivity and recovery processes. Freshwater Biology 52:589-596. (i)

Jellyman, P.G., D.J. Booker, and A.R. Mcintosh. 2013. Quantifying the direct and indirect effects of flow-related disturbance on stream fish assemblages. Freshwater Biology 58:2614-2631. (i)

Kadoya, T. 2009. Assessing functional connectivity using empirical data. Population Ecology 51:5-15. (i)

Keeley J.E., G.H. Aplet, N.L. Christensen, S.G. Conard, E.A. Johnson, P.N. Omi, D.L. Peterson, and T.W. Swetnam. 2009. Ecological foundations for fire management in North American forest and shrubland ecosystems. PNW-GTR-779. U.S. Forest Service, Pacific Northwest Research Station, Portland, Oregon. (viii)

Lake, P.S. 2000. Disturbance, patchiness, and diversity in streams. Journal of the North American Benthological Society 19:573-592. (i)

Lowe, W.H., and G.E. Likens. 2005. Moving headwater streams to the head of the class. BioScience 55:196–197. (i)

Luce, C., P. Morgan, K. Dwire, D. Isaak, Z. Holden, and B. Rieman. 2012. Climate change, forests, fire, water, and fish: building resilient landscapes, streams, and managers. RMRS-GTR-290. U.S. Forest Service, Rocky Mountain Research Station, Fort Collins, Colorado. (viii)

Lytle, D.A., and N.L. Poff. 2004. Adaptation to natural flow regimes. Trends in Ecology and Evolution 19:94-100. (i)

Malanson, G.P. 1995. Riparian landscapes. Cambridge University Press, Cambridge, United Kingdom. (i)

Martins, E.G., S.G. Hinch, D.A. Patterson, M.J. Hague, S.J. Cooke, K.M. Miller, D. Robichaud, K.K. English, and A.P. Farrell. 2012. High river temperature reduces survival of Sockeye Salmon (*Oncorhynchus nerka*) approaching spawning grounds and exacerbates female mortality. Canadian Journal of Fisheries and Aquatic Sciences 69:330-342. (i)

May, C.L. 2002. Debris flows through different forest age classes in the central Oregon Coast Range. Journal of the American Water Resources Association 38:1097-1113. (i)

May, C.W., R.R. Horner, J.R. Karr, B.W. Mar, and E.B. Welch. 1997. Effects of urbanization on small streams in the Puget Sound Lowland Ecoregion. Watershed Protection Techniques 2:483-494. (i)

McBride, M., and D.B. Booth. 2005. Urban impacts on physical stream conditions: effects of spatial scale, connectivity, and longitudinal trends. Journal of the American Water Resources Association 41:565–580. (i)

Montgomery, D.R. 1999. Process domains and the river continuum. Journal of the American Water Resources Association 35:397-410. (i)

Montgomery, D.R., and J.M. Buffington. 1997. Channel-reach morphology in mountain drainage basins Bulletin of the Geological Society of America 109:596-611. (i)

Montgomery, D.R., J.M. Buffington, N.P. Peterson, D. Schuett-Hames, and T.P. Quinn. 1996. Stream-bed scour, egg burial depths, and the influence of salmonid spawning on bed surface mobility and embryo survival. Canadian Journal of Fisheries and Aquatic Sciences 53:1061-1070. (i)

Moore, J.W. 2006. Animal ecosystem engineers in streams. BioScience 56:237-246. (i)

Morley, S.A., and J.R. Karr. 2002. Assessing and restoring the health of urban streams in the Puget Sound Basin. Conservation Biology 16:1498-1509. (i)

O'Callaghan, J. 2012. Thinking big: linking rivers to landscapes. Science Findings, Issue 139. U.S. Forest Service, Pacific Northwest Research Station, Portland, Oregon. (viii)

Osborne, L.L., and D.A. Kovacic. 1993. Riparian vegetated buffer strips in water-quality restoration and stream management. Freshwater Biology 29:243-258. (i)

Pausas, J.G., and J.E. Keeley. 2014. Abrupt climate-independent fire regime changes. Ecosystems 17:1109-1120. (i)

Perkin, J.S., and K.B. Gido. 2012. Fragmentation alters stream fish community structure in dendritic ecological networks. Ecological Applications 22:2176-2187. (i)

Pollock, M.M., M. Heim, and D. Werner. 2003. Hydrologic and geomorphic effects of Beaver dams and their influence on fishes. American Fisheries Society Symposium 37:213-233. (i)

Raymond, K.L., and B. Vondracek. 2011. Relationships among rotational and conventional grazing systems, stream channels, and macroinvertebrates. Hydrobiologia 669:105-117. (i)

Reid, L.M., N.J. Dewey, T.E. Lisle, and S. Hilton. 2010. The incidence and role of gullies after logging in a coastal redwood forest. Geomorphology 117:155-169. (i)

Richardson, J.S., R.E. Bilby, and C.A. Bondar. 2005. Organic matter dynamics in small streams of the Pacific Northwest. Journal of the American Water Resources Association. 41:921-934. (i)

Robinson, C.T., K. Tockner, and J.V. Ward. 2002. The fauna of dynamic riverine landscapes. Freshwater Biology 47:661-677. (i)

Roper, B.B., B. Jarvis, and J.L. Kershner. 2007. The role of natural vegetative disturbance in determining stream reach characteristics in central Idaho and western Montana. Northwest Science 81:224-238. (i)

Ryan, D.F., and J.M. Calhoun. 2010. Riparian adaptive management symposium: a conversation between scientists and management. PNW-GTR-830. U.S. Forest Service, Pacific Northwest Research Station, Portland, Oregon. (viii)

Stanley, S., S. Grigsby, D.B. Booth, D. Hartley, R. Horner, T. Hruby, J. Thomas, P. Bissonnette, R. Fuerstenberg, J. Lee, P. Olson, and G. Wilhere. 2011. Puget Sound characterization. volume 1: the water resources assessments (water flow and water quality). Publication #11-06-016. Washington State Department of Ecology, Olympia. Available: https://fortress.wa.gov/ecy/publications/publications/1106016.pdf. (January 2019). (viii)

Talbot L.M. 1996. The linkage between ecology and conservation policy. Pages 368-378 *in* S.T.A. Pickett, R.S. Ostfeld, M. Shachak, and G.E. Likens, editors. The ecological basis of conservation. Chapman & Hall, New York. (i)

Taylor, P.D., L. Fahrig, K. Henein, and G. Merriam. 1993. Connectivity is a vital element of landscape structure. Oikos 68:571-573. (i)

Taylor P.D., L. Fahrig, and K.A. With. 2006. Landscape connectivity: a return to the basics. Pages 29–43 *in* K. Crooks and M.A. Sanjayan, editors. Connectivity conservation. Cambridge University Press, Cambridge, United Kingdom. (i)

Thorstad, E.B., F. Økland, K. Aarestrup, and T.G. Heggberget. 2008. Factors affecting the within-river spawning migration of Atlantic Salmon, with emphasis on human impacts. Reviews in Fish Biology and Fisheries 18:345-371. (i)

Tockner, K., F. Schiemer, and J.V. Ward. 1998. Conservation by restoration: the management concept for a river-floodplain system on the Danube River in Austria. Aquatic Conservation: Marine and Freshwater Ecosystems 8:71-86. (i)

Vannote, R.L., G.W. Minshall, K.W. Cummins, J.R. Sedell, and C.E. Cushing. 1980. The river continuum concept. Canadian Journal of Fisheries and Aquatic Sciences 37:130-137. (i)

Vietz, G.J., M.J. Sammonds, C.J. Walsh, T.D. Fletcher, I.D. Rutherfurd, and M.J. Stewardson. 2014. Ecologically relevant geomorphic attributes of streams are impaired by even low levels of watershed effective imperviousness. Geomorphology 206:67-78. (i)

Wallbrink, P.J., B.P. Roddy, and J.M. Olley. 2002. A tracer budget quantifying soil redistribution on hillslopes after forest harvesting. Catena 47:179-201. (i)

Walsh, C.J., A.H. Roy, J.W. Feminella, P.D. Cottingham, P.M. Groffman, and R.P. Morgan II. 2005. The urban stream syndrome: current knowledge and the search for a cure. Journal of the North American Benthological Society 24:706-723. (i)

Wang, L., J. Lyons, P. Kanehl, and R. Bannerman. 2001. Impacts of urbanization on stream habitat and fish across multiple spatial scales. Environmental Management 28:255-266. (i)

Ward, J.V., K. Tockner, D.B. Arscott, and C. Claret. 2002. Riverine landscape diversity. Freshwater Biology 47:517-539. (i)

Wiens, J.A. 2002. Riverine landscapes: taking landscape ecology into the water. Freshwater Biology 47:501-515. (i)

Chapter 9. Science Synthesis to Management Implications

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9.1. Introduction

This chapter summarizes important scientific findings from chapters 1 through 8 and provides a brief discussion of scientific themes that can inform thoughtful approaches to protecting or restoring riparian ecosystems and associated aquatic habitats. The current state of the science, as reviewed in chapters 1 through 8, clearly demonstrates the importance of an intact riparian ecosystem to the proper functioning of aquatic habitats. It also introduces new studies on conservation of watershed-scale processes that directly affect aquatic habitats and that help maximize the ecological benefits of riparian ecosystems.

Riparian ecosystems are a priority habitat because their composition, structure, and functions dramatically affect a multitude of fish, amphibian, reptile, bird, mammal, and invertebrate species (Cummins 1974; Richardson et al. 2005). Although riparian ecosystems are a small portion of the landscape, approximately 85% of Washington's wildlife species use them (Thomas et al. 1979). Protecting or restoring high function to this relatively small portion of the landscape can disproportionally benefit many species and other important ecosystem goods and services (e.g., clean water, fisheries, and flood control) (NRC 2002).

Our definition of riparian ecosystem is integral to the development of management recommendations. Riparian ecosystems are transitional areas (ecotones) between terrestrial and aquatic ecosystems and are distinguished by gradients in biophysical conditions, ecological processes, and biota (NRC 2002). Riparian ecosystems include areas through which surface and subsurface hydrology connect waterbodies with uplands. They include those portions of terrestrial area that significantly influence exchanges of energy and matter with aquatic ecosystems (i.e., a zone of influence). Following Naiman and Bilby (1998), we include active floodplains and the terraces and adjacent uplands that contribute organic matter to active channels or active floodplains as part of the riparian ecosystem.

9.2. Summary of Chapters 2 Through 8

Chapters 2 through 8 discussed five key riparian ecosystem functions including bank stability, stream shading, wood recruitment, litter fall, and pollutant removal, as well as other topics related to the riparian ecosystems including stream channel morphology, nutrient dynamics, dryland riparian areas, and watershed-scale processes. Here we summarize the main points of each chapter.

9.2.1. Stream Channel Morphology (Chapter 2)

The stream morphology chapter explained how the composition, structure, and functions of riparian ecosystems and their associated aquatic habitats

depend on dynamic interactions of water, sediment, wood, and riparian vegetation. Important points from this chapter are:

- Erosion, transport, and deposition of sediment are part of a hierarchy of disturbance processes that continually create, maintain, destroy, and recreate the variety of aquatic habitats.

- Geomorphic processes related to the input of sediments to streams (from local stream bank erosion to mass wasting events) are integral to a watershed's natural disturbance regime and necessary for long-term ecological sustainability. For example, sediments delivered to streams from hillslope mass wasting events are often the predominant source of gravel, which is essential for salmon spawning habitat.

- Bank stability is one of five key ecological functions of riparian areas. Vegetation has mechanical and hydrologic effects on bank stability, and these effects can be stabilizing or destabilizing. However, in general, the net effect of vegetation is stabilizing.

- Simple models suggest that in an old-growth riparian forest, the full contribution of root strength to streambank stability is provided by trees within approximately 33 ft (10 m) of the streambank.

- Over a period of decades to centuries, a river or stream will travel across the entirety of its channel migration zone. Because the riparian ecosystem is defined by proximity to water, as the active channel moves back and forth across the channel migration zone, the riparian ecosystem moves with it.

9.2.2. Wood (Chapter 3)

Chapter 3 focused on the role of wood in aquatic ecosystems, and the recruitment of large wood to aquatic ecosystems. Wood plays a critical role in the composition, structure, and functions of riparian and aquatic ecosystems. In-stream large wood increases hydraulic complexity, i.e., creates a wider range of flow velocities, which causes pool formation, streambed scour, sediment deposition, and channel migration. The net result is a diversity of aquatic habitat types. Main points from the wood chapter include:

- The effects of wood on aquatic ecosystems in the Pacific Northwest are well-understood and ecologists are very confident about the critical role of wood in fish habitats.

- Ecologists are also confident about the role of riparian forests in supplying large wood to aquatic systems.

- Source distances for in-stream wood are a function of tree height in riparian ecosystems. Source distances are longer for riparian forests with taller trees.

- The main uncertainties for management are: the shape of the wood recruitment function, and in particular, the shape under different site-level and watershed conditions; and the potential contributions from recruitment mechanisms outside the riparian forest, such as landslides, debris flows, and extreme channel migration.

- In an unmanaged natural riparian area, 100% of a site's large wood recruitment potential comes from a distance of about 85 to 230 ft (26 to 70 m), depending on site productivity class. This does not account for additional wood recruitment through landslides, debris flows, or extreme channel migration.

9.2.3. Stream Temperature (Chapter 4)

The chapter on stream temperature presented a conceptual model for stream thermal regimes, discussed the effects of water temperature on fish, herpetofauna, and invertebrates; and reviewed the impacts of various land uses on stream thermal regimes. The chapter's key points include:

- Riparian vegetation can strongly affect stream thermal regimes (i.e., the spatial and temporal distribution of temperatures) which affects the survival and productivity of aquatic species. The importance of the thermal regime, not just summer peak temperatures, to aquatic species is increasingly acknowledged, but our ability to manage for suitable thermal regimes is limited.

- Fish and other aquatic organisms use different stream habitats, defined in part by specific water temperature ranges. However, the scientific literature is conclusive about the importance of cool stream temperatures (≤60°F [15.6°C]) for salmonid survival and productivity.

- Shade can substantially reduce the amount of direct solar radiation to the stream, which is one of the main sources of heating, especially in narrow low-order streams.

- Shade from riparian vegetation is affected by vegetation height, canopy density, and stem density. The width of a riparian area affects the amount of shading to the stream.

- A stream's thermal regime is also affected by latitude, elevation, aspect, topographic shading, channel bed shape, and water volume in addition to tributary, groundwater, and hyporheic flows.

- Structures such as large wood can reduce stream temperature by increasing pool depths, causing the development of undercut banks that provide shade, and by enhancing hyporheic exchange through redirecting surface flow to subsurface flow.

9.2.4. Pollution Removal (Chapter 5)

The pollutant removal function is unique in that it only exists in the presence of human activities that generate polluted water, and it is only necessary when nonpoint source runoff from upland activities threaten to degrade water quality. The pollution removal chapter covered the common sources, biological impacts, in situ chemistry, transport pathways, and results of removal efficacy studies for five types of pollutants—sediments, excess nutrients, metals, pesticides and other organic compounds, and pathogens. Key points from the pollution removal chapter include:

- There is overwhelming evidence in the scientific literature that riparian buffers[1] reduce nonpoint source water pollution for a variety of pollutants, and that riparian buffer width is the most important variable explaining removal efficacy.

- Research also indicates that the second most important variable in pollution removal is the vegetative composition and structure in riparian buffers.

[1] Riparian buffer refers to a strip of land adjacent to a stream that helps protect the stream from nonpoint source pollutants originating from upslope areas.

- Riparian buffer width recommendations depend on the particular pollutant to be removed and the desired removal efficacy. Policy makers must choose the desired removal efficacy.

- Models from four separate peer-reviewed meta-analyses show that riparian buffer widths for 95% removal efficacy of sediment range from 56 to 251 ft (17 to 76 m). Meta-analyses for other pollutants exhibit a similar degree of uncertainty with regard to riparian buffer width.

- Due to uncertainty regarding riparian buffer widths needed for a desired removal efficacy, management of riparian areas for the removal of pollutants should be monitored within an adaptive management program.

9.2.5. Nutrient Dynamics (Chapter 6)

The nutrient dynamics chapter explained the many effects of riparian areas on the three primary macro-nutrients: nitrogen, phosphorus, and carbon. Riparian areas can be nutrient sources or sinks, and riparian areas mediate the movements of nutrients between uplands and surface waters. Key points from the nutrient dynamics chapter include:

- Organic matter from riparian areas is an essential source of nutrients and chemical energy for aquatic ecosystems. Nutrients enter streams via plant litter fall or via surface and subsurface water flow.

- Streams in the Pacific Coastal Ecoregion of Washington (Naiman et al. 2000) are generally nutrient-poor and well shaded. Hence, additional nutrients (e.g., salmon carcasses) may enhance aquatic ecosystem productivity. However, aquatic communities may be adversely impacted by excessive anthropogenic nutrients such as nitrogen and phosphorus.

- One study suggests that riparian area widths needed to deliver 95% of annual litter input from mature conifer forests to streams ranges from 39–54% of mean tree height depending on a site's slope and wind exposure.

- Empirical evidence suggests increasing salmon carcasses, and their marine-derived nutrients and energy, to riparian ecosystems could contribute significantly to the recovery of imperiled salmon populations.

- More research is needed on the effects of riparian litter fall on stream productivity and on the relationship between salmon harvest escapement and salmon population productivity.

9.2.6. Riparian Areas of the Columbia Plateau (Chapter 7)

The chapter on riparian areas of the Columbia Plateau covered aspects of riparian ecology that are unique to this semi-arid to arid (i.e., dryland) ecoregion. The chapter clarified the definition of riparian ecosystem in dryland ecoregions, and reviewed the history of human impacts to riparian areas in the Columbia Plateau. It also reviewed the scientific literature on the five key riparian ecosystem functions – bank stability, stream shading, wood recruitment, litter fall, and pollutant removal – and it added a function of particular importance in the Columbia Plateau – alluvial water storage. Other important points include:

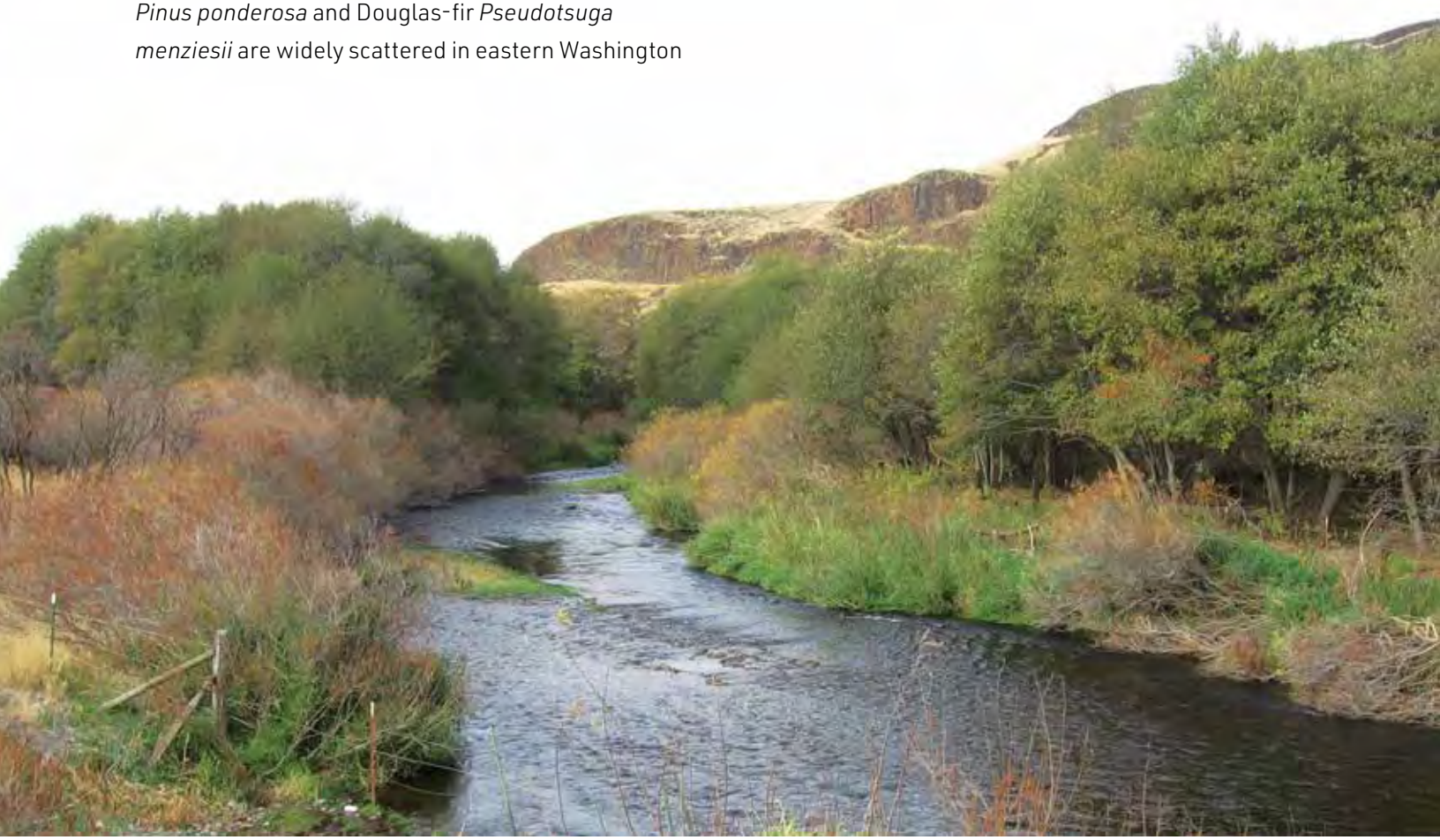
- Vegetation within riparian ecosystems of the Columbia Plateau often exhibits an abrupt demarcation between the riparian zone and the zone of influence. Phreatophytic trees and shrubs and hydrophytic herbaceous plants are confined to moist streamside areas, but the upland zone of influence may consist of sagebrush or bunchgrass communities.

- Nearly all riparian areas in the Columbia Plateau have been significantly impacted by human land use (grazing, intensive agriculture), resource exploitation (Beaver *Castor canadensis* trapping, timber harvest), water management (dams, diversions, reservoirs), or invasive plant species.

- Riparian areas in the Columbia Plateau are inhabited by a variety of deciduous woody plants, with the largest being Black Cottonwood *Populus trichocarpa* and White Alder *Alnus rhombifolia*. Pondersoa Pine *Pinus ponderosa* and Douglas-fir *Pseudotsuga menziesii* are widely scattered in eastern Washington riparian areas and were likely more common historically than at present. Compared to forested ecoregions, large woody debris play a much smaller role in fluvial processes.

- A rudimentary classification system based on overstory conveys obvious differences in stream shading provided by riparian areas: tall tree, short tree, tall shrub, shrub, grass-like, grass, and forb. The obvious implication of these vegetation types is that some stream channels in the Columbia Plateau receive little or no shade from vegetation, even historically. However, the actual historical condition of many riparian areas is unknown.

- Where the riparian zone is narrow (<100 ft [<30 m]) or the zone of influence lacks tall trees (<100 ft), the width of the riparian ecosystem is based on the pollutant removal function.



The Tucannon River flows generally northwest from headwaters in the Blue Mountains of southeastern Washington to the Snake River/Terra Hegy, WDFW

9.2.7. Watersheds (Chapter 8)

The chapter on watershed-scale processes looked beyond the site-level perspective at which riparian ecosystems are normally studied and managed. The chapter presented a conceptual framework that identified the key watershed processes and their primary influences on riparian ecosystems. The key points from the watersheds chapter are:

- Riparian ecosystems occupy perhaps the most dynamic and disturbance-prone area in a watershed. Nevertheless, the relative abundances of various aquatic habitat types in unmanaged, natural watersheds tends to remain constant over long periods (decades to centuries). In other words, at the watershed scale, habitat types appear to be in dynamic equilibrium.

- Riparian areas and surrounding watersheds are complex and dynamic systems comprised of many interacting components. These interactions across the watershed and through time create a mosaic of stream conditions necessary for self-sustaining populations of fish and other aquatic organisms.

- Some animal species have major impacts on the composition and structure of stream networks. Salmon, for example, restructure channel bed substrates during spawning and Beaver restructure the morphology and hydrology of floodplains. These "ecosystem engineers" are vital components of riparian ecosystems.

- Longitudinal, lateral, and vertical connectivity are critical for maintaining or restoring riparian ecological composition, structure, and functions. Studies have shown the importance of connectivity along the riparian corridor, but are often lacking specific guidance for management beyond "more is better."

- The composition, structure, and functions of riparian areas are affected by surrounding land uses (e.g., forestry, agriculture, residential).

- The effectiveness of riparian ecosystems to protect aquatic habitats can be circumvented by anthropogenic changes at the watershed scale. The routing of water from human development to streams via channelized flow, for example, can result in changes to the stream hydrograph, changes in channel morphology, reduced efficacy of the riparian pollutant removal function, and increases in fine sediment inputs to streams.

- More research is needed on practical ways to maintain or emulate natural disturbances in watersheds dominated by human land uses (e.g., agriculture, residential). This includes disturbances such as flooding and landslides that are essential for maintaining aquatic habitats.

9.3. Key Management Implications from Chapters 1 through 8

- Protection and restoration of riparian ecosystems continues to be critically important because: a) they are disproportionately important, relative to area, for aquatic species, e.g., salmon, and terrestrial wildlife, b) they provide ecosystem services such as water purification and fisheries (Naiman and Bilby 2001; NRC 2002; Richardson et al. 2012), and c) by interacting with watershed-scale processes, they contribute to the creation and maintenance of aquatic habitats.

- Stream riparian ecosystems encompass the riparian zone, the active floodplain including riverine wetlands, and the terraces and adjacent uplands that contribute matter and energy to the active channel or active floodplain (Gregory et al. 1991; Naiman and Bilby 1998).



Engineered large wood structure in the north fork of the Lewis River/ Chuck Stambaugh, WDFW

Such terraces and adjacent uplands are called the zone of influence.

- The width of the riparian ecosystem is estimated by one 200-year site-potential tree height (SPTH) measured from the edge of the active channel or active floodplain. Protecting functions within at least one 200-year SPTH is a scientifically supported approach if the goal is to protect and maintain full function of the riparian ecosystem.

- Where the riparian zone is narrow (<100 ft [30 m]) and the zone of influence lacks tall trees (<100 ft), (e.g., in parts of the Columbia Plateau Ecoregion) the pollution removal function may determine the width of the zone of influence.

- The riparian ecosystem begins at the edge of the active channel or active floodplain, whichever is wider. As the active channel moves back and forth across the channel migration zone (CMZ), the riparian ecosystem moves with it. Consequently, there are times when the riparian ecosystem lies adjacent to and immediately outside the CMZ. Hence, to maintain riparian ecosystem functions, management must anticipate and protect future locations of the riparian ecosystems.

- A near consensus of scientific opinion holds that the most effective and reliable means of maintaining viable self-sustaining fish, especially salmon, is to maintain/restore ecosystems to conditions that resemble or emulate their historical range of natural variability (Swanson et al. 1994; Reeves et al. 1995; Bisson et al. 2009). This opinion is based in part on the complexity of processes that affect the expression of habitats over time and space.

- The protection and restoration of watershed-scale processes, especially related to hydrology, water quality, connectivity, and inputs of wood, shade, and sediment are important for aquatic system function, and help maximize the ecological benefits of riparian ecosystem protections.

- Riparian areas and surrounding watersheds are complex and dynamic systems comprised of many interacting components. Natural disturbances (floods, fire, and landslides) across the watershed and through time create the mosaic of conditions necessary for self-sustaining populations of fish, especially salmon, and other aquatic organisms.

- Impending changes to aquatic systems as a result of climate change increase risk to species already threatened by human activities. The effects of climate change on rivers and streams threaten to reduce fish distribution and viability throughout the Pacific Northwest (Beechie et al. 2013).

- The use of the precautionary principle and adaptive management are particularly appropriate when dealing with complex and dynamic systems, and when we have uncertainty related to exactly how management activities affect functioning of watersheds and riparian ecosystems.

9.4. Width of Riparian Ecosystems

The width of the riparian ecosystem is based on the zone of influence, and the zone of influence is based on riparian ecosystem functions (or processes) that affect aquatic habitats. FEMAT's (1993) curves are conceptual models describing how four key riparian ecosystem functions change with distance from the stream channel (Figure 9.1). The four functions are root strength (i.e., streambank stability), stream shading, litter fall (i.e., input of detrital nutrients), and coarse wood debris to

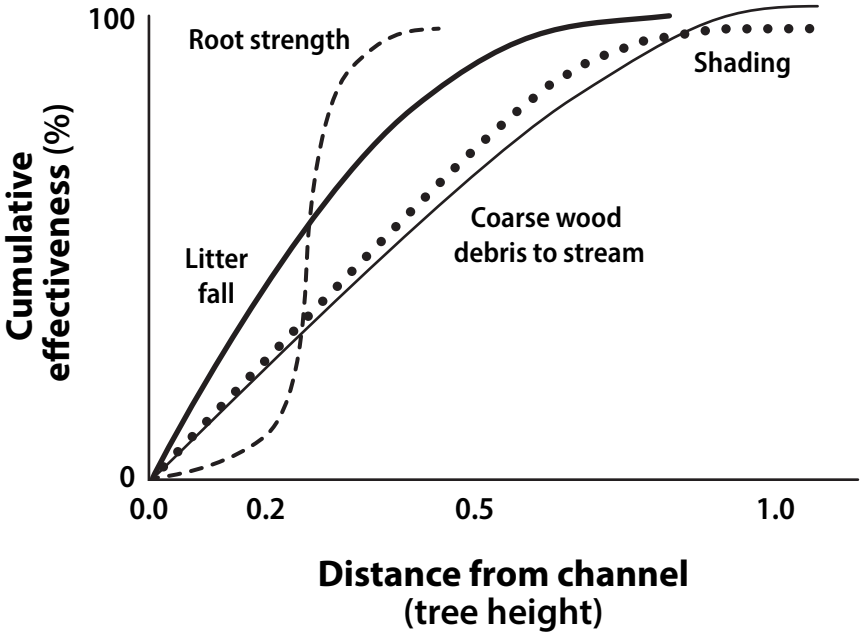


Figure 9.1. The "FEMAT Curves" (FEMAT 1993) are generalized conceptual models describing some riparian ecosystem functions and processes as the distance from a stream channel increases. "Tree height" in this figure is based on the average maximum height of the tallest dominant trees (200 years old or greater) and is referred to as site-potential tree height (SPTH).

stream (i.e., recruitment of large wood). FEMAT (1993) also included the pollution removal function (i.e., water quality) but did not create a curve for it. Originally, the curves were meant to convey two important points: 1) these four riparian ecosystem functions occur within one SPTH, and 2) the marginal return for each function decreases as distance from the stream channel increases. In other words, the FEMAT curves show that areas closer to the stream provide more of each function per unit width than areas farther from the stream.

The FEMAT curves are generalizations that ignore site-specific variability in riparian function among stream reaches. Nevertheless, FEMAT's conceptual models have influenced the width of riparian management zones (RMZs) in a number of important conservation plans such as the Forests and Fish Habitat Conservation Plan (DNR 2005).[2] Protecting natural vegetation within at least one SPTH is a scientifically supported approach if the goal is to protect and maintain ecological functions of riparian areas for the benefit of aquatic species. All else being equal, protecting areas narrower than one SPTH will result in lower levels of ecological function, and generally increase risk to fish and aquatic wildlife.

Although not all riparian functions are strongly associated with tree height (e.g., pollution removal), several key functions are, e.g., large wood recruitment, stream shading, and litter fall. Hence, the FEMAT curves use tree height of the dominant tree species to help estimate the amount of function provided by riparian areas of different widths. Consequently, the area within a site-potential tree height has often been used to define the extent of the "riparian ecosystem." However, FEMAT curves dealt strictly with functions strongly associated with vegetation and thus did not attempt to represent all aspects of the riparian ecosystem, such as other riparian functions or habitats for terrestrial species. For example, FEMAT curves did not explicitly address floodplains and riverine wetlands, sub-surface water movements, nutrient dynamics, pollutant removal, or groundwater recharge.

Given its utility, the height of site-potential trees has been described for a wide variety of tree species and can be readily found in the silvicultural literature. Fox (2003) found that mean heights of dominant trees in riparian old-growth forest of Washington range from 100 to 240 ft (30 to 70 m). The wide range of heights reflects differences in site productivity, i.e., local differences in soil nutrients and moisture, light and temperature regimes, and topography (Avery and Burkhart 1994: 278). Site productivity is described quantitatively through a site index, which is the average height that dominant trees of a particular species are expected to attain at a specified tree age. Tables (e.g., King 1966) have been developed to predict the future average height of dominant trees on a site.

FEMAT (1993:V-34) defined site-potential tree height as "the average maximum height of the tallest dominant trees (200 years or more) for a given site class." The key phrase in this definition is "200 years or more" which refers to the approximate minimum age of old-growth forests (Franklin and Spies 1991). This reflects FEMAT's underlying assumption that old-growth forest conditions are needed for full riparian ecosystem functions. Because Douglas-fir can continue height growth for more than 200 years (Herman and Lavender 1990), site-potential height based on age 200 years is the minimum width for full riparian ecosystem functions according to FEMAT. Moreover, in addition to changes in SPTH with increasing forest age, other riparian forest components (e.g., basal area of live trees, species composition, volume of dead woody material) continue to change after 200 years of age (Fox 2003) resulting in what may be important but relatively unstudied implications for riparian ecosystem functions and values.

[2] However, we note that the Forests and Fish Habitat Conservation Plan (FFHCP) did not adopt the FEMAT (1993) definition of site-potential tree height. The FFHCP defined SPTH as the height of dominant trees at age 100 years.



Quinault River/Wendy Cole, WDFW

9.5. The Condition of Riparian Ecosystems

Many scientific experts (Swanson et al. 1994; Reeves et al. 1995; Bisson et al. 2009) believe that the most likely way to realize viable self-sustaining fish, especially salmon, populations is to maintain/restore ecosystems to conditions that resemble their historical range of natural variability[3] (hereafter historical conditions). The scientific rationale for this opinion is that fish species have over many millennia adapted to particular disturbance regimes and consequent habitat conditions. Therefore, many scientists believe that dramatic deviation from historical conditions reduces the average survival and fecundity of animal populations, and thus puts species at risk of extinction (Swanson et al. 1994).

We define the historical conditions as the dynamic range of ecosystem composition, structure, and functions prior to significant impacts by Euro-American settlement (Swanson et al. 1994). Landres et al. (1999) suggest that the historical conditions provides guidance, context, and benchmarks for management. Understanding changes to historical conditions imposed by past management action (e.g., clearcutting riparian areas) can inform decisions on future management and realistic future objectives, such as desired future condition (DFC). Articulating riparian DFC with awareness of historical conditions provides a meaningful benchmark for assessing potential loss of riparian function and potential risks to fish and wildlife populations (Landres et al. 1999; Morgan et al. 1994). Because historical composition and structure were driven by disturbances, Landres et al. (1999) also suggest that managers should maintain, or at least emulate, the disturbance processes that created historical conditions. In other words, historical conditions describe relationships between species and habitats and thus provide context and guidance for managing ecological systems in the future. Emulating historical conditions could include the appropriate use of engineered solutions (e.g., stormwater basins to reduce peak flows, placing large wood in streams) to protect or restore habitats. Bisson et al. (2009) promote this same concept for conserving freshwater habitats of anadromous salmonids.

Managing a site, reach, or watershed to more closely resemble historical conditions may also effectively serve as a coarse-filter conservation strategy. Coarse filter strategies are based on the idea that managing for a habitat type, perhaps by emulating historical

[3] Also referred to as "historical natural variability," "natural variability," "range of natural variability," "natural range of variability," "historical range of variability," or "reference variability" (Landres et al. 1999).



Riparian ecosystem near Naches/Mary Huff, WDFW

conditions, will more efficiently conserve many species rather than managing for each species separately (Hunter et al. 1988; Swanson et al. 1994). Consistent with Landres et al. (1999), managing riparian areas with a goal of emulating historical conditions may be more cost effective in the long run than other approaches as it should require fewer investments in mitigation for degraded riparian ecosystem functions. In other words, managing for historical conditions is consistent with the idea that avoiding impacts to habitat is less expensive and more scientifically defensible than restoring habitat for each species after impacts.

Emulating an ecosystem's historical conditions poses both empirical and conceptual challenges. Empirical data needed to estimate the historical conditions are seldom available, and when available, the data are usually inadequate for the task of reliably estimating historical variation over time and space (Keane et al. 2009). The biggest conceptual challenge is posed by the ever-changing environment, much of it wrought by humans. While the historical conditions provides the best description of habitats that supported fish and wildlife species in the past, we recognize the challenge of applying that knowledge to watersheds that have been drastically altered by exotic species, fire suppression, intensive land uses, and climate change. Despite these challenges, Keane et al. (2009) still believe that the historical conditions provides an essential perspective for managers.

Historical conditions are the result of natural processes such as frequent floods, landslides, and wildfire – some of catastrophic magnitude – occurring throughout a watershed. Hence, for obvious reasons, managing riparian areas so that they roughly match their historical conditions may be unrealistic, especially in residential or agricultural settings. Furthermore, WDFW acknowledges that other uses of riparian areas as legitimate and worthwhile. Such uses and a wide variety of societal values must also be considered when developing strategies, plans, or rules for riparian areas. Therefore, rather than a goal, the historical conditions may better serve as a guide.

Dynamic mosaics of riparian and aquatic habitats are created, maintained, and altered in predictable (e.g., seasonally) and unpredictable ways (e.g., due to random events like storms, fires, and landslides).

9.6. Other Important Issues

We highlight three important issues that deserve more in-depth discussion: complexity, connectivity, and climate change. We also consider management implications of each issue for riparian areas and watersheds.

9.6.1 Complexity

The ecologist Frank Egler stated, "Ecosystems are not only more complex than we think, but more complex than we can think" (Egler 1977). Riparian ecosystems fit that description – they are dynamic, nonstationary, nonlinear systems comprised of many interacting components. In dynamic systems, conditions continually change over time. Dynamic equilibrium, for instance, means that conditions continually fluctuate about an average state, and the long-term statistics describing that process – mean, variance, fluctuation frequency – remain virtually constant. Nonstationary means that a system's functional relationships are changing over time, and consequently, the long-term statistics describing the process are changing. Some scientists believe that future climate change will lead to more pronounced nonstationarity in aquatic ecosystems (Milly et al. 2008). Nonlinear implies that functional relationships between ecosystem components are complicated. Under certain conditions, some types of nonlinear relationships may exhibit chaotic behavior. Not surprisingly, predicting the effects of management actions on dynamic, nonstationary, nonlinear systems is challenging.

Frissell et al. (1986) helped conceptualize watersheds as hierarchical systems where larger scale components, structures, and processes act primarily in the downstream direction on smaller scale components, structures, and processes. Factors that affect processes



The Nooksack River is located in the northwest part of Washington. It drains an area of the Cascade Range around Mount Baker, and flows through a fertile agricultural area before emptying into Bellingham Bay./Department of Natural Resources

over the longest duration can be considered "drivers" of the conditions and processes at lower levels in the hierarchy. Climate, geology, topography (and land cover) largely determine watershed characteristics and processes (paraphrasing the framework of Montgomery 1999). However, the composition, structure, and functions of streams and riparian ecosystems do not simply arise from these drivers. They are created and modified by continuous and episodic fluxes of materials (particularly water, sediment, and wood) and energy, which are broadly termed watershed processes. Dynamic mosaics of riparian and aquatic habitats are created, maintained, and altered in predictable (e.g., seasonally) and unpredictable ways (e.g., due to random events like storms, fires, and landslides).

These types of nonlinear dynamics are intrinsic properties of all ecosystems and important for the creation and maintenance of habitats that fish and wildlife populations depend on (Fausch et al. 2002; Ward et al. 2002; Wiens 2002), including salmon (Merz et al. 2015). The availability of multiple types of habitat (i.e., habitat heterogeneity) within and among streams may be essential for the persistence of multiple life history strategies in salmon species (Hilborn et al. 2003; Bisson et al. 2009; Waples et al. 2009; Merz et al. 2015) and the coexistence of other aquatic and riparian-dependent species (Bellmore et al. 2015).

The availability of multiple types of habitat within and among streams may be essential for the persistence of multiple life history strategies in salmon species and the coexistence of other aquatic and riparian-dependent species.

How should we approach the management of ecosystem complexity? Because ecosystems are wickedly complex (Ludwig 2001) and exhibit irreducible natural variability at multiple spatial and temporal scales, managers should adopt an attitude of humility. Over-confident managers who approach decisions with resolute certainty may fail to anticipate problems or recognize potential risks. Humility should instill in managers a desire to understand more before acting and a further desire to continually improve one's understanding of the system. The former is a quality of the precautionary principle, and the latter is a philosophical underpinning of adaptive management. Adaptive management is discussed later in this chapter.

9.6.2. Connectivity

Several chapters in this volume introduce the idea of watershed connectivity, in particular, longitudinal, lateral, and vertical connectivity. Connectivity is vital to aquatic ecosystem function and especially important at conferring resiliency to the negative effects of climate change (see section 9.6.3). Streams and their associated riparian ecosystems transport water, wood, sediment, nutrients, and organisms predominantly, but not exclusively in the downstream direction. Longitudinal (upstream to downstream) fragmentation of streams, for example by road crossings that block passage of fish, can reduce habitat capacity for individual species and change aquatic community composition by impeding movements of fish and other animals. Dams and undersized culverts also reduce the transport of large wood and sediment from upstream areas, which can adversely impact habitat composition and structure. Loss of lateral connectivity between streams and their floodplains due to levees, dams, or channel incision can reduce development of off-channel aquatic habitats, alter riparian plant communities, and impact processes such as water storage and nutrient cycling. Reduction of vertical connectivity, i.e., exchanges between stream water and deeper groundwater in the

hyporheic zone, can increase stream water temperatures, alter stream chemistry, and impact macroinvertebrate populations.

The importance of connectivity is also supported by our understanding of the extents at which aquatic species, especially fish, use stream habitat (Fausch et al. 2002). Movement of individuals among reaches and watersheds to locate specific habitat conditions (e.g., suitable water temperatures) is increasingly acknowledged as important to fish population persistence, particularly in light of climate change.



Bull trout in Deep Creek, Yakima County/Eric Anderson, WDFW

Maintaining connectivity in aquatic ecosystems likely requires management at site and watershed-scales. Management to protect or restore salmon and other aquatic species should ensure that all parts of a stream network that could be accessible to fish are in fact accessible to fish. That is, artificial structures should not impede fish movement. This requires watershed-scale stream network inventories and site-scale correction of artificial barriers. Additionally, barriers to the longitudinal or lateral transport of sediment and wood should be corrected, and hyporheic exchange should be enhanced by restoring the processes that supply in-stream large wood and coarse sediments. Where practical, management should ensure that the flows of water, sediment, and wood continue to flow as they did historically.

9.6.3. Climate Change

Climate change is expected to directly affect aquatic ecosystems by increasing air and water temperatures, altering stream hydrology, and impacting sediment yields throughout Washington. Indirect effects are too numerous to mention here but are likely to include changes to riparian plant communities, changes in fire regime, introduction of new diseases, exotic pests, and competitors with salmon. Because water temperature is widely recognized as one of the most important environmental factors influencing the geographic distribution, growth, and survival of fish (Regier et al. 1990; Armour 1991; McCullough 1999), the warming effects of climate change on rivers and streams threaten to reduce fish distribution and population viability (Beechie et al. 2013). The Pacific Northwest experienced a significant warming trend in summer stream temperatures of approximately 0.40°F/decade (0.22°C/decade) between 1980 and 2009 (Isaak et al. 2012). In the future, August stream temperatures are expected to increase an average of 5.1°F (2.8°C) by the 2080s (Isaak et al. 2015), and stream temperatures are expected to increase in all seasons of the year. The effects of climate change on surface water temperatures are compounded by other anthropogenic increases of water temperature caused by removal of riparian vegetation, water withdrawals, and channelization of streams (Poole and Berman 2001; Moore et al. 2005).

Climate change is projected to cause major changes in hydrology across Washington. Scientists have already detected negative trends in glacier volume and snowpack (Granshaw and Fountain 2006, Sitts et al. 2010, Stoelinga et al. 2010) and earlier peak streamflow in many rivers (Stewart et al. 2005). These trends are expected to continue in the future, along with increasing flood magnitudes, declining summer minimum flows, and rising stream temperatures (Elsner et al. 2010, Mantua et al. 2010). In Washington State, projected changes in future annual total precipitation are generally small compared to year-to-year fluctuations in seasonal and annual rainfall. Nonetheless, hydrological projections for the mid to late 21st century show a shift in flood frequencies that results in larger peak flows at all recurrence intervals , e.g., 2-year, 5-year, 10 year, etc. in some watersheds (Salathè et al. 2014). Changes are projected to be most pronounced in middle elevation basins, where a substantial proportion of the basin is located near the snowline (i.e., the "mixed rain and snow" zone). In these watersheds, warming will cause more precipitation to fall as rain instead of snow, which will decrease snow accumulation, hasten melt, and increase runoff (Hamlet et al. 2007).

Changes in stream flow are expected to alter sediment transport and channel morphology, however, published research analyzing the potential impact of future climate change on fluvial processes is limited. Praskievicz (2015) modeled the effects of future climate on geomorphic responses in three snow-dominated river basins of Idaho and eastern Washington. The results from the first site on the Tucannon River indicate that net sediment deposition is likely to occur, with increasing mid-channel bars. The second study site on the Coeur d'Alene River projects net erosion, and results for the third site forecast minimal changes on the Red River. These varying results indicate that the impacts of climate on sediment movement also depend on local context, i.e., how reach traits, such as substrate size or riparian vegetation, affect a stream channel's morphological stability or lateral mobility.

Management to minimize direct detrimental effects of climate change on aquatic habitat includes: 1) increasing shade to streams by protecting or restoring riparian forests, 2) decreasing thermal sensitivity of surface waters by increasing summer low flows, 3) maintaining longitudinal, lateral, and vertical connectivity within watersheds, 4) monitoring and mitigating stream temperatures, especially when management actions are known to cause stream temperature increases, and 5) developing contingency plans for responding to climate related changes to water temperature, hydrology, or channel morphology. Because riparian areas can provide longitudinal habitat connectivity, link aquatic and terrestrial ecosystems, and create thermal refugia for wildlife, climate change makes the restoration of riparian areas especially important (Seavy et al. 2009).

9.7. Uncertainty and Management

Chapters 2 through 8 demonstrate that management of riparian ecosystems often involves substantial and unavoidable uncertainty, despite the fact that many riparian ecosystem functions are well understood. We include a discussion on uncertainty in management because effective use of scientific knowledge requires an understanding of its uncertainty (Fischhoff and Davis 2014) and because addressing uncertainty can lead to better long-term outcomes (Steel et al. 2009) for all stakeholders.

Some uncertainty is due to limited knowledge. For instance, the historical composition and structure of native riparian vegetation in the Columbia Plateau remains relatively unknown (see Chapter 7). Research can improve knowledge and reduce this type of uncertainty. A less well-appreciated type of uncertainty is associated with stochastic environmental variability, which introduces irreducible uncertainty or "unavoidable unpredictability" (sensu Spielgelhalter and

Riesch 2011) into the expected effects of management decisions. In other words, the longer one's time horizon for management decisions, the more likely that less expected, or even unexpected effects are going to occur. This type of uncertainty can be quantified through research, but never reduced. For example, large floods may unexpectedly alter channel form (e.g., widen a channel) and as a result change a stream's thermal regime. This in turn can decrease the effectiveness of management aimed at maintaining stream temperature based on pre-flood riparian conditions (see Chapter 4). This concept is important because conditions created by some land management actions are ubiquitous and long-lived (e.g., young forests after timber harvest), thus creating a situation where less expected effects due to environmental variability are virtually guaranteed.

Using stream temperatures to discuss uncertainty is instructive because our understanding of riparian effects on stream temperatures is arguably the best developed of any riparian function (see Chapter 4). We know for instance how certain ecosystem composition, structures, and functions (predictor variables) affect stream temperatures, so we could accurately predict the effects of common management actions with high certainty. Unfortunately, logistical or economic constraints of collecting predictor variable data usually preclude the development and use of such models. Instead, we often employ simpler, statistical models or correlations to inform management. For instance, we can generally predict changes to water temperatures based on changes to shade from riparian vegetation because changes in shade are often strongly correlated with changes in water temperatures (Cristea and Janisch 2007).

Figure 9.2 shows the results of several studies relating changes in summer stream temperatures to changes in riparian buffer width. Stream temperatures were measured before and after reducing the widths of forested riparian buffers, which decreased shading of streams. The results of such studies are often assumed to predict the effects of shade reduction on stream temperatures in other locations. However, because each stream is unique (e.g., differences in stream widths, topographic shade, groundwater flows, etc.), changes in water temperature based solely on shade are relatively uncertain. For example, Jackson et al. (2001) found that 30-ft wide forested buffers caused summer stream temperatures to increase by an average of 4.2°F (2.4°C), but the 95% confidence interval for the average was -0.1° to 8.6°F (0.0 to 4.8°C). At one site, temperatures decreased, likely due to unmeasured effects on groundwater flow (Janisch et al. 2012). Such uncertainty is common. Additional studies of this type might narrow confidence intervals and more accurately estimate the average response, but predictions of stream temperature based on buffer width alone will remain highly uncertain despite our knowledge that shade can strongly affect water temperature.

Similarly, empirical data describe wood recruitment from riparian areas as increasing with distance from the channel (i.e., riparian area width), but this relation varies widely among streams (Figure 9.3). Other potential predictor variables might include the wood recruitment mechanism, topography, fire regime, and forest age. However, we are unaware of other recruitment models that include variables that would allow us to predict the effects of management actions on wood recruitment with high certainty.

Currently, most riparian ecosystem functions described in this volume are best described with statistical models or correlations that often reliably predict the direction or sign (+ or -) of the correlation and some of the variability around the central tendency. Many such models rely on data from few sites that poorly describe the average or range of relations. For example, sample sizes for studies in Figure 9.2 are small, i.e., $N = 6, 3, 5,$ and 5. Additional studies with larger sample sizes could better describe responses to shade reduction but are unlikely to substantially reduce uncertainty if they do not consider other important predictors in addition to buffer width.

Even as we conduct studies that reduce uncertainty associated with a lack of knowledge, we are continually challenged to make sound decisions into the future by irreducible uncertainty due to stochastic events, such as natural disturbances, and non-stationary processes like climate change. As riparian ecosystems change through time, whether due to future wildfire, floods, or climate change, we must ensure that our management strategies meet their intended goals. Uncertainty about the future effects of current management actions is perhaps the biggest challenge faced by managers because those effects of management often persist over long periods or may be practically irreversible (e.g., loss of riparian areas due to residential development). With this uncertainty comes the risk that the unpredictable may convert current and successful regulatory policies or management practices into future failures.

We can never eliminate uncertainty, but we can make management decisions that are appropriate given our current level of uncertainty. We recommend reducing risk to riparian ecosystems by: 1) reducing uncertainty through new research, 2) explicitly acknowledging and directly addressing uncertainty in policy and management decisions that affect fish and wildlife habitats, 3) considering the application of the precautionary principle to reduce unacceptable risk (O'Riordan and Jordan 1995; Gullet 1997). That is, erring on the side of caution, particularly when dealing with environmental impacts that are difficult to undo (irreversible damage or long recovery times), and 4) practicing adaptive management.

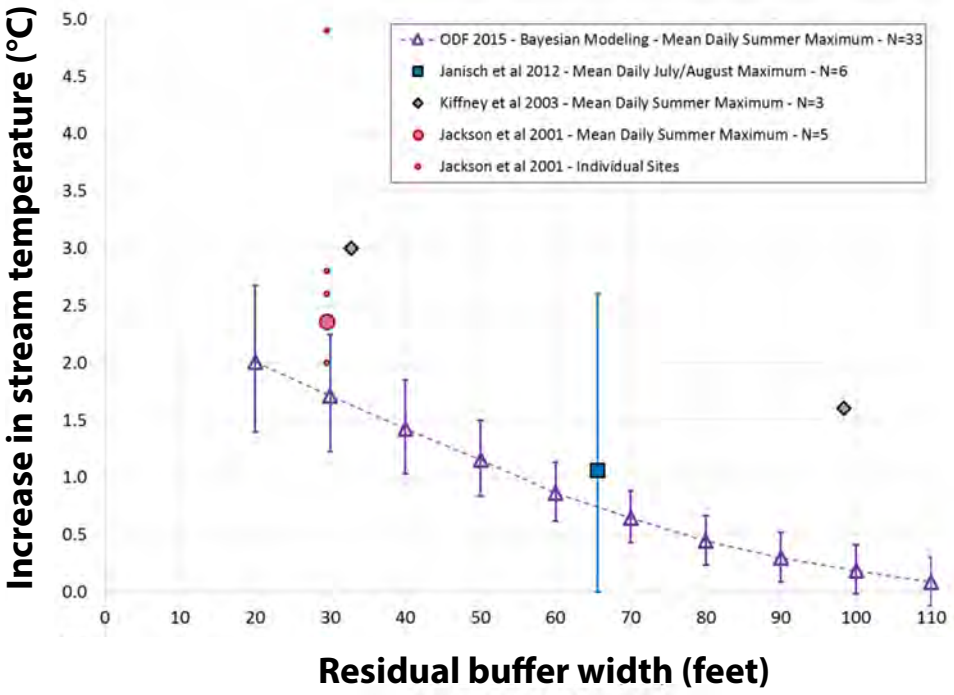


Figure 9.2. Observed temperature response associated with "no-cut" riparian buffers with adjacent clearcut harvest. Only studies that employed a Before-After-Control-Impact design and conducted in Pacific Northwest forests are included. Bayesian modeling results (and 90% credible intervals) were derived from data collected as part of Groom et al. (2011). A change of 1°C is equivalent to a 1.8°F change. Analyses provided by P. Leinenbach, USEPA Region 10 (See Chapter 4 for a more complete description of this figure).

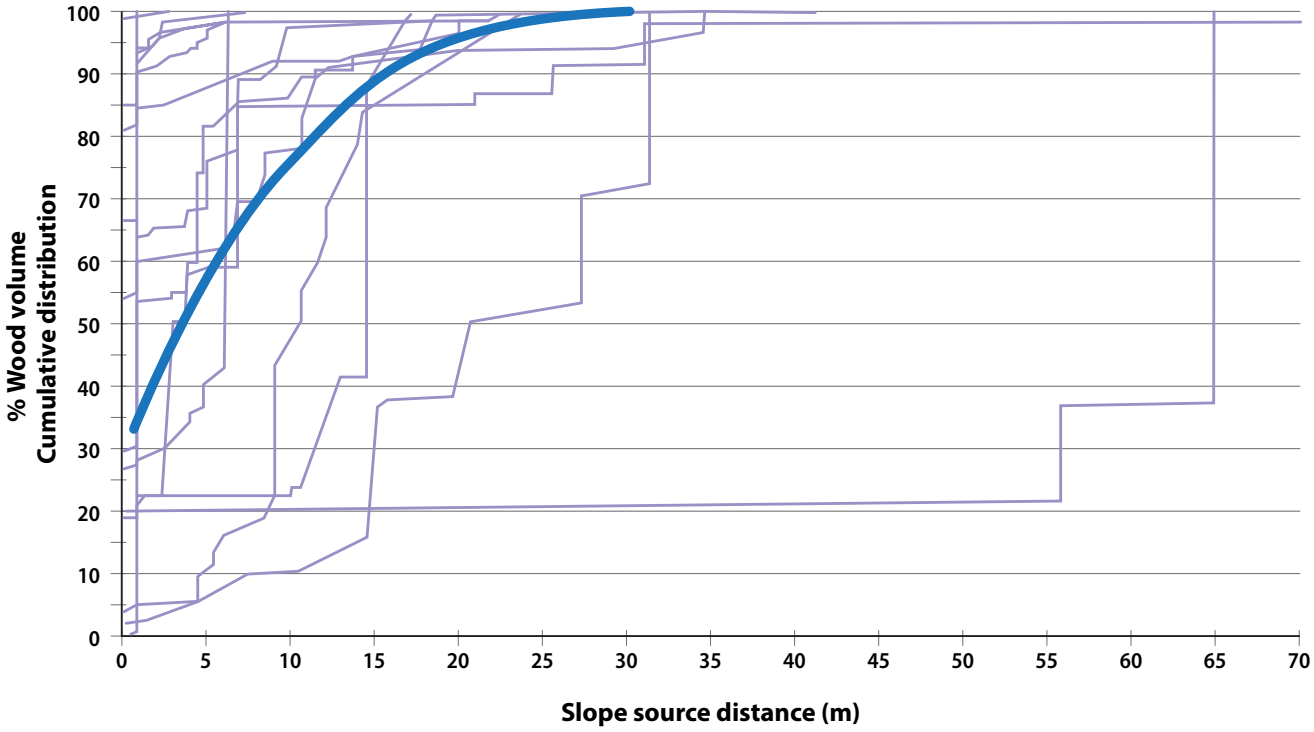


Figure 9.3. Sixteen large wood recruitment curves for second-growth redwood forest on 16 sites in northern California (from Benda et al. 2002). The theoretical prediction curve (thick line) is based on mortality recruitment only using random 360° fall trajectories. Curves to the left of the theoretical curve are sites where bank erosion is a major recruitment mechanism. Curves to the right of the theoretical curve are sites where landsliding is a major recruitment mechanism. (See Chapter 3 for a more complete description of this figure).

9.8. Adaptive Management

Despite new insights into ecosystems dynamics and better understanding of the effects of management actions on species and their habitats, natural resource management decisions will always struggle with some level of uncertainty. Adaptive management is widely recognized as a sensible, if not essential, approach to the management of natural resources under uncertainty. As originally conceived, adaptive management can be defined as the systematic acquisition and application of reliable information to improve management over time (Wilhere 2002). Reliable information is acquired through statistically-valid research and monitoring. Furthermore, adaptive management can facilitate a way forward when levels of uncertainty become high enough to threaten stakeholder agreement about environmental policies (Wilhere and Quinn 2018).

The adaptive management process is a continual cycle consisting of planning, action, monitoring, evaluation, and adjustment (Bormann et al. 1994, Wilhere 2002) (Figure 9.4). Monitoring and evaluation form a feedback loop that provides information for management decisions. However, feedback alone cannot fulfill the goal of adaptive management, that is, the continual improvement of management. Ideally, an "adaptive management plan" integrates every phase of management with monitoring, and considers how information collected through monitoring will lead to future changes in management. Developing an adaptive management plan should be a collective endeavor of policy makers, managers, field staff, and scientists.

Successful adaptive management requires an understanding of all stakeholder perspectives. Hence, developing an adaptive management plan should begin with discussions amongst stakeholders about their concerns regarding uncertainty and risk. The plan should be developed through a negotiated process, and it should explain how specific risks will be addressed through a program of systematic learning (e.g., management experiments, focused monitoring, targeted literature reviews, etc.). Importantly, the best adaptive management plans have agreements about the specific information necessary to change policy or management and what those changes might be.

Adaptive management programs can fall victim to the widespread confusion between the roles of values and science in management decisions (Wilhere and Quinn 2018). Maintaining a clear distinction between values (cultural, social, and economic) and science, and between the roles of policy makers and scientists, is critical to success. That said, WDFW recognizes that natural resource management or land use policies must often balance competing ecological, economic, and social values. In fact, one of WDFW's conservation principles is that management decisions should integrate ecological, economic, and social perspectives. This volume addresses only the ecology of riparian area management; it does not cover economic and social aspects. Determining an acceptable balance requires a political process involving stakeholders, local governments, tribes, and state agencies. We hope this volume can help to inform that process.

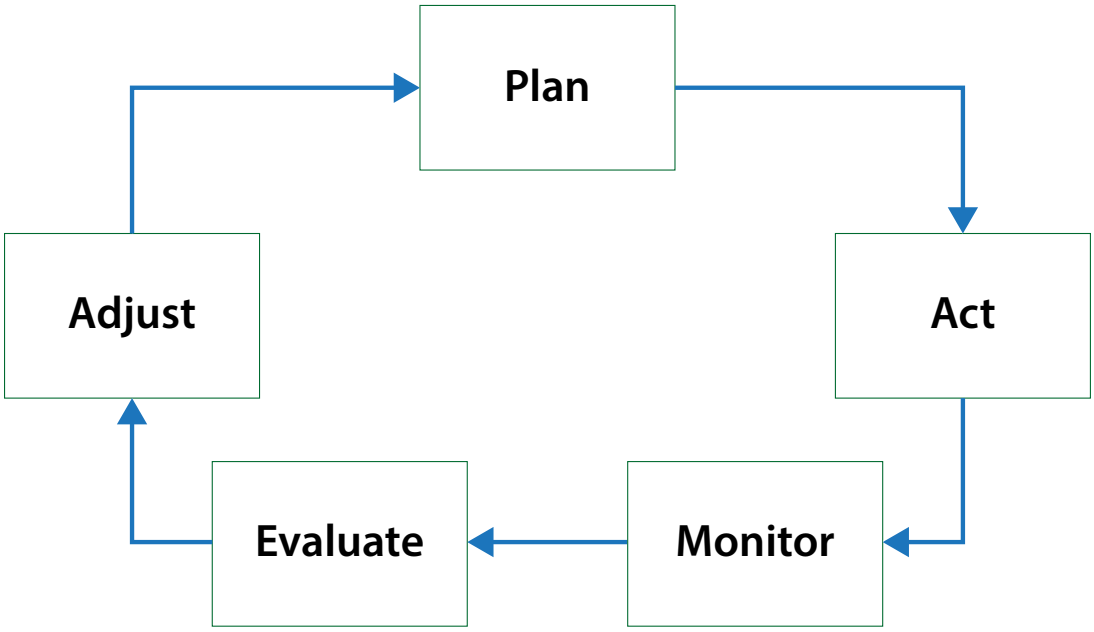


Figure 9.4. The adaptive management cycle (modified from Bormann et al. 1994).

9.9. Literature Cited[4]

Armour, C. 1991. Guidance for evaluating and recommending temperature regimes to protect fish. Biological Report 90(22). Fish and Wildlife Service, Washington, D.C. (viii)

Avery, T.E., and H.E. Burkhart. 1994. Forest measurements. McGraw-Hill, New York. (i)

Beechie, T.J., H. Imaki, J. Greene, A. Wade, H. Wu, G. Pess, P. Roni, J. Kimball, J. Stanford, P. Kiffney, and N. Mantua. 2013. Restoring salmon habitat for a changing climate. River Research and Applications 29:939–960. (i)

Bellmore, J.R., C.V. Baxter, and P.J. Connolly. 2015. Spatial complexity reduces interaction strengths in the meta-food web of a river floodplain. Ecology 96:274-283. (i)

Benda, L.E., P. Bigelow, and T.M. Worsley. 2002. Recruitment of wood to streams in old-growth and second-growth redwood forests, northern California, U.S.A. Canadian Journal of Forest Research 32:1460-1477. (i)

Bisson, P.A., J.B. Dunham, and G.H. Reeves. 2009. Freshwater ecosystems and resilience of Pacific salmon: habitat management based on natural variability. Ecology and Society 14(1):45. (i)

Bormann, B.T., P.G. Cunningham, M.H. Brookes, V.W. Manning, and M.W. Collopy. 1994. Adaptive ecosystem management in the Pacific Northwest. PNW-GTR-341. U.S. Forest Service, Pacific Northwest Research Station, Portland, Oregon. (viii)

Cristea, N., and J. Janisch. 2007. Modeling the effects of riparian buffer width on effective shade and stream temperature. Washington Department of Ecology, Olympia. (viii)

Cummins, K.W. 1974. Structure and function of streams ecosystems. BioScience 24:631-641. (i)

DNR (Washington Department of Natural Resources). 1999. Forests and fish report. Forest Practices Division, Olympia, Washington. (viii)

DNR (Washington Department of Natural Resources). 2005. Final forest practices habitat conservation plan. Forest Practices Division, Olympia, Washington. (viii)

Egler, F.E. 1977. The nature of vegetation: its management and mismanagement. Aton Forest, Norfolk, Connecticut. (viii)

Elsner, M.M., L. Cuo, N. Voisin, J.S. Deems , A.F. Hamlet, J.A. Vano , K.E.B. Mickelson, S.Y. Lee, and D.P. Lettenmaier. 2010. Implications of 21st century climate change for the hydrology of Washington State. Climatic Change 102:225–260. (i)

Fausch, K.D., C.E. Torgersen, C.V. Baxter, and H.W. Li. 2002. Landscapes to riverscapes: bridging the gap between research and conservation of stream fishes. BioScience 52:483-498. (i)

FEMAT (Forest Ecosystem Management Assessment Team). 1993. Forest ecosystem management: an ecological, economic and social assessment. U.S. Department of Agriculture and U.S. Department of the Interior, Portland, Oregon. (viii)

Fischhoff, B., and A.L. Davis. 2014. Communicating scientific uncertainty. Proceedings of the National Academy of Science 111(Supplement 4): 13664-13671. (i)

Fox, M.J. 2003. Spatial organization, position, and source characteristics of large woody debris in natural systems. Doctoral dissertation. University of Washington, Seattle. (i)

Franklin, J.F., and T.A. Spies. 1991. Composition, function, and structure of old-growth Douglas-fir forests. Pages 71-82 *in* L.F. Ruggerio, K.B. Aubry, A.B. Carey, and M.H. Huff, technical coordinators. Wildlife and vegetation of unmanaged Douglas-fir forests. PNW-GTR-285. U.S. Forest Service, Pacific, Northwest Research Station, Portland, Oregon. (viii)

Frissell, C.A., W.J. Liss, C.E. Warren, and M.D. Hurley. 1986. A hierarchical framework for stream classification: viewing streams in a watershed context. Environmental Management 10:199-214. (i)

4 References are classified according to RCW 34.05.271 (see Appendix 1) denoted by a lower case roman numeral (i – viii) in parentheses at the end of the citation.

Granshaw, F.D., and A.G. Fountain. 2006. Glacier change (1958–1998) in the North Cascades National Park Complex, Washington, USA. Journal of Glaciology 52:251-256. (i)

Gregory, S.V., F.J. Swanson, W.A. McKee, and K.W. Cummins. 1991. An ecosystem perspective of riparian zones: focus on links between land and water. Bioscience 41:540-551. (i)

Groom, J.D., L. Dent, and J. Madsen. 2011. Stream temperature change detection for state and private forests in the Oregon Coast Range. Water Resources Research 47:1-12. (i)

Gullet, W. 1997. Environmental protection and the "precautionary principle": a response to scientific uncertainty in environmental management. Environmental Planning and Law Journal 14:52-69. (i)

Hamlet, A. F., P.W. Mote, M.P. Clark, and D.P. Lettenmaier. 2007. Twentieth-century trends in runoff, evapotranspiration, and soil moisture in the western United States. Journal of Climate 20:1468-1486. (i)

Herman, R.K., and D.P. Lavender. 1990. *Pseudotsuga menziesii*. Pages 527-540 *in* R.M. Burns and B.H. Honkala, technical coordinators. Silvics of North America volume 1: conifers. Agriculture Handbook 654. U.S. Forest Service, Washington, D.C. (viii)

Hilborn, R. 1987. Living with uncertainty in resource management. North American Journal of Fisheries Management 7:1-5. (i)

Hilborn, R., T.P. Quinn, D.E. Schindler, and D.E. Rogers. 2003. Biocomplexity and fisheries sustainability. Proceedings of the National Academy of Sciences 100:6564-6568. (i)

Hunter, M.L. Jr., G.L Jacobson Jr., and T. Web III. 1988. Paleoecology and the coarse filter approach to maintaining biological diversity. Conservation Biology 2:375-385. (i)

Independent Scientific Group. 1999. Scientific issues in the restoration of salmonid fishes in the Columbia River. Fisheries 24:210-219. (i)

Isaak, D., S. Wenger, E. Peterson, J. Ver Hoef, C. Luce, S. Hostetler, J. Dunham, J. Kershner, B. Roper, D. Nagel, D. Horan, G. Chandler, S. Parkes, and S. Wollrab. 2015. Development and application of NorWeST stream temperature climate scenarios for the Pacific Northwest. Webinar, January 27. North Pacific Landscape Conservation. Cooperative, Lacey, Washington. (viii)

Isaak, D.J., S. Wollrab, D. Horan, and G. Chandler. 2012. Climate change effects on stream and river temperatures across the northwest U.S. from 1980 - 2009 and implications for salmonid fishes. Climate Change 113:499-524. (i)

Jackson, C.R., C.A. Sturm, and J.M. Ward. 2001. Timber harvest impacts on small headwater stream channels in the coast ranges of Washington. Journal of the American Water Resources Association 37:1533–1549. (i)

Janisch, J.E., S.M. Wondzell, and W.J. Ehinger. 2012. Headwater stream temperature: interpreting response after logging, with and without riparian buffers, Washington, USA. Forest Ecology and Management 270:302-313. (i)

Keane, R.E., P.F. Hessburg, P.B. Landres, and F.J. Swanson. 2009. The use of historical range and variability (HRV) in landscape management. Forest Ecology and Management 258:1025-1037. (i)

Kiffney, P.M., J.S. Richardson, and J.P. Bull. 2003. Responses of periphyton and insect consumers to experimental manipulation of riparian buffer width along headwater streams. Journal of the American Water Resources Association 40:1060-1076. (i)

King, J.E. 1966. Site index curves for Douglas-fir in the Pacific Northwest. Weyerhaeuser Forestry Paper No. 8. Forestry Research Center, Weyerhaeuser Company, Centralia, Washington. (viii)

Landres, P.B., P. Morgan, and F.J. Swanson. 1999. Overview of the use of natural variability concepts in managing ecological systems. Ecological Applications 9:1179-1188. (i)

Ludwig, D. 2001. The era of management is over. Ecosystems 4:758–764. (i)

Mantua, N., I. Tohver, and A. Hamlet. 2010. Climate change impacts on streamflow extremes and summertime stream temperature and their possible consequences for freshwater salmon habitat in Washington State. Climatic Change 102:187-223. (i)

McCullough, D.A. 1999. A review and synthesis of effects of alterations to the water temperature regime on freshwater life stages of salmonids, with special reference to Chinook salmon. EPA 910-R-99e010. U.S. Environmental Protection Agency, Region 10, Seattle, Washington. (viii)

Merz, J.E., D.G. Delaney, J.D. Setka, and M.L. Workman. 2015. Seasonal rearing habitat in a large Mediterranean-climate river: management implications at the southern extent of Pacific salmon (*Oncorhynchus* spp.). River Research and Applications 32:1220-1231. (i)

Milly, P.C.D., J. Betancourt, M. Falkenmark, R.M. Hirsch, Z.W. Kundzewicz, D.P. Lettenmaier, and R.J. Stouffer. 2008. Stationarity is dead: whither water management? Science 319: 573-574. (i)

Montgomery, D.R. 1999. Process domains and the river continuum. Journal of the American Water Resources Association 35:397-410. (i)

Moore, R.D., D.L. Spittlehouse, and A. Story. 2005. Riparian microclimate and stream temperature response to forest harvesting: a review. Journal of the American Water Resource Association 41:813-834. (i)

Morgan, P., G.H. Aplet, J.B. Haufler, H.C. Humphries, M.M. Moore, and W.D. Wilson. 1994. Historical range of variability: a useful tool for evaluating ecosystem change. Journal of Sustainable Forestry 2:87-111. (i)

Naiman, R.J., and R.E. Bilby, editors. 1998. River ecology and management: lessons from the Pacific Coastal Ecoregion. Springer-Verlag, New York. (i)

Naiman, R.J., R.E. Bilby, and P.A. Bisson. 2000. Riparian ecology and management in the Pacific Coastal Rain Forest. BioScience 50:996-1011.

NRC (National Research Council). 2002. Riparian areas: functions and strategies for management. National Academy Press. Washington, D.C. (i)

O'Riordan, T., and A. Jordan. 1995. The precautionary principle in contemporary environmental politics. Environmental Values 4:191-212. (i)

Poole, G.C., and C.H. Berman. 2001. An ecological perspective on in-stream temperature: natural heat dynamics and mechanisms of human-caused thermal degradation. Environmental Management 27:787-802. (i)

Praskievicz, S. 2015. A coupled hierarchical modeling approach to simulating the geomorphic response of river systems to anthropogenic climate change. Earth Surface Processes and Landforms 40:1616-1630. (i)

Reeves, G.H., L.E. Benda, K.M. Burnett, P.A. Bisson, and J.R. Sedell. 1995. A disturbance-based ecosystem approach to maintaining and restoring freshwater habitats of evolutionary significant units of anadromous salmonids in the Pacific Northwest. American Fisheries Society Symposium 17:334-349. (i)

Regier, H.A., J.A. Holmes, and D. Pauly. 1990. Influence of temperature changes on aquatic ecosystems: an interpretation of empirical data. Transactions of the American Fisheries Society 119:374-389. (i)

Richardson, J.S., R.J. Naiman, F.J. Swanson, and D.E. Hibbs. 2005. Riparian communities associated with Pacific Northwest headwater streams: assemblages, processes, and uniqueness. Journal of the American Water Resources Association 41:935-947. (i)

Salathé Jr., E.P., A.F. Hamlet, C.F. Mass, S.-Y. Lee, M. Stumbaugh, and R. Steed. 2014. Estimates of twenty-first-century flood risk in the Pacific Northwest based on regional climate model simulations. Journal of Hydrometeorology 15:1881-1899. (i)

Seavy, N.E., T. Gardali, G.H. Golet, F.T. Griggs, C.A. Howell, R. Kelsey, S.L. Small, J.H. Viers, and J.F. Weigand. 2009. Why climate change makes riparian restoration more important than ever: recommendations for practice and research. Ecological Restoration 27:330-338. (i)

Sitts D., A.G. Fountain, and M. Hoffman. 2010. Twentieth century glacier change on Mount Adams, Washington, USA. Northwest Science 84:378-385. (i)

Spiegelhalter, D.J., and H. Reisch. 2011. Don't know, can't know: embracing deeper uncertainties when analysing risks. Philosophical Transactions of the Royal Society A 369:4730–4750. (i)

Stanford, J.A., J.V. Ward, W.J. Lis, C.A. Frissell, R.N. Williams, J.A. Lichatowich, and C.C. Coutant. 1996. A general protocol for restoration of regulated rivers. Regulated Rivers: Research & Management 12:391-414. (i)

Steel, E.A., T.J. Beechie, M.H. Ruckelshaus, A.H. Fullerton, P. McElhany, and P. Roni. 2009. Mind the gap: uncertainty and model communication between mangers and scientists. American Fisheries Society Symposium 71:357–372. (i)

Stewart, I.T., D.R. Cayan, and M.D. Dettinger. 2005. Changes toward earlier streamflow timing across western North America. Journal of Climate 18:1136-1155. (i)

Stirling, A., and D. Gee. 2003. Science, precaution, and practice. Public Health Reports 117:521-533. (i)

Stoelinga, M.T., M.D. Albright, and C.F. Mass. 2010. A new look at snowpack trends in the Cascade Mountains. Journal of Climate 23:2473-2491. (i)

Suter, G.W., L.W. Barnthouse, and R.V. O'Neill. 1987. Treatment of risk in environmental impact assessment. Environmental Management 11:295-303. (i)

Swanson, F.J., J.A. Jones, D.O. Wallin, and J.H. Cissel. 1994. Natural variability-implications for ecosystem management. Pages 80-94 *in* M.E. Jensen and P.S. Bourgeron, technical coordinators. Volume II: ecosystem management: principles and applications. PNW-GTR-318. U.S. Forest Service, Pacific Northwest Research Station, Portland, Oregon. (viii)

Thomas, J.W., technical editor. 1979. Wildlife habitats in managed forests the Blue Mountains of Oregon and Washington. Agriculture Handbook No. 553. U.S. Forest Service, Washington, D.C. (viii)

Walker, B., C.S. Holling, S.R. Carpenter, and A. Kinzig. 2004. Resilience, adaptability and transformability in social–ecological systems. Ecology and Society 9(2):5. Available: http://www.ecologyandsociety.org/vol9/iss2/art5. (January 2019) (i)

Waples, R.S., T. Beechie, and G.R. Pess. 2009. Evolutionary history, habitat disturbance regimes, and anthropogenic changes: what do these mean for resilience of Pacific salmon populations? Ecology and Society 14(1):3. Available: http://www.ecologyandsociety.org/vol14/iss1/art3/. (January 2019) (i)

Ward, J.V., K. Tockner, D.B. Barscott, and C. Claret. 2002. Riverine landscape diversity. Freshwater Biology 47:517–539. (i)

Wiens, J.A. 2002. Riverine landscapes: taking landscape ecology into the water. Freshwater Biology 47:501-515. (i)

Wilhere, G.F. 2002. Adaptive management in habitat conservation plans. Conservation Biology 16:20-29. (i)

Wilhere, G.F., and T. Quinn. 2018. How wide is wide enough?: values, science, and law in riparian habitat conservation. Natural Resources Journal 58:279-318. (i)

Wohl, E. 2005. Compromised rivers: understanding historical human impacts on rivers in the context of restoration. Ecology and Society 10(2):2. Available: http://www.ecologyandsociety.org/vol10/iss2/art2. (January 2019) (i)

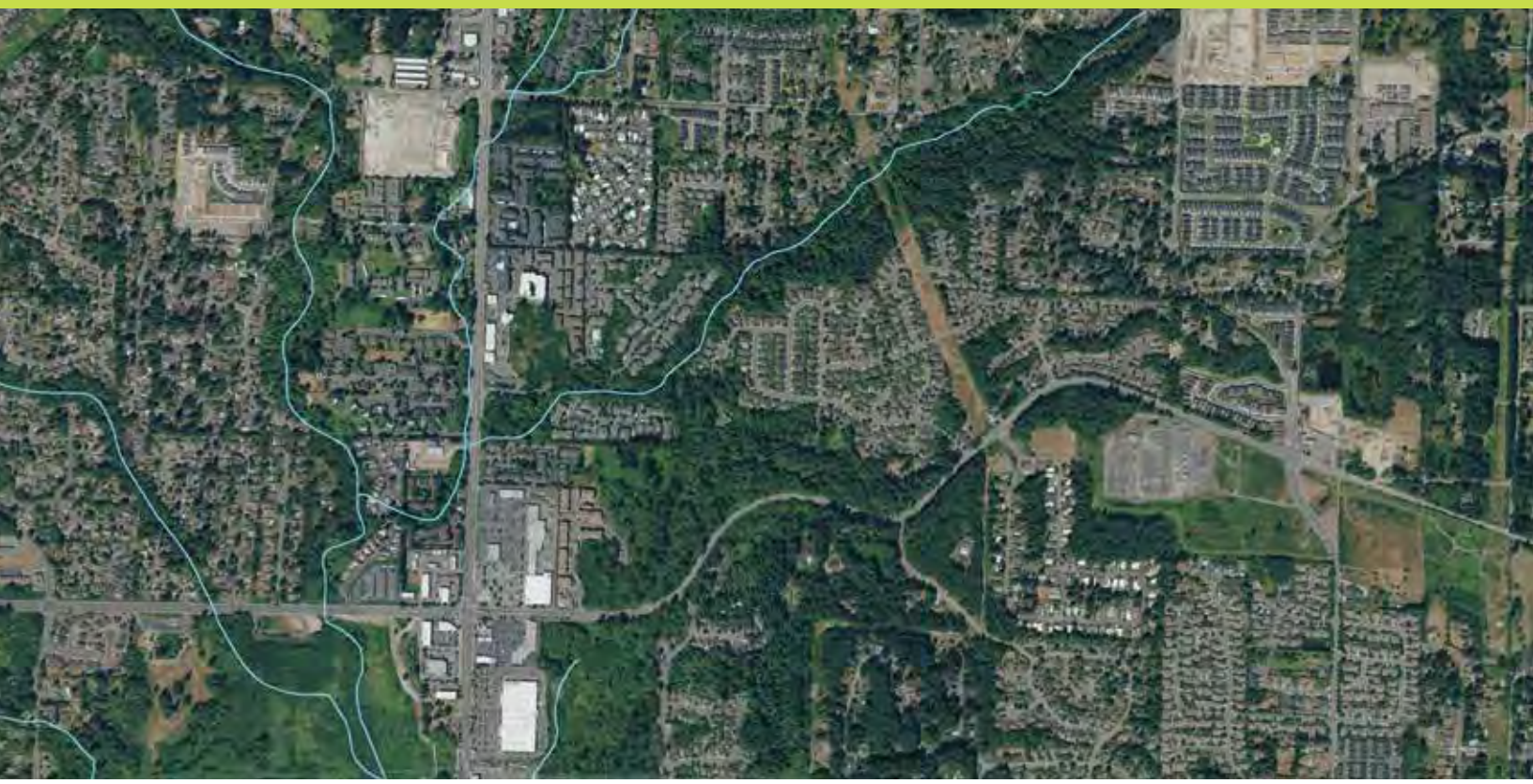
Wynne, B. 1992. Uncertainty and environmental learning: reconceiving science and policy in the preventive paradigm. Global environmental change 2:111-127. (i)

Zar, J.H. 1996. Biostatistical analysis. Prentice-Hall, Upper Saddle, New Jersey. (viii)



Grande Ronde River/Alan Bauer

Appendix 1: Glossary



Riparian areas along streams (blue lines) in north King County/Terry Johnson, WDFW

Active channel

The portion of a stream channel defined by the lower limit of continuous riparian vegetation, and it may be delineated by absence of both moss on rocks and rooted vegetation. The upper most elevation of the active channel is sometimes equated with the ordinary high water mark.

Active floodplain

A portion of floodplain that is located between the active channel and adjacent terrace or hillslopes. Depending on the watershed, the flood return interval of the active floodplain varies between 1 and 10 years.

Adaptive management

The systematic acquisition and application of reliable information to improve management over time. Ideally, adaptive management treats management decisions as experiments in order to address critical uncertainties and learn more quickly from experience. It involves setting targets, monitoring outcomes, and adjusting management decisions based on results. Hallmarks of a well conceived adaptive management program include: 1) adequate funding for research, 2) a willingness to change course when pre-established triggers are reached, and 3) a commitment to monitor and evaluate conditions at appropriate spatial and temporal scales. See Ecosystem-based management.

Anthropogenic

Caused by human activity.

Channel confinement

A description of how much a channel can laterally move within its valley determined by the ratio of valley width (distance between toe of hillslopes on both sides of a

valley) to active channel width. Typically, a segment is considered confined when the ratio is less than two and unconfined when greater than four.

Channel migration zone
The area within which a river channel is likely to move laterally over a specified period (e.g., 100 years).

Channel morphology
A stream channel's shape, which changes over time due to the interplay of water, sediments, vegetation, and certain animals, e.g., Beaver *Castor canadensis* and salmon.

Channel reach (stream)
A continuous segment of a channel that has similar physical features, such as gradient and confinement.

Channel slope or gradient
The average steepness of a stream segment measured as its change in elevation divided by its length. Typically, a segment's gradient is considered low if less than 2%, moderate between 2% and 4%, and high if greater than 4%.

Composition: See *Ecological composition*.

Disturbance regime
The frequency, magnitude, and duration of disturbance events.

Disturbance
A disturbance is any relatively discrete event in time that disrupts the composition, structure, or functions of ecosystems, communities, or populations.

Dynamic equilibrium
An ecological system's long-term state of relative stability that is maintained through opposing processes. Understanding an ecosystem's equilibrium, is a goal of ecosystem-based management.

Ecological (biological) integrity
Capacity of an ecological system to maintain a community of organisms that has species composition, diversity, and functional organization comparable to those of natural habitats within a region. An ecological system has integrity when its dominant ecological characteristics (e.g., composition, structure, function) occur within their historical ranges of natural variation.

Ecological composition
A term encompassing all parts of an ecosystem that include both living (biotic) and nonliving (abiotic) parts. Ecosystem composition is an important consideration in conservation.

Ecological function(ing)
1) The process or cause-effect relationships between two or more interacting ecosystem components; 2) the sum of processes that sustain the system; or 3) the capacity of natural processes to provide goods and services that satisfy human needs, either directly or indirectly.

Ecological process
Interactions among components of an ecosystem, both biotic (living organisms) and abiotic (chemical and physical) components. Many processes involve the transfer, conversion, or storage of matter and energy. This term is synonymous with the first definition of *ecological function.*

Ecological structure
The arrangement of and relations among the parts or components of an ecosystem.

Ecosystem
A spatially explicit unit of the Earth that includes all of the organisms, along with all components of the abiotic environment. Ecosystems have *composition, structure,* and *functions.*

Ecosystem-based management (EBM)
An integrated management approach that recognizes the full array of interactions within an ecosystem, including humans, rather than considering single issues, species, or ecosystem services in isolation. EBM often involves balancing ecological, economic, and social trade-offs within the context of existing laws and policies.

Erosion
The loosening and transport of soil particles and other sediment by water. Terrestrial erosion includes raindrop splash erosion, overland flow sheet erosion, surface flow rill (shallow) and gully (deeper) erosion. Channel erosion includes streambank erosion and channel incision. Rill and gully erosion diminishes the capacity of riparian areas to trap sediment and pollutants and often can be avoided with intact riparian vegetation.

FEMAT curve
A conceptual model that describes the relationship between various riparian *ecosystem functions* and distance from channel. The model consists of generalized curves that show the cumulative effectiveness of litter fall, root strength, shading, and coarse wood debris recruitment to stream as a function of distance from channel.

Flow regime
The distribution of stream discharges through space and time. Flow regimes can be described by their magnitude (e.g., mean annual, hourly maximum), timing, frequency or return periodicity, duration, spatial distribution, and rate of change. The pathways that water takes to reach a stream (e.g., surface runoff) exert a strong influence on the flow regime.

Function
Physical, chemical, or biological processes that occur within an ecosystem. See *ecological function(ing)* and *ecological process.*

Historical conditions: See *Range of natural variability.*

Hot moments
Periods of elevated denitrification rates. Hot moments can occur during a rainfall event. Also see *hot spots.*

Hot spots
Areas that exhibit high denitrification rates. Hot spots often occur in floodplains and other riparian areas with oscillating groundwater levels and/or higher hyporheic flows. Locations of hot spots can vary through time.

Hydrology
Study of the occurrence, distribution, movement, and properties of the water and their relationship with land.

Hyporheic zone
The area beneath the bed of a river or stream that is saturated with water.

Impervious surface
Ground surfaces that resist or prevent water infiltration, e.g., roofs of houses and roadways.

Incision
The process of downcutting into a stream channel leading to a decrease in the channel bed elevation. Incision is often caused by a decrease in sediment supply or an increase in stream flows capable of transporting (scouring) sediment.

Infiltration
The rate or process by which water on the ground surface enters the soil.

Macroinvertebrates
Animals, including insects, mollusks, crustaceans, and worms, that do not have a backbone, and are large enough to be seen without a microscope. Aquatic macroinvertebrates are commonly used as an indicator of habitat and water quality.

Mass wasting
The down slope movement of soil, sediments, and rock due to gravity (rather than water, wind, or ice, for example).

Nutrient cycling
The movement, uptake, transformation, storage, and release of nutrients, especially carbon, nitrogen, and phosphorus. Riparian characteristics that affect nutrient cycling include flow path, vegetation composition and structure, topography, groundwater level, and soil type.

Nutrient spiraling length
The distance nutrients move downstream during a complete cycle; a measure of nutrient utilization to nutrient supply. Long spiraling lengths indicate that the system is saturated with nutrients and organisms can no longer use the incoming nutrient loads. Streams in Washington forests typically have relatively short nutrient spiraling lengths.

Ordinary high water mark
This mark occurs along stream channels where the presence and action of waters are so common and usual, and so long continued in all ordinary years, as to mark upon the soil a character distinct from that of the abutting upland.

Precautionary principle
Erring on the side of causing no negative impact to natural resources when faced with uncertainty, especially for harm that is essentially irreversible. The precautionary approach involves: 1) taking preventive action (avoiding impacts), 2) shifting the burden of proof to the project proponents, 3) exploring a wide range of potential alternatives, and/or, 4) including multiple stakeholders and disciplines in decision making.

Process: See *Ecological process.*

Range of natural variability (or historical range of natural variability)
Refers to the range of ecological conditions (composition, structure, and functions) in a time period before widespread anthropogenic changes.

Riparian
An adjective meaning adjacent to a water body: stream, river, lake, pond, bay, sea, ocean. Riparian areas are sometimes referred to by different names: riparian ecosystems, riparian habitats, riparian corridors, or riparian zones. Depending on the context, these different terms may have somewhat different meanings.

Riparian buffer
Buffer refers to its purpose, which is to reduce or prevent adverse impacts to water quality, fisheries, and aquatic biodiversity from human activities occurring upslope of the buffer. Riparian buffers may also be called a riparian management zone. Riparian buffers managed specifically for pollutant removal may also be called a vegetated filter strip.

Riparian ecosystem
Riparian ecosystems are transitional between terrestrial and aquatic ecosystems and are distinguished by gradients in biophysical conditions, ecological processes, and biota. They are areas through which surface and subsurface hydrology connect waterbodies with their adjacent uplands. They include those portions of terrestrial ecosystems that significantly influence exchanges of energy and matter with aquatic ecosystems (i.e., a zone of influence). Our definition of riparian ecosystem does not include adjacent waters (i.e., river or streams, but does include riverine wetlands) and recognizes the riparian zone as a distinctive area within riparian ecosystems.

Riparian management zone
Riparian management zone is often synonymous with riparian buffer. See *Riparian buffer.*

Riparian zone
A distinctive area within riparian ecosystems. The riparian zone contains wet or moist soils and plants adapted to growing conditions associated with periodically saturated soils.

Riverscape
A landscape organized around a river system that includes the river network and contributing watershed along with other components that are not organized by watershed boundaries such as wildfire, mobile organisms, and wind-borne seeds. Distinct from uplands, it is primarily organized in a downstream direction (e.g., movement of water, sediment, and wood) but also contains lateral elements (e.g., floodplain interaction), vertical elements (e.g., interaction of surface and hyporheic flow), and upstream elements (e.g., migrating salmon).

Salmonid
A family of fish comprised of salmon, trout, and whitefish. Native salmonid species in Washington State include: Chinook Salmon *Oncorhynchus tshawytscha,* Chum Salmon *O. keta,* Coho Salmon *O. kisutch,* Pink Salmon *O. gorbuscha,* Sockeye Salmon/Kokanee *O. nerka*, Steelhead/Rainbow Trout *O. mykiss,* Cutthroat Trout *O. clarki,* Bull Trout *Salvelinus confluentus,* Dolly Varden *Salvelinus malma,* Pygmy Whitefish *Prosopium coulteri,* and Mountain Whitefish *P. williamsoni.* This list does not include names of subspecies.

Site class
The classification of a site's productivity based on the growth of the dominant tree species. Site classes vary based on local differences in soil nutrients and moisture, light and temperature regimes, and topography. Site classes are typically described as most productive (I) through least productive (V).

Site-potential tree height
The average maximum height of the tallest dominant trees for a given age and site class.

Stochastic process
An event involving chance or probability (e.g., landslide, flood). Stochastic processes may have patterns that can be analyzed statistically but cannot be precisely predicted.

Stream order
A hierarchical stream classification system in which headwater tributaries are classified as first order; when two first order tributaries meet they form a second order tributary, when two second order tributaries meet they form a third order tributary, and so on. Low order (1st-3rd) streams make up ~88% of the state's stream miles. Below its confluence with the Snake and Yakima rivers, the Columbia River is a 10th order river.

Structure: See *Ecological structure*.

Thermal loading potential
The potential amount of solar radiation (sunlight) available at a given location. Primary factors include shading (topographic and vegetative), latitude, elevation, and date.

Thermal regime (stream)
The distribution of stream temperatures through space and time. Thermal regimes can be described by their magnitude (e.g., monthly mean, hourly maximum), timing, frequency, duration, spatial distribution, and rate of change.

Thermal sensitivity (stream reach)
The susceptibility of a stream reach to changes in temperature. Thermal sensitivity typically increases with less stream flow, less groundwater input, and a wider channel to depth ratio.

Uncertainty (scientific)
The absence of information about something. Sources of uncertainty include, but are not limited to: natural variation (i.e., because ecosystems vary in unpredictable ways through time and space), model

uncertainty (e.g., we do not understand a process), systematic error (e.g., poorly designed experiments), or measurement error.

Vegetative filter strips

A riparian buffer designed to capture nutrients, contaminant compounds, and sediment transported by run-off. Filter strips are sometimes synonymous with riparian buffers.

Water quality

Physical, chemical, and biological characteristics of water that describe its suitability to meet human needs or habitat requirements for fish and wildlife.

Watershed processes

The fluxes of energy (e.g., chemical, sunlight, wildfire) and materials (particularly water and sediment) that interact with biota (e.g., vegetation, salmon, Beavers, soil microbes) to form a watershed's physical features and characteristics, which give rise to its instream physical and ecological conditions. These processes occur within a context that reflects the watershed's climate, geology, topography, and existing human land use. Also see *Ecosystem process*.

Watershed

An area of land that drains to a common waterbody.

Wood recruitment

The process of wood moving from a riparian area to the stream channel. Sources of recruitment include bank erosion, windthrow, landslides, debris flows, snow avalanches, ice storms, Beaver, and tree mortality due to fire, insects, or disease.



Northwestern salamander/WDFW

Appendix 2: Categorization of Information Sources

Legal Requirement: RCW 34.05.271

The Revised Code of Washington (RCW) 34.05.271 requires the Washington Department of Fish and Wildlife (WDFW) to categorize sources of information used to inform technical documents that directly support implementation of a state rule or statute. Because WDFW Priority Habitat and Species documents—such as this one—are referenced in regulations for the Growth Management Act [e.g., WAC 365-190-130(4)] and Shoreline Management Act [e.g., WAC 173-26-221(5)(b)], we classify all references in the literature cited sections of Volume 1 into the following RCW 34.05.271 categories:

(i) Independent peer review: Review is overseen by an independent third party;
(ii) Internal peer review: Review by staff internal to the department of fish and wildlife;
(iii) External peer review: Review by persons that are external to and selected by the department of fish and wildlife;
(iv) Open review: Documented open public review process that is not limited to invited organizations or individuals;
(v) Legal and policy document: Documents related to the legal framework for the significant agency action including but not limited to:
(A) Federal and state statutes;
(B) Court and hearings board decisions;
(C) Federal and state administrative rules and regulations; and
(D) Policy and regulatory documents adopted by local governments;
(vi) Data from primary research, monitoring activities, or other sources, but that has not been incorporated as part of documents reviewed under the processes described in (i), (ii), (iii), and (iv) of this subsection;
(vii) Records of the best professional judgment of department of fish and wildlife employees or other individuals; or
(viii) Other: Sources of information that do not fit into categories i - vii.

Meeting the Intent of RCW 34.05.271

Assigning references to categories requires judgement where methods of peer-review are not clearly defined. We assigned all scientific journal articles, science related books by independent science book publishers, universities, the National Research Council (NRC), and the National Academy of Engineering; symposia volumes sponsored by professional organizations (e.g., American Fisheries Society); and graduate theses and dissertations to category i –*independent peer review.* Government agency documents including those published by the Fish and Wildlife Service (USFWS), Environmental Protection Agency (EPA), Geologic Survey (USGS), Forest Service (USFS), and the Canadian Wildlife Service were assigned to category *viii*. Others references were assigned as described above.



Headwater wetland that flows north to Stavis Creek and south to Tahuya River/Keith Folkerts, WDFW













Washington Department of FISH and WILDLIFE

Riparian Ecosystems, Volume 2: Management Recommendations



A Priority Habitats and Species Document of the Washington Department of Fish and Wildlife

Washington Department of FISH and WILDLIFE

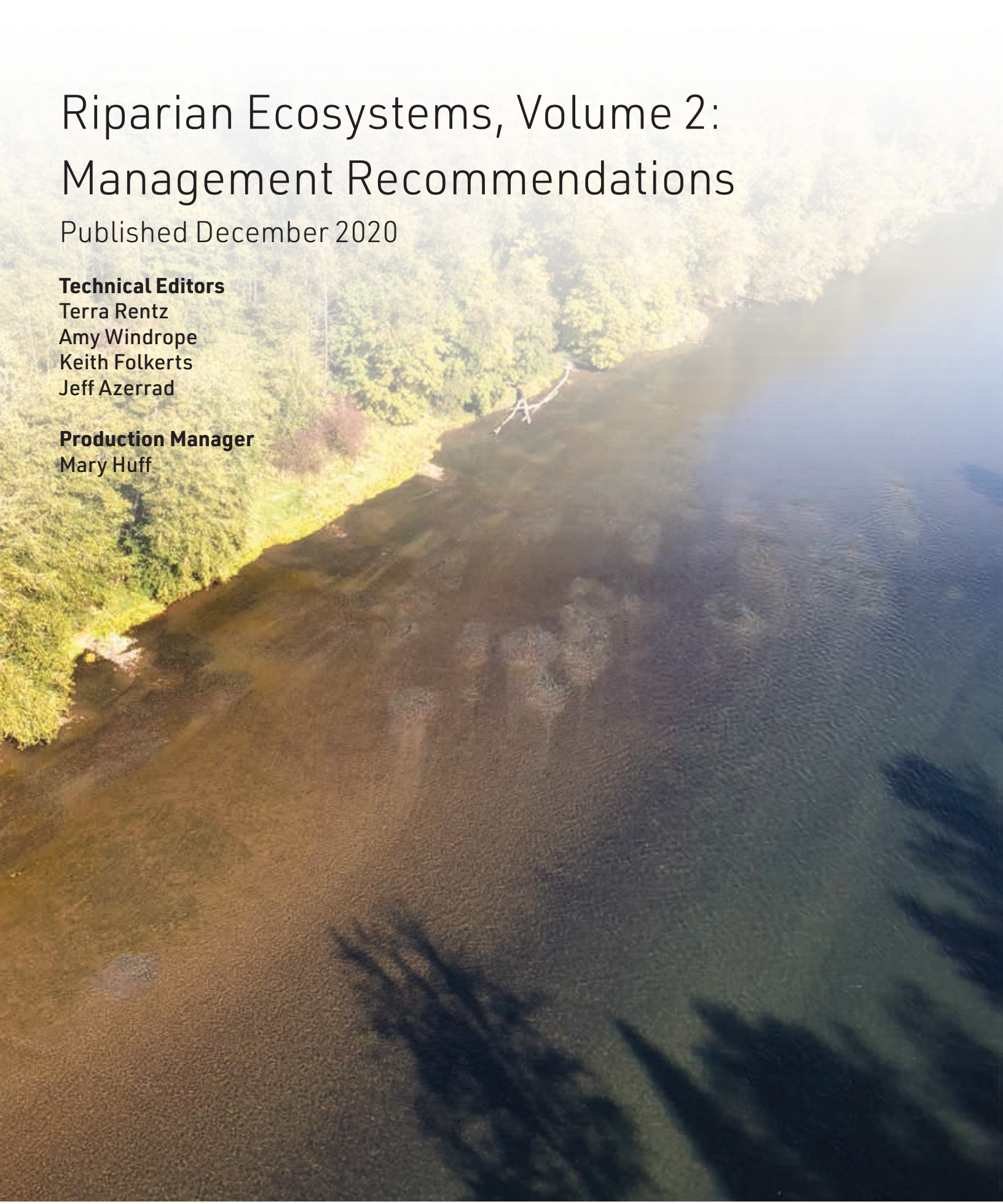
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Salmon redds along the Cowlitz River, Lewis County/George Fornes, WDFW

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Federal (EPA and NOAA Fisheries) and tribal entities (individual tribes, the Northwest Indian Fisheries Commission, Columbia River Inter-Tribal Fish Commission, and Upper Columbia United Tribes) as well as numerous state agencies (Washington State departments of Ecology, Natural Resources, and Commerce; Recreation and Conservation Office; Washington State Conservation Commission; and Puget Sound Partnership) reviewed draft versions of this document. During the summer 2018 public comment period, local governments and members of the public provided valuable feedback that led to a more concise and user-friendly final version of Volume 2.

Within WDFW, Keith Folkerts led coordination, contract planning and budgeting for this work. Tim Quinn and George Wilhere were integral in ensuring a strong relationship with information in Volume 1 and provided additional valuable feedback on multiple drafts. Terry Johnson developed the Site-Potential Tree Height mapping tool and wrote the associated user guide information in the Appendix to this Volume 2. Alison Hart produced final graphics and ensured consistent formatting and stylistic usage throughout. Mary Huff provided editorial support, improved the document's organization, and (in late 2020) took it across the finish line.

WDFW recognizes and appreciates the significant role that tribes, local governments, conservation organizations, and others play in accomplishing our agency's mission. Indeed, we are certain that without these concerted efforts to designate and protect the riparian ecosystems that are essential for most of the state's fish and wildlife species, WDFW would be unable to fulfill its mandate on behalf of all of Washington's residents.

While we acknowledge and have deep appreciation for all the review and comments provided, WDFW bears sole responsibility for this document and any errors contained herein.

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This document is available in alternative formats upon request. Please contact WDFW's ADA Program Manager at 360-902-2349, TTY (711), or ADAProgram@dfw.wa.gov.

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Acronyms for Volume 2

CAO	Critical Areas Ordinance
CMZ	Channel Migration Zone
CREP	Conservation Reserve Enhancement Program
DFC	Desired Future Condition
DNR	Department of Natural Resources (Washington State)
EBM	Ecosystem Based Management
EPA	Environmental Protection Agency (U.S.)
ESA	Endangered Species Act
FEMA	Federal Emergency Management Agency
FEMAT	Forest Ecosystem Management Assessment Team
FPA	Forest Practices Act
FWHCA	Fish and Wildlife Habitat Conservation Area
GIS	Geographic Information System
GMA	Growth Management Act
HMP	Habitat Management Plan
HRCD	High Resolution Change Detection
LID	Low Impact Development
NHD	National Hydrography Dataset
NOAA	National Oceanographic and Atmospheric Administration
NRCS	Natural Resources Conservation Service
OHWM	Ordinary High-Water Mark
OSS	On-site Sewage Systems
PHS	Priority Habitats and Species
RCO	Recreation and Conservation Office (Washington State)
RCW	Revised Code of Washington
RMZ	Riparian Management Zone
RZ	Riparian Zone
SMA	Shoreline Management Act
SMP	Shoreline Master Program
SPTH	Site-Potential Tree Height
$SPTH_{200}$	Site-Potential Tree Height (at age 200 years)
USFS	United States Forest Service
USFWS	United States Fish and Wildlife Service



Watershed lesson/Brittany Gordon, WDFW

UWCIG	University of Washington Climate Impacts Group
VSP	Voluntary Stewardship Program
WAC	Washington Administrative Code
WDFW	Washington Department of Fish and Wildlife
WFPB	Washington Forest Practices Board
WRIA	Water Resource Inventory Area
WSCC	Washington State Conservation Commission
WWRP	Washington Wildlife and Recreation Program

Chapter 1. Overview

1.1. Our Role as Washington's Conservation Agency

The mission of the Washington Department of Fish and Wildlife (WDFW) is to preserve, protect, and perpetuate the state's fish, wildlife, and ecosystems while providing sustainable fish and wildlife recreational and commercial opportunities. We offer the following science-based guidance to further that mission through the preservation, protection, and–where possible–restoration of healthy, intact, and fully functioning riparian ecosystems statewide. As described throughout this volume, we believe that protection *and* restoration[1] of Washington's riparian ecosystems is a foundational conservation action; considering a growing population and changing climate, it is also an urgent one.

Within the State of Washington's land use decision-making framework, WDFW's role is that of advisor. We provide information relative to our mission about the habitat needs of fish and wildlife, and the likely implications of various land use decisions on those resources over time. Through the Priority Habitats and Species (PHS) Program, we work cooperatively with land use decision makers and landowners to facilitate solutions that accommodate their needs and the needs of fish and wildlife. We provide this PHS document, *Riparian Ecosystems Volume 2: Management Recommendations* in support of that effort.

Priority Habitats are places that warrant special consideration for protection when land use decisions are made and should also be prioritized for restoration or enhancement wherever possible. To qualify as a "Priority Habitat" in WDFW's PHS program, an ecosystem or habitat component must provide unique or significant value to many species. Specifically, it must have one or more of the following attributes (WDFW 2008):

- Comparatively high fish and wildlife density
- Comparatively high fish and wildlife species diversity
- Important fish or wildlife breeding habitat
- Important fish or wildlife seasonal ranges
- Important fish or wildlife movement corridors
- Limited availability
- High vulnerability to habitat alteration
- Unique or dependent species

Riparian areas (comprised of riparian ecosystems, active floodplains, and riverine wetlands) meet all these criteria, and were among the first Priority Habitats described by WDFW. Riparian areas provide important ecological functions that help create and maintain aquatic habitats in addition to supporting terrestrial wildlife. Riparian areas alongside

[1] Restoration of riparian ecosystems is critically important because legacy of environmental impacts resulting from the ways land use has affected riparian areas over the past 200 years. In other words, what remains available for protection is not enough to provide the full functions and values Washington's fish and wildlife need.



Hundreds of fish and widlife species, like this female Wood Duck, depend on or use the state's riparian areas. This includes over 150 species of birds, mammals, amphibians, reptiles, and invertebrates designated as Species of Greatest Conservation Need in the 2015 State Wildlife Action Plan./Jeanne Hannah

rivers and streams are the focus of this document, however much of the science reviewed in Volume 1 and the recommendations in this Volume 2 are relevant for lakes, ponds, and marine shorelines as well.

As previously mentioned, one role of WDFW in land use decision making is that of advisor. In that role, recommendations like those contained in this document and in complementary PHS documents (available at https://wdfw.wa.gov/species-habitats/at-risk/phs/recommendations) provide critical information for the protection (and where necessary, recovery) of Washington's fish and wildlife. We recognize landowners and land managers most often face situations where various human needs must also be met; and thus, considerations other than fish and wildlife will be incorporated into land use decision making.

The information presented in this management recommendation document is not, in and of itself, science. Rather, it consists of policy recommendations which are informed by the best available science

WDFW's Mission

To preserve, protect, and perpetuate Washington's fish, wildlife, and ecosystems while providing sustainable fish and wildlife recreational and commercial opportunities.

WDFW'S Riparian Values

We value the protection and restoration of healthy, intact, and fully functioning riparian ecosystems statewide.

WDFW'S Recommendation

Within the context of wise watershed management, preserve, protect, and–where possible–restore the full extent of riparian ecosystems.

Ecosystem Based Management & WDFW's Conservation Principles

In 2013, WDFW adopted ecosystem-based management principles into policy (WDFW Policy 5004). Ecosystem-based management is an integrated, science-based approach to natural resource management that aims to sustain the ability of ecosystems to provide goods and services upon which humans and other species depend. Importantly, ecosystem-based management recognizes the magnitude of humans as change agents in the ecosystem, and the role of social, economic, and ecological factors in managing complex and dynamic systems.

We believe that conservation is best achieved through employing the following ecosystem-based management principles:

1. **We practice conservation by managing, protecting, and restoring ecosystems for the long-term benefit of people, and for fish wildlife and their habitats.**

2. **We work across disciplines to solve problems because of their connections among organisms, species and habitats.**

3. **We integrate ecological, social, economic, and institutional perspectives into our decision-making.**

4. **We embrace new knowledge and apply best science to address changing conditions through adaptive management.**

5. **We collaborate with our co-managers and conservation and community partners to help us achieve our shared goals.**

summarized in Volume 1[2] and which reflect WDFW's mission and legislative mandate. To that end, these recommendations represent WDFW's guidance for the protection and restoration of healthy, intact, and fully functioning riparian ecosystems and for how land managers and land use regulators can utilize best available science to protect these ecosystems within the scope of their authority and/or ability.

For example, local governments are encouraged to use information provided through PHS to guide critical area ordinance (CAO) updates and other land use policies, plans, or regulations. More specifically, WDFW advises using the information in this PHS Riparian Volume 2 for designating riparian areas as Fish and Wildlife Habitat Conservation Areas (FWHCAs) and protecting them for their inherent value, rather than just as buffers for rivers and streams. This is because riparian areas are so important for helping sustain endangered, threatened, and sensitive species; providing habitat connectivity for both aquatic and terrestrial wildlife; and for their critical role in protecting salmonid habitat (WAC 365-190-130).

In short, Volumes 1 and 2 focus on the science and management, respectively, of riparian ecosystems to support fish and aquatic wildlife species. Volume 1 characterizes riparian ecosystem functions and essential processes, while Volume 2 provides management guidance for riparian ecosystems in the context of watershed processes. To be clear, these two volumes do not provide a summary of science or recommendations regarding the contribution of riparian ecosystems for the protection of terrestrial wildlife species. However, our first generation PHS Riparian-specific document, *Management Recommendations for Washington's Priority Habitats: Riparian* (Knutson and Naef 1997) does provide terrestrial species information related to riparian areas. Further, PHS has separate, species-specific management recommendations that address the needs of many terrestrial Priority Species.

This document provides recommendations applicable across the State of Washington but does not address unusual, site-scale environmental conditions or issues specific to particular ecological communities. We strongly encourage addressing such matters at a local level with the assistance of WDFW regional habitat biologists, and other technical experts and stakeholders such as tribal biologists and conservation organizations.

2 The original manuscript of *Riparian Ecosystems, Volume 1: Science Synthesis and Management Implications* was publicly released in May 2018. In 2020, the format of the document was professionally designed, which included making limited updates to content focused on copyediting and improving usability. In accordance with standard citation practice, Volume 1 is now cited as having a 2020 publication date, but substantively, the current document is equivalent to the original 2018 version.

1.2. Purpose and Applicability of Volume 2

The purpose of this document is to provide guidance to protect and–where possible–restore healthy, intact, and fully functioning riparian ecosystems, which are fundamental for clean water, healthy salmon populations, and climate resilient watersheds.

Volume 2 provides information to:

- Protect existing and restore degraded riparian ecosystem functions in support of aquatic and terrestrial species recovery;
- Assist local governments with their responsibilities to protect priority fish and wildlife and their habitats;
- Assist landowners and local groups in implementing voluntary restoration actions on and off working lands; and
- Incorporate monitoring and adaptive management to understand how well regulatory and non-regulatory efforts are protecting riparian functions and values.

This guidance is applicable to riparian ecosystems statewide. We offer a specific focus on lands within the purview of the Growth Management Act (GMA) and Shoreline Management Act (SMA), although a broader application by local governments and other users is also appropriate.

While many other federal, state, and tribal government programs and policies pertain to riparian ecosystems, they are not specifically addressed in this document. For instance, we do not discuss holistic protection of floodplains, nor do we discuss specific Endangered Species Act (ESA) requirements relative to listed salmonids and other species. Also, we do not address commercial forestlands that fall under the jurisdiction of the Forest Practices Act (FPA), or the Department of Ecology's clean water regulations. These other programs and policies were developed with specific goals and objectives that may be different from the goals of this document, and as such may differ with guidance provided herein.

1.3. Science Synthesis and Management Implications (Volume 1) Summary

As stated above, Volume 1 (Quinn et al. 2020; see footnote 2) provides important information integral to the development of these management recommendations. It includes both overarching as well as specific considerations important to all efforts, large and small, to protect rivers and streams for the benefit of the aquatic species associated with them. Volume 1 focuses on the science of riparian ecosystems–specifically, how riparian areas interact with large-scale drivers (e.g., topography, geology, climate, and land use) and watershed processes to create and maintain riparian and aquatic habitat in support of fish and wildlife. Thus, we provide here an explicit definition of riparian ecosystems from Volume 1 that combines a variety of conceptual riparian descriptions from the scientific literature:

> Riparian ecosystems are transitional between terrestrial and aquatic ecosystems, distinguished by gradients in biophysical conditions, ecological processes, and biota. They are areas through which surface and subsurface




Many adult flying insects, such as the blue damselfly (above, left) spend their larval stage as freshwater macroinvertebrates. During this early period, some of those species, like the stonefly nymph (above, right) help fallen leaf litter to decompose by shredding it while feeding. At both life stages, these animals provide important food for fish and other aquatic and terrestrial widlife./Jim Cummins and Taylor Cotten, WDFW

hydrology connect waterbodies with adjacent uplands. They include those portions of terrestrial ecosystems (i.e., *a zone of influence*) that significantly influence exchanges of energy and matter with aquatic ecosystems and the portion of the ecosystem characterized by moist soils and plants adapted to periodically saturated soils – the *riparian zone* (RZ). The width of the riparian ecosystem is typically defined by the outer edge of the zone of influence, which, in forested regions, is based on site-potential tree height (SPTH) measured from the edge of the active channel. While our definition of riparian ecosystem does not include the water in river or streams, it does include riverine wetlands and recognizes the riparian zone as a distinctive area within riparian ecosystems.

To assist managers in understanding important implications of the science synthesized in Volume 1, we reiterate the ten overarching findings of that document below. These findings are also discussed in more detail in later chapters.

1. Protection and restoration of riparian ecosystems continues to be critically important because: (a) they are disproportionately important, relative to area, for aquatic species (e.g., salmon) and terrestrial wildlife; (b) they provide ecosystem services such as water purification and fisheries (Naiman and Bilby 2001, NRC 2002, Richardson et al. 2005); and (c) by interacting with watershed-scale processes, they contribute to the creation and maintenance of aquatic habitats.

2. Stream riparian ecosystems encompass the riparian zone; the active floodplain, including riverine wetlands and the terraces; and adjacent uplands that contribute matter and energy to the active channel or active floodplain (Gregory et al. 1991, Naiman and Bilby 1998). Such terraces and adjacent uplands are called the zone of influence.

3. The width of the riparian ecosystem is estimated by one 200-year SPTH measured from the edge of the active channel or active floodplain. Protecting functions within at least one 200-year SPTH is a scientifically supported approach if the goal is to protect and maintain full function of the riparian ecosystem.

4. Where the riparian zone is narrow (<100 ft [30 m]) and the zone of influence lacks tall trees (<100 ft), (e.g., in parts of the Columbia Plateau Ecoregion), the pollution removal function may determine the width of the zone of influence.

5. The riparian ecosystem begins at the edge of the active channel or active floodplain, whichever is wider. As the active channel moves back and forth across the channel migration zone (CMZ), the riparian ecosystem moves with it. Consequently, there are times when the riparian ecosystem lies adjacent to or overlaps the CMZ (see Figure 2.3). Hence, to maintain riparian ecosystem functions, management must anticipate and protect future locations of the riparian ecosystem.

6. A near consensus of scientific opinion holds that the most effective and reliable means of maintaining viable self-sustaining fish, especially salmon, and wildlife populations is to maintain/restore ecosystems to conditions that resemble or emulate their historical range of natural variability (Swanson et al. 1994, Reeves et al. 1995, Bisson et al. 2009). This opinion is based in part on the complexity of processes that affect the expression of habitats over time and space.

7. The protection and restoration of watershed-scale processes, especially related to hydrology, water quality, connectivity, and inputs of wood, shade, and sediment are important for aquatic system function, and help maximize the ecological benefits of riparian ecosystem protections.

8. Riparian areas and surrounding watersheds are complex and dynamic systems comprised of many interacting components. Natural disturbances (flood, fire, and landslides) across the watershed and through time create the mosaic of conditions necessary for self-sustaining populations of fish, especially salmon, and other aquatic organisms.

9. Impending changes to aquatic systems as a result of climate change increase risk to species already threatened by human activities. The effects of climate change on rivers and streams threaten to reduce fish distribution and viability throughout the Pacific Northwest (Beechie et al. 2013).

10. The use of the precautionary principle and adaptive management are particularly appropriate when dealing with complex and dynamic systems, and when we have uncertainty related to exactly how management activities affect functioning of watersheds and riparian ecosystems.

1.4. Key Findings and Recommendations

WDFW recognizes that there is a significant amount of work currently being done throughout the state to protect and restore riparian areas. This focus is longstanding and has ranged from regulatory protections that guide Washington's growing population to voluntary conservation on our working lands. Below, we highlight what we believe—based on best available science and our agency's mission—are the most important recommendations to ensure healthy, intact, and fully functioning riparian ecosystems that provide for the preservation, protection and perpetuation of Washington's fish and wildlife:



A tributary stream (lower left of photo) contributes sediment to a side channel of the Stillaguamish River as precipitation levels rise in autumn. Snohomish County/Mary Huff, WDFW

1. **Designate riparian ecosystems as critical areas:** WDFW recognizes riparian ecosystems as a Priority Habitat for fish and wildlife and recommends that local jurisdictions designate those ecosystems as Fish and Wildlife Habitat Conservation Areas (FWHCAs), a type of critical area. We define the bounds of the riparian ecosystem as the riparian management zone (RMZ), and this RMZ should be designated as the location where protection and restoration of riparian ecosystem functions and values are addressed. RMZs provide a framework for delineating, evaluating, planning, and managing functions and values. In this volume, we provide a process for RMZ delineation (Chapter 2).

2. **Include watershed–scale management considerations:** Watershed-scale management is critical to realizing the full benefits of riparian ecosystem protection and restoration. Certain types of anthropogenic changes at the watershed scale can dramatically reduce the effectiveness of riparian ecosystems to protect aquatic habitat. For example, unmitigated delivery of stormwater from impervious surfaces like roads, parking lots, and rooftops to streams, for example, dramatically increases peak stream flows, alters channel form, and short-circuits the capacity of riparian areas to remove pollutants from runoff. Similarly, road-crossing culverts that are impassible to fish can reduce stream-network connectivity and dramatically reduce amounts of otherwise suitable habitat.

3. **Use reference points to locate the inner edge of the RMZ:**

    - For streams without Channel Migration Zones (CMZs), the inner edge of the RMZ should be delineated starting at theouter edge of active floodplain, if this has or can be determined; otherwise, from the active channel, as delineated by the Ordinary High-Water Mark (OHWM)[3].

    - For streams with CMZs, the unpredictable nature of channel migration should be accommodated through delineation of an RMZ that encompasses both the entire CMZ and future locations of the riparian ecosystem. In these instances, the inner edge of the RMZ should be located at the outer edge of the CMZ.

Whether or not a stream has a CMZ, the distance from the inner edge of the RMZ to the outer edge of the RMZ should be one $SPTH_{200}$.

4. **Include CMZs in delineation of the RMZ:** CMZs are important to protect for maintaining riparian functions and values, and so are included in the delineation of RMZs. Over time, a riparian ecosystem will occupy different parts of the CMZ and uplands outside the CMZ. Lateral channel migration and related streambank erosion processes can pose risks to homes and communities located near rivers; however, when channels are constrained from moving, aquatic and riparian ecosystems may degrade over time. To maintain riparian ecosystem functions, land managers must anticipate and protect future locations of the riparian ecosystem and thus delineate the RMZ accordingly.

5. **Establish RMZ widths based on site-specific conditions:** From the perspective of those riparian ecosystem functions affecting aquatic systems, the width of the riparian ecosystem varies with ecological conditions. The most efficient way to protect riparian functions is to adopt protections that recognize these differences, rather than uniform-width (i.e., one-size-fits-all) RMZs, as these may result in over-protection in some places and under-protection in others.

3 Active floodplain delineations are rarely available, and we currently lack a repeatable, well-vetted, and widely accepted method for the delineation of active floodplains. Therefore, until such a process is developed, we recommend delineating the RMZ's inner edge using the OHWM for streams without CMZs.



Dryland ecoregion riparian area, Whitman County/Michael Townsend



Forested ecoregion riparian area, Chelan County/George Wilhere, WDFW

a. **In forested ecoregions, start with SPTH$_{200}$**: At most riparian areas in forested ecoregions, SPTH$_{200}$ is 100 feet or greater, and so the RMZ is delineated using one SPTH$_{200}$. If SPTH$_{200}$ is less than 100 feet, the RMZ is delineated by the pollution removal function (see below).In highly altered areas where soil data are not available, it may be necessary to estimate SPTH$_{200}$ values based on nearby soils.

b. **In dryland ecoregions, start with SPTH$_{200}$** (if available), or the width of the riparian vegetation community: If site conditions do not support tree species or SPTH$_{200}$ is less than 100 feet, then RMZ width is determined by the full extent of all riparian vegetation (the riparian zone) or by the pollution removal function–see below.

c. **For both forested and dryland ecoregions, use the pollution removal function when appropriate:** Where the SPTH$_{200}$ and/or the width of the riparian vegetative community is less than 100 feet, we recommend that RMZ width be delineated at a minimum of 100 feet, as this provides the width necessary for 95% pollution removal target for most pollutants (approximately 85% for surface nitrogen.)[4]

To aid with site-specific RMZ delineation, WDFW created an internet-based mapping tool that reports recommended widths for RMZs (Appendix 1) statewide based on SPTH$_{200}$. The tool also notes instances where a 100-foot RMZ should be applied to support the pollution removal function.

6. **Apply the recommended RMZ delineation steps to all streams, whether or not they are fish-bearing:** In 1997, WDFW recommended a lower level of protection for non-fish bearing streams than fish-bearing streams. In reviewing the current science literature for Volume 1, we found no evidence that full riparian ecosystem functions

[4] See Chapter 2, Section 2.3.5 for more information about surface nitrogen removal and other site-specific characteristics that may require RMZ distances greater than 100 feet in order to ensure an adequate pollution removal function.



Deer tracks and fallen leaves near Scatter Creek, Thurston County/Janet Anthony, WDFW

along non-fish-bearing streams are less important to aquatic ecosystems than full riparian ecosystem functions along fish-bearing streams. This recommendation is based on four additional considerations. Non-fish-bearing streams:

- Support a unique community of aquatic and riparian-obligate wildlife;
- Provide movement corridors for wildlife, particularly in the face of changing climate conditions;
- Provision fish-bearing streams with matter and energy; and
- Provide cool water to downstream reaches. Washington State has already experienced increased stream
- temperatures due to climate change and expect further increases, which have direct implications for the persistence of fish.

7. **Establish monitoring and adaptive management frameworks:** We believe it is critical to understand if riparian ecosystems protections are working as intended, and if not, to adjust them accordingly. We recommend the establishment of monitoring and adaptive management designed to improve (where necessary) local permit implementation and compliance, and to increase effectiveness of actions intended to protect aquatic species.

8. **Consider needs of relevant terrestrial species:** As stated earlier, a review of new literature related to the needs of terrestrial Priority Species was not a focus of Volume 1. Nonetheless, riparian areas provide important functions for threatened, endangered, and sensitive terrestrial wildlife that require consideration by landowners and land managers. WDFW regional habitat biologists, tribal biologists and/or other local habitat experts can assist in identification of site-specific terrestrial species needs. Because riparian protections benefit both aquatic and many terrestrial wildlife species, concentrating protections around riparian areas may also be an efficient use of resources.

1.5. Relationship with Washington's Development Laws and Regulations

1.5.1. Relationship with the Growth Management Act (GMA)

The GMA requires local jurisdictions to designate and protect critical areas, and in so doing, use best available science and give special consideration to anadromous species[5]. The GMA also encourages state agencies to provide technical assistance to counties and cities in the review of their critical areas ordinances (CAOs), comprehensive plans, and development regulations [RCW 36.70A.130(6)(g)]. While the Washington State Department of Commerce (Commerce) administers the GMA, WDFW is the lead state agency for advising local governments on matters related to one type of critical area: Fish and Wildlife Habitat Conservation Areas (FWHCAs), and we produce PHS Management Recommendations like this Volume 2 in support of that role.

This document provides guidance that is consistent with the GMA, under which local governments exercise their land use responsibilities: specifically, protection of the functions and values of critical areas. It also reflects the legal and policy framework within which WDFW and the PHS program operate, which includes among other things providing a source of best available science necessary to support local governments in distinguishing and delineating those critical areas (e.g., FWHCAs).

WAC 365-190-130
FISH AND WILDLIFE HABITAT CONSERVATION AREAS

(1) "Fish and wildlife habitat conservation" means land managed for maintaining populations of species in suitable habitats within their natural geographic distribution, so that the habitat is sufficient to support viable populations over the long term and isolated subpopulations are not created. This does not mean maintaining all individuals of all species at all times, but it does mean not degrading or reducing populations or habitats so that they are no longer viable over the long term. Counties and cities should engage in cooperative planning and coordination to help assure population viability.

Fish and wildlife habitat conservation areas contribute to the state's biodiversity and occur on both publicly- and privately-owned lands. Designating these areas is an important part of land use planning for appropriate development densities, urban growth area boundaries, open space corridors, and incentive-based land conservation and stewardship programs."

WDFW understands that local jurisdictions have existing critical area regulations that have been approved by elected officials and in many cases have been found to be compliant with GMA through the Growth Management Hearings Board and courts. We acknowledge that revising a critical area regulation can be a lengthy, expensive, and contentious process, and so jurisdictions frequently do not make updates to their CAOs more frequently than required by law or rule. In this volume, we aim to be more precise about where recent science has improved our certainty around the need for riparian protections, as well as for specific practices; and how to incorporate best available science and WDFW's management recommendations.

WDFW also recommends local jurisdictions continue considering PHS best available science (e.g., Volume 1; PHS maps), incorporating PHS Management Recommendations, and seeking technical assistance from WDFW's regional habitat biologists not just when updating and implementing critical area policies and regulations, but in all land use planning efforts.

5 RCW 36.70A.172(1): "In designating and protecting critical areas under this chapter, counties and cities shall include the best available science in developing policies and development regulations to protect the functions and values of critical areas. In addition, counties and cities shall give special consideration to conservation or protection measures necessary to preserve or enhance anadromous fisheries."

1.5.2. Relationship with the Shoreline Management Act (SMA)

As with GMA, WDFW plays a role of technical advisor under SMA, working directly through locally led development processes, with the goal of addressing needs for fish and wildlife. Under SMA, the Department of Ecology (Ecology) has a role approving Shoreline Master Program (SMP) updates when they are deemed consistent with all statutory and regulatory requirements. Ecology also has a direct role in implementation of SMPs, including issuing the final decision to approve, deny, or put conditions on locally issued conditional use permits and variances. [Under GMA, Commerce does not approve comprehensive plan updates or CAOs.]

The goal of SMA is "to prevent the inherent harm in an uncoordinated and piecemeal development of the state's shorelines" (RCW 90.58.020). To achieve that end, WDFW recommends local jurisdictions designate riparian areas and provide the same levels of protection for them within the SMA jurisdiction areas as they do under GMA. While the SMA does not apply to streams with 20 cubic feet per second (cfs) or less mean annual flow, we recommend the application of the guidelines in this Volume 2 to all rivers and streams, regardless of size.

WAC 173-26-186 GOVERNING PRINCIPLES OF THE [SMP] GUIDELINES

(8) "Through numerous references to and emphasis on the maintenance, protection, restoration, and preservation of "fragile" shoreline "natural resources," "public health," "the land and its vegetation and wildlife," "the waters and their aquatic life," "ecology," and "environment," the act makes protection of the shoreline environment an essential statewide policy goal consistent with other policy goals of the act. It is recognized that shoreline ecological functions may be imparted not only by shoreline development subject to the substantial development permit requirements of the act but also by past actions, unregulated activities, and development that is exempt from the act's permit requirements. The principle regarding protecting shoreline ecological systems is accomplished by these guidelines in several ways, and in the context of related principles."



The Shoreline Management Act includes a goal to balance multiple uses, including protecting natural resources and providing public access to waters of the state./ Andy Walgamott






Riparian areas provide habitat for many types of birds at one or more life stages, especially during breeding season and for food year round. Photo credits: Sandpiper chicks in nest/Laura Rogers; Northern Harrier foraging low over marshy vegetation/Brad Collins; male Belted Kingfisher watching for fish from fallen tree limb/Anna Owen; Purple Martin pair resting on piling above their nest-box/Kim Eggleston

1.6. Organization of Volume 2

Chapter 1 aims to establish Volume 2's purpose and intent; articulate WDFW's values; and provide policy context regarding protection and designation of riparian ecosystems.

In Chapter 2, we define the RMZ based on $SPTH_{200}$ with special considerations for urban and dryland landscapes; and provide a stepwise process for identifying and delineating the RMZ both for requiring riparian protections and for classifying RMZs as a FWHCA under GMA.

Chapter 3 articulates policies, plans, and practices that protect riparian ecosystems. WDFW recognizes that counties and cities have a long history of providing such protections, and the responsibility to include best available science when updating CAOs. The protection recommendations described in this chapter are intended to help counties and cities moving forward with reviewing and updating their CAOs and other relevant policies and plans.

Chapter 4 explains the importance of restoration in riparian management, which is necessary for recovery of the degraded riparian functions present in many locations and is critical to recover salmon stocks and preserve Washington's riparian-dependent Priority Species. To that end, we outline voluntary approaches to improve riparian functions. Although Volume 2 is not a restoration guide, it is applicable to restoration practitioners in that it describes management actions that enhance riparian functions and values. We do not address restoration project design or standards but provide links within this chapter to resources that do.

Chapter 5 will assist with developing monitoring programs in support of adaptive management, designed to ensure transparent programs that consistently deliver sufficient protection of riparian functions. Careful monitoring and adaptive management are particularly important when a land use may harm a critical area and scientific information about the likely severity of harm is lacking. Although specific to local governments, this chapter provides valuable resources for any land manager interested in engaging in adaptive management.

Finally, this volume includes an appendix that contains a "how-to" process for utilizing WDFW's SPTH mapping tool to help determine recommended minimum RMZ widths around the state. The tool itself is available at wdfw.maps.arcgis.com/apps/MapSeries/index.html?appid=919ea98204eb4f5fa70eca99cd5b0de1.

Chapter 2. Riparian Management Zone Delineation

2.1. Introduction

We define the extent of the riparian ecosystem as the area that provides full ecological function for bank stability, shade, pollution removal, contributions of detrital nutrients, and recruitment of large woody debris. For the purposes of management or regulatory protection, the riparian management zone (RMZ) encompasses the riparian ecosystem, and–when present–the channel migration zone (CMZ) to account for lateral movement of the riparian ecosystem over time. RMZs can also provide habitat for many terrestrial wildlife species including movement corridors. WDFW categorizes the riparian ecosystem as a Priority Habitat, and thus recommends local jurisdictions designate all riparian areas as critical areas: specifically, Fish and Wildlife Habitat Conservation Areas (FWHCAs), as mentioned in Chapter 1.

The RMZ provide an initial framework for delineating, assessing, planning, and managing riparian ecosystems. The RMZ as defined here is not necessarily the same as setbacks or buffers. Setbacks are areas meant to protect an important feature (e.g., a stream or wetland) from certain types of adjacent activities, e.g., the area separating a building from the bank of a river. Setbacks are not typically designed to provide ecological function. On the other hand, buffers, which also protect important features, are commonly undeveloped, naturally vegetated areas that can contribute habitat and in the case of a stream, to riparian functions. In this document, we reserve the use of the term RMZ to mean the area capable of providing full function and managed to that end.

2.2. Foundational Concepts in RMZ Determinations

2.2.1. Desired Future Condition

A major goal in fulfilling WDFW's mission to preserve, protect, and perpetuate Washington's fish, wildlife, and ecosystems is the protection and restoration of healthy, intact, and fully functioning riparian areas. More specifically, the goal will be achieved through management strategies that result in ecosystem composition and structure that provides the five key ecological functions associated with riparian ecosystems. A useful benchmark for this goal is desired future condition (DFC) for riparian areas. DFC describes what land managers are attempting to achieve, often in terms of composition and structure (e.g., vegetation or land-use), over a period of time in a given geographic area. The DFC we recommend results in fully functioning riparian ecosystems as measured by the five key ecological functions (bank stability, shade, pollution removal, contributions of detrital nutrients, and recruitment of large woody debris) in western

Washington. The DFC for composition and structure is old, structurally complex conifer-dominant forest. Such forests exhibit large diameter trees, contain numerous large snags and logs, and have multi-layered canopies and canopy gaps, which promote understory plant diversity.

Throughout the Columbia Plateau, differences in hydrology and geomorphology manifest substantial site-level differences in composition and structure of riparian vegetation, and hence, the DFC for composition and structure is more site-dependent in the Columbia Plateau than in western Washington. Nonetheless, the DFC in the Columbia Plateau is based on the same concepts of ecosystem composition and structure that support the same five key ecological functions in forested regions; specifically, biologically diverse vegetation communities consisting of native trees, shrubs, grasses and forbs. In addition, the DFC for the upland portion of the riparian ecosystem which serves as the zone of influence and contributes to the pollution removal function in the Columbia Plateau is often intact native shrub-steppe or prairie vegetation.

2.2.2. Site-Potential Tree Height (SPTH) Background

A fundamental component of our recommendation is the use of site-potential tree height (SPTH). In this section, we provide background information on its origin, applicability, and usefulness (see also Volume 1, Chapter 9).

In 1993, a group of experts (Forest Ecosystem Management Assessment Team [FEMAT]) was convened to develop a conceptual model to determine how to protect riparian areas in forested landscapes. This model has come to be known as the FEMAT curves (FEMAT 1993). Though this model is over 25 years old, it continues to be one of the most useful conceptual models informing riparian management.

The FEMAT curves provide a conceptual model of important riparian functions and how those functions change with increased distance from the stream channel (Figure 2.1). The model conveys two important points: (1) four of the five riparian ecosystem functions or processes occur within one 200-year SPTH; and (2) the marginal return for each function or process decreases as distance from the stream channel increases. Thus, designating a riparian area based on at least one $SPTH_{200}$ is a scientifically supported approach if the goal is to protect and maintain full function of the riparian ecosystem for aquatic habitat and species, including salmon.

The FEMAT curves and SPTH have been used to describe the lateral extent of riparian ecosystems, and accordingly, the width of the RMZ needed to provide full riparian ecosystem function.

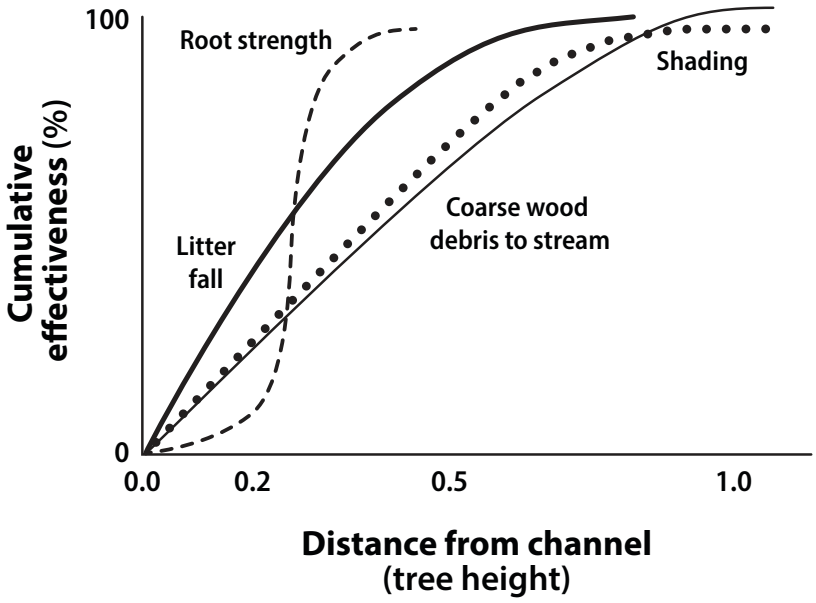


Figure 2.1. The "FEMAT Curves" (FEMAT 1993): a generalized conceptual model describing contributions of key riparian ecosystem functions to aquatic ecosystems as the distance from a stream channel increases. "Tree height" refers to average height of the tallest dominant tree (200 years old or greater); referred to as site-potential tree height (SPTH).

FEMAT (1993, p. V-34) defined SPTH as "the average maximum height of the tallest dominant trees (200 years or more) for a given site class." The key phrase in this definition is "200 years or more" which refers to the approximate minimum age of old-growth forests. This reflects FEMAT's underlying assumption that old-growth forest conditions are needed for full riparian ecosystem functions. WDFW uses SPTH at 200 years (abbreviated $SPTH_{200}$) in our recommendations in this Volume 2.

FEMAT defined Site potential tree height (SPTH) as "the average maximum height of the tallest dominant trees (200 years or more) for a given site class."

"200 years or more" is the approximate minimum age of old-growth forests which are thought to be necessary for full riparian ecosystem functions.

Given its utility, the height of site-potential trees has been described for a variety of tree species and can be readily found in silvicultural literature. Mean heights of dominant trees in riparian old-growth forest of Washington range from 100 to 240 feet (Fox 2003). The wide range of heights reflects differences in site productivity, i.e., local differences in soil nutrients and moisture, light and temperature regimes, and topography. Site productivity is described quantitatively through a site index, which is the average height that dominant trees of a species are expected to obtain at a specified tree age at a given location.

2.2.3. The Importance of Channel Migration Zones (CMZs)

Not all streams have CMZs, but where CMZs are present, it is necessary to map the CMZ in order to establish an RMZ. The Washington Forest Practices Board Manual (DNR 2004) provides a useful definition of the CMZ as "the area where the active channel of a stream is prone to move and this results in a potential near-term loss of riparian function and associated habitat adjacent to the stream, except as modified by a permanent levee or dike" (DNR 2004, Section M2).

Protecting the CMZ from incompatible land uses (e.g., development) is important for providing riparian ecosystem functions. Human alterations to river channels that limit channel migration and bank erosion can degrade aquatic and riparian habitats. For these reasons, geomorphologists have developed protocols for delineating CMZs. Further, RMZ delineation along streams with CMZs ensures that riparian functions do not degrade as a channel moves. Proper delineation also helps landowners avoid siting homes and infrastructure in CMZs that coincide with geologically hazardous critical areas and floodplains (**WAC 365-190-120[6f]**).

2.2.4. Relationship of CMZs and Floodplains

This document does not include guidance on the integration of floodplains into RMZ delineation (see footnote 4 for a brief explanation about the active floodplain). However, a general understanding of floodplains and their relationship to CMZs is valuable, as the two often overlap.



Beavers are considered to be ecosystem engineers. The dams they build, the resulting ponds created, and the surrounding areas from which they fell trees all provide habitat for many other animals./Liz Bocksteigel, WDFW

Both federal and state regulations establish floodplain protections. Floodplain data and **maps** (typically 100-year floodplains) are readily available through the Federal Emergency Management Agency's National Flood Insurance Management Program. Ecology is the state's authority as lead on floodplain management and we support their recommendations for management of **Frequently Flooded Areas** (another type of critical area specified in GMA) and the use of the **Floodplains by Design** grant program to reduce hazards and restore natural functions. Proper floodplain delineation and protection helps landowners and land managers avoid placing homes and infrastructure in areas at high-risk of flooding.

The Bureau of Land Management provides common clues to help determine the presence of an active floodplain (BLM 2015) such as visual evidence of frequent inundation, which may include but is not limited to:

- Fresh deposits of fine sediment;
- Floodplain vegetation matted down or lying flat on floodplain from overbank flow or by deposition or overbank sediment;
- Debris piled on the upstream side of tree trunks; or
- High water marks seen on rocks, trees, or other stationary objects; and ice-rafted deposits on the floodplain.

However, BLM advises caution when relying on these visual clues. Furthermore, looking for signs that an active floodplain is present is only the first step toward delineating the outer edge of an active floodplain. We recommend reviewing BLM's technical reference titled *Proper Functioning Condition Assessment for Lotic Areas* (BLM 2015) and to consult Ecology for assistance regarding floodplain delineation and protections.

Good floodplain management is not only beneficial for human communities, it is also good for fish and wildlife. Although we do not describe use of the 100-year floodplain to measure the RMZ in Volume 2, we recommend that landowners and land use decision makers treat floodplains similarly to RMZs due to their importance to instream health, as habitat, and for their ecological services.

2.3. Procedures for RMZ Delineation

To conserve riparian habitat, one must first establish the lateral extent (i.e., width) of the RMZ. In Chapter 1, we noted that an RMZ encompasses the riparian zone and zone of influence (Figure 2.2), and, where present, considers the CMZ (Figure 2.3). In this section, we outline general steps for collecting site-specific information essential to map an RMZ. These steps will help you identify a site's proximity to streams as well as essential site characteristics. With this information, we then explain how to delineate an RMZ.

In the rest of this section, we explain how to:

- Identify the ecoregion in which the riparian ecosystem is located (e.g., forested or dryland);
- Verify the presence of a stream;
- Identify the inner edge of the RMZ; and finally
- Determine the RMZ width.

2.3.1. Determining Ecosystem Location

We have identified two distinct types of ecoregions statewide, each with a slightly different RMZ delineation procedure: (1) Forested, and (2) Dryland. In general, forested ecoregions dominate western Washington, northeastern Washington, and portions of southeast, north central, and eastern Cascades. Dryland ecosystems are more readily contained in the Columbia Plateau Ecoregion east of the Cascade Range.

Landowners and land use planners should utilize the SPTH mapping tool, described in Appendix 1, to determine the ecoregion where the river or stream lies. Appendix 1 also provides instructions for using this tool to determine the 200-year site-potential tree height ($SPTH_{200}$) at a given location.



Site visits are important because small streams are often unmapped, including in GIS tools commonly used for planning and permitting. Shaner Creek, Thurston County/Janet Anthony, WDFW

2.3.2. Verifying the Presence of a Stream

Once you have identified which ecoregion you are in (e.g., Columbia Plateau), a qualified professional[6] should visit the site to verify the stream's location on or near the project area. It is very important not to rely solely on "stream maps" (e.g., DNR stream layer, National Hydrography Dataset) in place of a site visit (which is also important for mapping RMZs) because existing mapped stream layers often have errors, including streams whose locations are mapped inaccurately on the landscape, and streams actually present on the landscape that are missing from maps. Instead, use the site visit to validate existing stream maps.

[6] Qualified professionals can be entities and individuals identified by the jurisdiction, WDFW regional habitat biologists, tribal biologists, Ecology staff, and/or other individuals familiar with stream verification and who have local expertise (e.g., Conservation District staff, Stream Teams, etc.).

2.3.3. Identifying the Inner Edge of the RMZ

Once you have verified a stream's location, proceed to locate the inner edge of the RMZ. Accurate RMZ delineation is dependent on using the correct starting point. In this section, we describe how to determine the location of the RMZ's inner edge using either the Channel Migration Zone (CMZ), if one is present; or the Ordinary High-Water Mark (OHWM). Ecology, as the state's water quality lead, provides extensive guidance and resources associated with OHWM or CMZ, and those resources are referenced here forward.

2.3.3 (A). Identifying Ordinary High-Water Mark (OHWM)

Delineate the RMZ's inner edge by identifying the OHWM along both sides of the stream following the procedure in Chapter 3 of Ecology's **OHWM delineation manual** (Anderson et al. 2016).

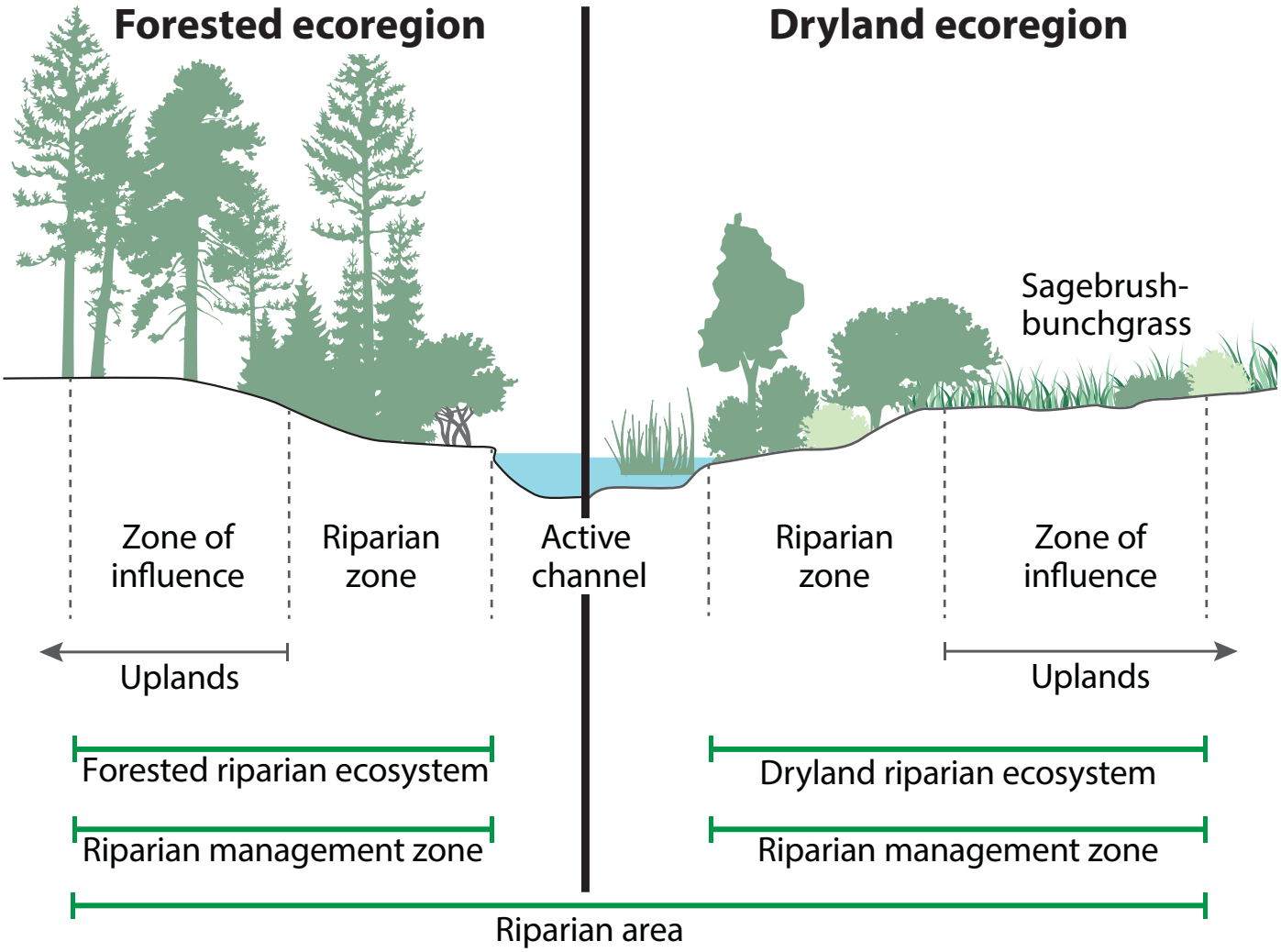


Figure 2.2. The diagram depicts the riparian management zone (RMZ) for both forested (left) and dryland (right) ecoregions. The RMZ is coincident with the riparian ecosystem, *which consists of the* riparian zone *(riparian vegetative community) and the* zone of influence. *The* riparian zone *extends from the edge of the active channel towards the uplands and it includes areas where vegetation is influenced at least periodically by flowing waters. The* zone of influence *includes areas where ecological processes significantly influence the stream, at least periodically.*



A drone photo showing an area of the Nooksack River in Whatcom County. Taken during summertime low flows, the existence of multiple braided channels is evident./Ross Zimmerman, Department of Natural Resources

2.3.3 (B). Identifying the Channel Migration Zone

Delineate the RMZ's inner edge by identifying the edge of the CMZ. Information about CMZs is available for certain streams in the state. For example:

- **SMA-Covered Shorelines** – During Shoreline Master Program comprehensive updates, many jurisdictions map the general location of CMZs associated with shorelines that fall under the jurisdiction of SMA (RCW 36.70A.480). Note that even smaller streams not subject to SMA jurisdiction can have CMZs. In these cases, we recommend jurisdictions still identify and analyze CMZs to protect riparian ecosystems and public health and safety.
- **Puget Sound Streams** – The federal Endangered Species Act may require CMZ delineation in Puget Sound basin streams under the FEMA National Flood Insurance Program Biological Opinion for Puget Sound.
- **Other Local Examples** – Check with your jurisdiction to see if they have more detailed CMZ maps.

Ecology provides the following resources which can help landowners and land managers assess the presence and extent of CMZs where maps and data on CMZs do not currently exist:

- CMZ Home Page provides a high-level look at CMZ identification, and references useful documents;
- Channel Migration Processes and Patterns in Western Washington (Legg and Olson 2014) describes the general channel migration processes that occur in western Washington;
- A Methodology for Delineating Planning-Level Channel Migration Zones (Olson et al. 2014) provides a process for delineating "planning-level" CMZs and gives a few good examples in the appendices;
- A Framework for Delineating Channel Migration Zones (Rapp and Abbe 2003) is a more in-depth guide on how to develop "detailed" CMZs; and
- Screening Tools for Identifying Migrating Stream Channels in Western Washington (Legg and Olson 2015) outlines the "CHAMP" (channel migration potential) GIS layer with guidance on using it to identify high-risk CMZs.

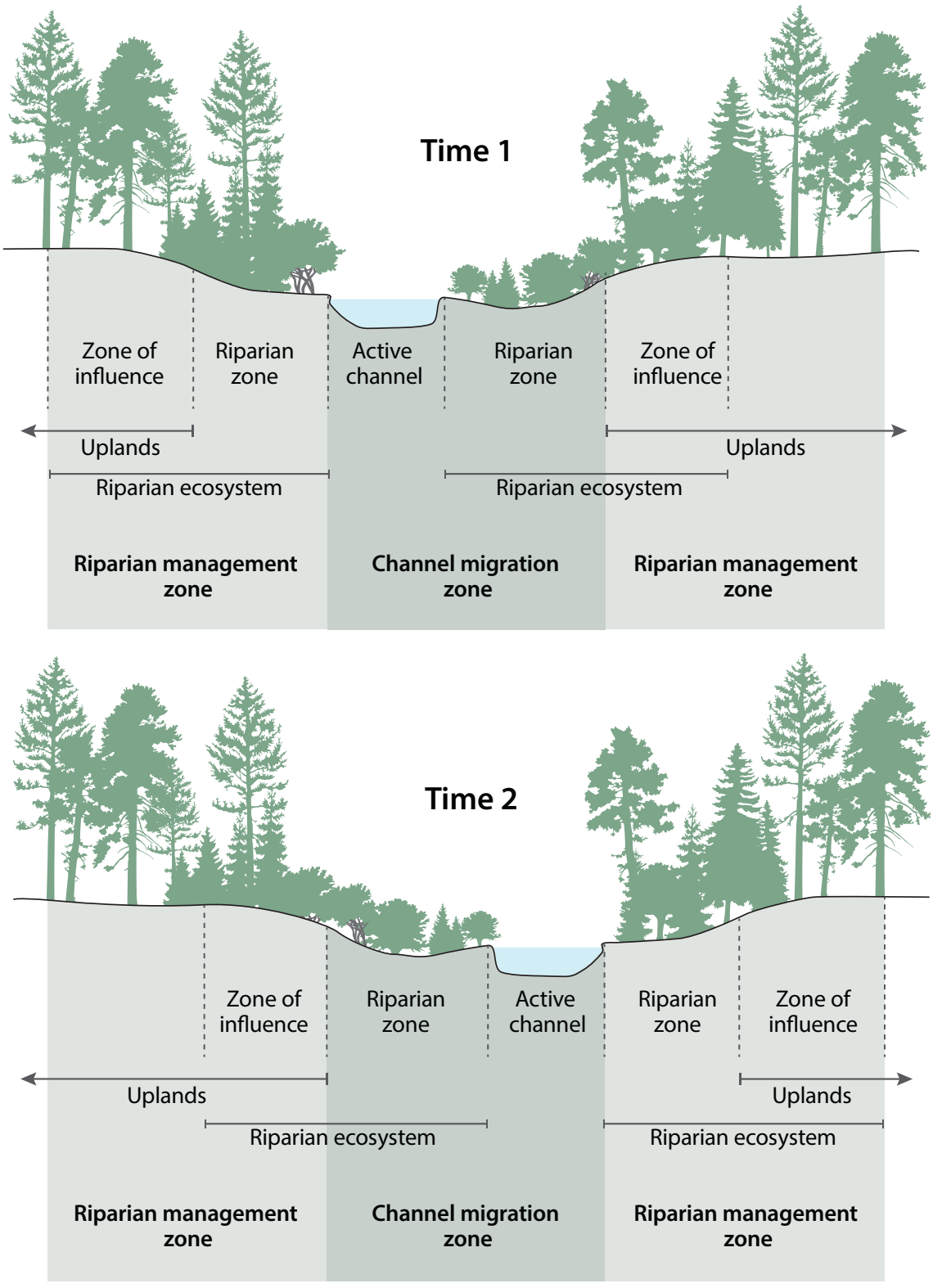


Figure 2.3. This diagram depicts the spatial relationship between the riparian management zone (RMZ) and channel migration zone (CMZ) over time. As the active channel moves laterally within the CMZ, the riparian ecosystem moves with it. As a result, when considering the establishment of an RMZ, delineation should occur at the edge of the CMZ to account for the full extent of both the present day and future riparian ecosystems. Time 1 and Time 2 could be separated by days or centuries. This depiction of a forested system is one representation of a CMZ, which are also present in dryland systems: both should be managed for accordingly.

2.3.4. Determining RMZ Width

Once you have determined the location of the RMZ's inner edge, you then establish the width of the RMZ. The following stepwise process aims to establish recommended minimum delineation distances based on $SPTH_{200}$, vegetation composition, and pollution removal function (Figure 2.4). We say "recommended minimum" because upland adjacent land uses may require further adjustment of the RMZ to provide adequate pollution removal functions. Landowners and land use regulators should also consider additional actions to support wildlife connectivity and/or to protect riparian adjacent Priority Habitats.

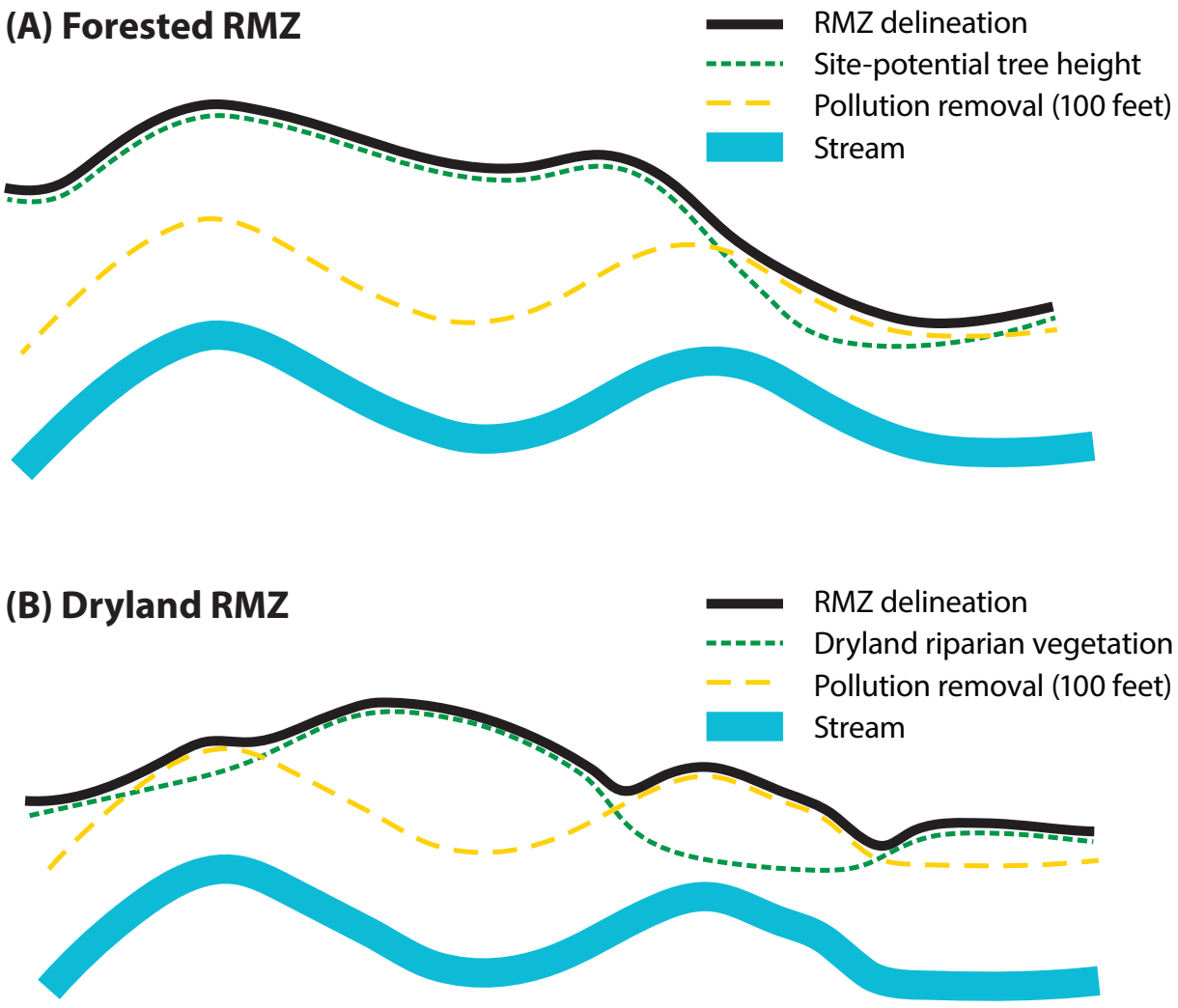


Figure 2.4. Aerial view of variable width RMZ delineation process for forested (A) and dryland (B) systems.

- *Step 1: Identify the SPTH or full extent of the riparian vegetative community (green);*
- *Step 2: Overlay a 100-foot pollution removal distance (yellow);*
- *Step 3: Delineate the RMZ (black) as the greater of the two distances.*

We tailor the following guidance based on two types of ecoregion: (1) Forested and (2) Dryland.

2.3.4 (A). Forested Ecoregions

Forested ecoregions are well-suited for using $SPTH_{200}$ consistently to establish RMZ widths, and so for these areas, landowners and land managers can rely on the $SPTH_{200}$ information provided in the SPTH mapping tool (see Appendix 1). The tool provides the derived average height attained by the dominant tree species at age 200 years ($SPTH_{200}$) using the U.S. Natural Resource Conservation Service (NRCS) forest productivity site index values, which we recommend for delineation of RMZs (see Sec 9.3 in Volume 1 for background on the origin and use of $SPTH_{200}$). In forested ecoregions, contributions of large wood as a riparian ecosystem function often define the farthest lateral extent of the RMZ.

Occasionally, the $SPTH_{200}$ may be less than 100 feet, in which case the pollution removal function (described in more detail in Section 2.3.5 below) defines the lateral extent of the RMZ.

In Washington, $STPH_{200}$ can be as large as 260 feet: therefore, be sure to evaluate each soil polygon within 260 feet of the stream channel to ensure that RMZ delineation is in fact being driven by the largest dominant tree species.

2.3.4 (B). Dryland Ecoregion

Riparian ecosystems in arid and semi-arid regions of North America (also referred to as the dryland ecoregion) make up less than 1 to 3 percent of the landscape (Patten 1998). Dryland riparian ecosystems are hydrologically linked to and influenced by adjacent surface waters; as a result, surface waters sustain riparian vegetation that is clearly distinct from upland vegetation.

Riparian ecosystems in dryland environments are highly variable due to various site-level conditions. While these ecosystems may support large trees in low gradient floodplains, tree presence in riparian ecosystems throughout the dryland ecoregion is much more varied than in forested ecoregions, and so in many cases, the contribution of large wood no longer serves as the outermost ecological function for RMZ delineation. Further, riparian vegetation may be minimal or even non-existent, particularly along degraded, incised streams. In dryland ecoregions, the outermost of

Protecting Columbia Plateau's Priority Habitats Supports Riparian Health

Native shrub-steppe vegetation and other drought-tolerant plant communities dominate Washington's dryland environments. Approximately 450 plant community associations occur in this region, with over 20% of these associations considered vulnerable (WDFW 2005, p. 523). Among the most imperiled ecosystems in North America, historical shrub-steppe has been greatly reduced due to conversion to other land uses (Vander Haegen 2007).

Riparian areas are critical to most animal species using shrub-steppe. Biodiversity in these vegetative communities increases dramatically where surface water occurs, and riparian areas directly support numerous species found only in or near water (Rogers et al. 1988, Johnson and O'Neil 2001). Linking and protecting upland adjacent Priority Habitat(s) not only aims to support Washington's wildlife and their associated habitat conservation goals, but also works to protect and maintain riparian ecosystem integrity.

three factors drives delineation of the RMZ: (1) $SPTH_{200}$ (if trees are present); (2) riparian vegetative community; or (3) pollution removal function.

2.3.4 (C). Considerations in Highly Modified and Urban Systems

In some locations, riparian systems have been substantially modified, and current site-specific conditions may not provide adequate indication of where riparian vegetation would naturally occur. On the whole, this is particularly true of riparian systems in dryland ecoregions. In these instances, we recommend considering nearby sites with unaltered vegetation or selecting a representative site with similar bank height and gradient conditions to identify adequate riparian vegetation delineation for both protection and restoration.



A modified riparian area within an agricultural landscape in Kittitas County. The stream channel was likely straightened decades ago. More recently, small bridges were built across the stream for pivot sprinklers to move back and forth. To allow ease of sprinkler movement, no woody vegetation is allowed to grow./Jennifer Nelson, WDFW

Similarly, four major urban areas (Seattle, Spokane, Tacoma, and Bellingham) in forested ecoregions lack NRCS soils data. For these areas, WDFW identified nearby NRCS soils polygons and calculated weighted averages as estimates reflective of the surrounding environment ("imputed $SPTH_{200}$"). Much like in forested areas where $SPTH_{200}$ data are available, we recommend using the imputed $SPTH_{200}$ values specified for each of these urban areas to delineate RMZs within them.

2.3.5. Width delineation steps

Step 1: Use $SPTH_{200}$ if it is at least 100 feet.

In **forested ecoregions,** WDFW recommends full protection within one $SPTH_{200}$, identified with the use of our SPTH mapping tool (https://arcg.is/1ueq0a). The mean $SPTH_{200}$ in western Washington ranges from 100 to 240 feet (Fox 2003). Some soil polygons have $SPTH_{200}$ information for multiple tree species; therefore, each soil polygon within one $SPTH_{200}$ should be evaluated to ensure RMZ delineation is driven by the largest dominant tree species. Occasionally the $SPTH_{200}$ in forested ecoregions is less than 100 feet; for example, red alder is a fairly common riparian tree species, yet the $SPTH_{200}$ for this species does not always exceed 100 feet. If red alder is the only species for which $SPTH_{200}$ information is available for a certain location, and it is less than 100 feet, then skip to Step 3.

In **dryland ecoregions,** it is less common, but still possible to find riparian vegetation which includes–and may even be dominated by–large trees. Examples of large tree species in these areas are black cottonwood (*Populus trichocarpa*) and ponderosa pine (*Pinus ponderosa*). If $SPTH_{200}$ in dryland ecoregions exceeds 100 feet, then it should be used for the RMZ width.

Step 2: In dryland ecoregions, if $SPTH_{200}$ is less than 100 feet or if no large trees are present, identify the extent of the riparian vegetative community.

In **dryland ecoregions,** the riparian vegetative community is often comprised of shrubs, sedges, grasses, and forbs that are distinct from upland communities. For example, in the Columbia Plateau, vegetation within riparian ecosystems often exhibits an abrupt demarcation between the riparian zone and zone of influence. Phreatophytic[7] trees and shrubs and hydrophytic[8] herbaceous plants are confined to moist streamside areas, but the upland zone of influence may consist of sagebrush or bunchgrass communities [for more information, see Volume 1, Chapter 7 (Section 7.1.1)]. Where trees are not present or consist only of small species (less than 100 feet tall), WDFW recommends full protection of the entire riparian vegetative community. In some places the community may only be a few feet wide but in others it may extend up to several hundred feet, particularly when associated with a wetland or floodplain (Bermingham et al. 2013). Where the riparian vegetative community is less than 100 feet wide, go to step 3.

Step 3: Overlay 100-foot pollution removal delineation

The following applies to both **forested and dryland ecoregions.**

Our recommendation to protect full riparian function recognizes the importance of the pollution removal function of riparian ecosystems. Because pollution removal depends on multiple factors, including slope, soils, plant community composition, and upland uses, establishing a standard RMZ width for 100% pollution removal even at the site scale was impractical.

Where neither $SPTH_{200}$ nor the extent of the riparian vegetative community is at least 100 feet, we recommend RMZ delineation of a *minimum* distance of 100 feet, because this distance will achieve 95% or more removal efficacy of phosphorous, sediment, and most pesticides. To be clear, we value a similar removal efficacy for nitrogen, and at a 100-foot width, an RMZ would achieve only 80% removal efficacy for surface runoff containing excess nitrogen. However, the literature reflects that both the actual risk posed by excess nitrogen, as well as the efficacy of its removal, are very site-specific. In recognition of this, we strongly recommend that, where upland uses contribute nitrogen, the 100-foot minimum pollution removal distance be extended accordingly when determining the appropriate RMZ width.

Further, if RMZ widths are being based on a minimum pollution removal function at locations with steep slopes or poorly drained soils, distances greater than 100 feet should also be considered: this applies for all pollutants. Additionally, WDFW recommends cities and counties identify high intensity land uses that may be located adjacent to riparian areas within their jurisdiction and establish wider RMZs to enhance the pollution removal function in these locations as well, following guidance from Ecology.

When dealing with variables such as those outlined above, it may be necessary to seek expert assistance in determining the appropriate adjustments to RMZ widths based on the pollution removal function.

7 A phreatopyhtic plant is a species that obtains water from the subsurface zone of saturation either directly or through the capillary fringe (Thomas 2014).
8 Hydrophytic plants are those that are adapted to growing conditions associated with periodically saturated soils. They include obligate wetland plants that almost always occur in wetlands under natural conditions, facultative wetland plants that usually occur in wetlands but are occasionally found in non-wetlands, and facultative plants that equally likely to occur in wetlands or non-wetlands (Lichvar et al. 2012).

Chapter 3. Riparian Regulatory Protections

3.1. Introduction

This chapter gives guidance to help local governments review, develop, and implement regulatory tools to protect riparian ecosystems as critical areas, i.e., Fish and Wildlife Habitat Conservation Areas (FWHCAs). We describe key steps toward creating effective programs to protect riparian ecosystems consistent with the goals of the Growth Management Act (GMA), Shoreline Management Act (SMA), and Voluntary Stewardship Program (VSP). More specifically, this chapter describes recommendations for carrying out common land use activities and provides steps for developing Habitat Management Plans (HMPs). The riparian management zone (RMZ) should serve as the focal area to apply our recommendations.

Parcel-scale regulations are foundational to Washington's traditional land use regulatory approaches for protecting rivers and streams and their adjacent riparian ecosystem. However, sole reliance upon a regulatory approach at this site scale may result in loss of aquatic system function over the long term (see Volume 1). Thus, we believe that site-scale regulations must work in coordination with watershed-scale planning (Chapter 4) and that both should be monitored and adaptively managed (Chapter 5). In this chapter, we present considerations and recommendations for managing and protecting riparian ecosystems at both site- and watershed-scales.

3.2. Recommendations to Local Jurisdictions

Protection of watersheds commonly falls under the purview of agencies other than WDFW. Nonetheless, we encourage local jurisdictions (and their long-range planners in particular) to consider how land use patterns at all scales collectively affect fish and wildlife and other important ecosystem services.

The scientific literature review (see Volume 1) informs WDFW's position that protecting the area within one $SPTH_{200}$ from the edge of a stream channel maintains full riparian ecosystem functions for all aquatic species, including salmon, and promotes healthy, intact riparian ecosystems. This recommendation provides the greatest level of certainty that land use activities do not impair functions and values of riparian ecosystems. We recommend the use of monitoring and adaptive management (see Chapter 5) to inform regulations and evaluate the complement of both regulatory and voluntary conservation measures in achieving outcomes.

Land use decision makers should ensure all programs that can affect riparian habitat (e.g., CAOs; SMPs; and ordinances for clearing and grading, fire hazard reduction, and tree protection) are coordinated to optimize the ability of local policies, rules, and management activities to protect those habitats. Further, jurisdictions should look for gaps

such as inconsistencies, exemptions and loopholes, or inefficient practices (e.g., inspection and monitoring protocols) that could impede protection of or cause harm to riparian ecosystems.

To that end, we provide important questions to consider when reviewing CAOs, Comprehensive Plans, or other plans that can affect riparian ecosystems:



The Coweeman River Joint Wetland and Conservation Bank in Cowlitz County includes riparian areas as a focus for both restoration and preservation./Chuck Stambaugh-Bowey, WDFW

1. Conservation Strategies:

- What external strategies exist (e.g., salmon recovery plans, reach-scale assessments, and incentive-based plans) to maintain, protect and restore riparian areas?
- Which of these strategies (if any) currently inform your regulatory, planning, and/or voluntary processes or programs?
- If these strategies are not in your current programs, could they be incorporated to provide additional benefits to riparian ecosystems? Are there other strategies that could also (or instead) benefit riparian ecosystems?
- Which of these strategies may help your jurisdiction satisfy mitigation obligations?
- How are riparian restoration and/or enhancement programs informed by these strategies?

2. Regulatory Buffers:

- Does your jurisdiction rely on $SPTH_{200}$ for delineating regulatory riparian buffers?
- If your jurisdiction does not rely on $SPTH_{200}$ for delineating those buffers, does your jurisdiction currently have regulatory buffers for riparian areas that are equal to or greater than the distance equal to $SPTH_{200}$?
- Are there buffer exemptions? If so, how do those affect riparian function across your jurisdiction?
- Do your buffers consider the CMZ?
- Do your buffers consider adjacent wetlands and appropriate wetland delineation methodology as prescribed by Ecology?
- If your jurisdiction's CAO or SMP buffers are less than $SPTH_{200}$, can you use the RMZ to identify areas to do mitigation or areas impacted that will require mitigation?

3. Restoration and Adaptive Management (see also Chapter 5):

- Can your jurisdiction use the RMZ to identify areas for incentive-based restoration?
- Do you have a monitoring and adaptive management program for improving permit implementation?

- Is your jurisdiction collecting information on effectiveness of protecting riparian areas?
- If you collect effectiveness information, what programs (e.g., incentives, regulations) could you improve to increase riparian conservation?

4. Other Programs and Regulations

- What other regulations separate from CAOs, may inadvertently affect riparian areas (e.g., clearing and grading ordinance that lack safeguards for riparian protection)?
- Are there opportunities to connect riparian areas with other protected areas (e.g., frequently flooded areas, geologically hazardous areas, green belts, parks, wetlands, and aquifer recharge areas)?

3.2.1. Recommendations for Common Activities in the RMZ

Local governments should regulate all land use activities that are likely to impact functions of a riparian ecosystem found within the RMZ to ensure, at a minimum, that the existing functions and values are protected from development actions. For the purposes of meeting requirements under GMA, SMA, and VSP, we describe the RMZ as the area in which functions and values are contributed to the riparian ecosystem: providing a delineated space not just for protection, but also for mitigation and management. We also recommend prioritizing the RMZ as the space for restoration[9]. We provide specific information and recommendations for the following ten common activities: (Note that neither the list of activities nor the recommendations themselves are exhaustive; for more information, contact your WDFW regional habitat biologist.)

1. On-site Sewage Systems (OSS)
2. Bank hardening
3. Clearing, grading, and placement of fill
4. Removal of noxious weeds
5. Forest practices and conversions
6. Firewise and wildfire hazard reduction
7. Removal of hazard trees
8. Non-compensatory restoration and enhancement
9. Emergency activities
10. Educational or Recreational Areas

1. **On-site Sewage Systems (OSS)** – Historically, developers sited OSS at lower elevations bordering streams, lakes and wetlands in order to use passive gravity flow. The disadvantage of these systems is that when drain fields are located near water features, they can more easily contaminate water with high loads of nutrients and toxic pollutants, causing significant impacts to flora, fauna and water quality. The State Department of Health adopted rules establishing public health standards for location, design, installation, operation, maintenance, and monitoring of OSS, including requiring setbacks from waterbodies (WAC 246-272A) which modern OSS systems, using pump systems, can support. Some OSS may meet public health standards even if located within RMZs; nevertheless, jurisdictions should exercise authority to require HMPs to ensure project proponents protect habitat functions of riparian critical areas.

[9] As explained previously, many riparian areas had already experienced a substantial degree of degradation before laws like GMA, SMA, and VSP were passed, so while protecting what level of riparian functions and values remain is essential, protection alone will not be sufficient for meeting the needs of the state's fish and wildlife species.

2. **Bank Hardening** – We recommend jurisdictions avoid allowing new development that requires bank protection now or is likely to in the future (consider channel migration, wind and wave action, and climate change), unless it addresses an imminent threat as an emergency activity (*see* Emergency Activities in this section below). Always look to alternative places to site a project so that no bank protection measures are needed. If measures cannot be avoided, require that a project proponent evaluate the effectiveness of bioengineering alternatives (also known as soft armoring) prior to proposing hard armoring. Follow bank protection recommendations in the Washington State Integrated Streambank Protection Guidelines (Cramer et al. 2002) when bank protection is unavoidable.

3. **Clearing, Grading, and Filling** – We recommend jurisdictions acknowledge impacts of clearing, grading, and filling on riparian areas in their CAOs by limiting these activities to areas outside the RMZ (unless directly related to restoration) as they can negatively affect riparian areas. If a clearing, grading, or filling project must encroach in an RMZ, limit disturbance and minimize effects to the greatest extent possible. Require that a qualified professional prepare an HMP describing how the project proponent will follow the mitigation sequence.

   Jurisdictions that exempt small areas from filling or grading ordinances in riparian ecosystems should calculate cumulative impacts from these exemptions. They should also mitigate impacts and subsequently establish monitoring to ensure that mitigation measures are effectively negating potential losses to habitat function.

4. **Invasive and/or Noxious Plant Removal** – Many CAOs do not require a permit for control and removal of invasive and/or noxious weeds within riparian ecosystem. We support this when weed control efforts (1) employ hand weeding with light equipment; (2) use only Ecology-approved aquatic herbicides and adjuvants (a substance added to herbicides to improve application); avoid use of hazardous substances; and (3) do not result in soil compaction. Local governments should retain some oversight authority for more extensive invasive and/or noxious plant control projects to ensure adequate protections of riparian functions, especially water quality. Most communities issue an exemption letter or permit, which should include conditions to ensure impacts to fish, wildlife, and habitat are minimal. It is important to note that even plants native to the region can, in certain circumstances, be detrimental to riparian areas. An example is in Puget Sound Prairies, where in the absence of periodic fire events (typically prescribed fire), common western Washington conifer species like Douglas fir outcompete native deciduous species (primarily Oregon white oak). In these circumstances, conifer removal and re-establishment of historical riparian conditions (oak and prairie vegetation) should occur under an approved HMP. WDFW regional habitat biologists can assist in preparing, reviewing, and implementing such a plan.

5. **Forest Practices and Conversions** – The state's Forest Practices Act (RCW 76.09 and WAC 222) regulates forest practice activities on forestland. We recommend that the proponent always contact DNR prior to conducting forest practice activities and seek technical assistance from a WDFW regional habitat biologist to ensure protections for Priority Habitats and Species. When conducting commercial forest practice activities, the forest practice rules—not the CAO—apply for protection of resources on site. Lands converted from forestry to another use require a special forest practice permit, and when converting land, local CAOs are applied. If conversion occurs, WDFW recommends timber harvests not be allowed within $SPTH_{200}$.

6. **Wildfire Hazard Reduction** – Wildfire is a concern in Washington, though the threat varies across the state. Local regulations to reduce wildfire hazards should be coordinated with a Firewise program in order to require landowners to consult with a Firewise professional (http://www.dnr.wa.gov/firewise) before removing trees or

manipulating vegetation in an RMZ. Understanding the composition of historical forest stands and shrub-steppe can help ensure retention of riparian functions when carrying out wildfire hazard reduction activities. When fuel (vegetation) reduction efforts involve the removal of merchantable trees, the proponent should check with the local jurisdiction and DNR, which may require a permit for tree removal.

7. **Removing Hazard Trees** – Tree trimming or removal in RMZs is sometimes necessary to address public safety concerns but should be balanced with the potential impacts to riparian ecosystem function. Jurisdictions should define a "hazard tree" (sometimes referred to as a "danger tree") as a threat to life, property or public safety, and require that the method of tree removal not adversely affect riparian ecosystem functions if possible. Specifically, we recommend that any removal of hazard trees involve an avoidance and minimization of damage to remaining trees and vegetation within the RMZ. We further recommend that local governments require a qualified arborist to evaluate requests for hazard tree removal.

   The qualified arborist should be able to establish when a tree presents an imminent threat to life, property or public safety. It is important to note that snags (dead trees) are a Priority Habitat feature for wildlife, and so should be preserved if not hazardous.



Like many dead and dying trees, this snag along the Chehalis River shows evidence of woodpecker activity. Grays Harbor County/Mary Huff, WDFW

   Some local governments use Forest Practice Rules (WAC 222-21-010[4]), which define a hazard tree as "any qualifying timber reasonably perceived to pose an imminent danger to life or improved property." This applies to any tree within 1.5 tree-lengths of the structure. A DNR forester can verify during a site visit that a tree is a hazard based on this definition, and thus removing the hazard would not be subject to the Forest Practice jurisdiction or require a Forest Practice Application.

8. **Restoration and Enhancement** – We encourage local governments to include in their CAOs allowances for restoration and/or enhancement of the riparian ecosystem, including in-channel or streamside work, especially on lands set aside for conservation. To the extent possible, jurisdictions should promote incentives and set up a streamlined review process for restoration or enhancement projects to help facilitate project proponents not just meeting the minimum requirements of the local CAO, but instead going "above and beyond". Significant resources are available to jurisdictions that address limiting factors in riparian areas or undertake high priority restoration activities that benefit salmon or other listed species (see Chapter 4 for information on restoration).

9. **Emergency Activities** – Local codes typically have provisions for emergency activities (e.g., bank stabilization to address imminent threats to homes) that provide relief from time delays related to procedural code requirements.

Local regulations should distinguish the immediate need to permit an emergency activity from the need to compensate for its impacts after-the-fact.

10. **Educational or Recreational Areas** – Public access to shorelines is a priority use under the SMA and providing educational and/or recreational developments such as trails, viewing platforms, or similar facilities may also enhance the public's understanding and appreciation of riparian areas, streams, and habitats. Thus, some focused use of the RMZ for educational and recreational activities may be desirable, if it does not create significant disturbances. Most CAOs include allowances for unpaved access to a stream for aesthetic or recreational enjoyment with defined limits on clearing to avoid impacts and minimizing soil, vegetation, and habitat disturbances: this is an allowance we support. That said, construction of trails could allow greater access for pets and other high intensity recreation, which may increase predation on, and/or disturbance of fish and wildlife species. Regulations should minimize impacts from recreational trails and interpretive facilities to the extent practicable, informed by PHS data and associated management recommendations.



A sculpture titled "The Indian Chief" greets visitors at the entrance to the Beebe Springs Natural Area along the Columbia River near Chelan./Alan Bauer

3.2.2. Project-specific Riparian Habitat Management Plans

When reviewing proposed projects near streams, local governments typically require applicants to provide detailed site-specific HMPs (often called a Critical Area Report). Here we describe six aspects of Riparian HMPs that we recommend be addressed in CAOs:

1. When HMPs are required;
2. Which additional critical areas must be delineated, and how;
3. Which specific land use actions must be identified, and how;
4. Mitigation requirements;
5. Monitoring and Adaptive Management requirements; and
6. Articulate who must prepare and review the HMP.

1. **When required** – We recommend jurisdictions require an HMP whenever someone proposes a land use activity in an RMZ (regardless of the jurisdiction's regulatory RMZ delineation) or when a proposal likely could affect riparian or aquatic functions. In cases where there is less confidence in the spatial accuracy of the RMZ, consider requiring a Riparian HMP when impacts occur adjacent to the RMZ's zone of influence.



It is not uncommon for riparian areas to overlap with other types of critical areas, including geologically hazardous areas, where landslides may bring input like large wood to streams./ Terra Hegy, WDFW

Maps, DNR's stream layers, the National Hydrography Dataset (NHD), and other (e.g., local) stream layers are important for triggering HMPs. An HMP should be required whenever a stream is present near proposed development activities, including but not limited to subdivisions (plats, short plats, and large lot subdivisions), land/vegetation disturbing activities (e.g., clearing and grading, septic drain field siting), and stormwater routing.

2. **Critical Area Delineation** – HMPs should have the extent of critical areas within and adjacent to a proposed project site identified, along with ecosystem functions that need protection. Follow the RMZ delineation procedure outlined in Chapter 2, along with locations of other critical areas on or near the site (e.g., wetlands, geologic hazards, frequently flooded, critical aquifer recharge areas; informed by Ecology). Also, identify salmon and other priority aquatic species that use the stream network in the immediate vicinity as well as up- and downstream. Likewise, HMPs should identify Priority Species that may use the riparian corridor and any other Priority Habitats to which the corridor is connected. Attach the delineation map (1) to the property's title to inform future property owners of the site's critical areas, and (2) use it to update the jurisdiction's critical areas maps.

3. **Land Use Action Identification** – A complete HMP should describe relevant management recommendations for Priority Habitats and Species found on or near the site. Include a map in the HMP showing the location of proposed land use actions. It should identify and quantify current and proposed disturbances to the RMZ and other FWHCAs.

4. **Mitigation** – The HMP should have a description of the project proponent's mitigation sequencing. It should describe in detail measures to avoid impacts and minimize unavoidable impacts (e.g., clustering, conservation easements, and seasonal construction restrictions). If mitigation or compensation is necessary, the HMP should identify ways to improve riparian ecosystem function by enhancing riparian corridor connectivity (e.g., removal of stream barriers) or by improving the quality of the riparian area (e.g., replacing invasive vegetation with appropriate native vegetation).

5. **Monitoring and Adaptive Management** –The HMP should describe requirements for monitoring and adaptive management. In addition, it should identify measurable standards and expectations to monitor compliance (e.g., areal extent of vegetative cover, composition of riparian tree species, maximum invasive plant cover). The HMP should identify frequency of visits to monitor the site (e.g., at year 1, 2, 3, 5, 8, and 10) as well as measurable triggers for requiring more actions (e.g., maximum percent area coverage of invasive plants). The HMP should specify who is responsible for preparing, reviewing, and submitting reports. Finally, if deemed necessary by the jurisdiction, the report should include a cost estimate for monitoring, and the project proponent should post a bond for this amount or more to allow for overages.

6. **Preparer and Reviewer** – A qualified professional biologist, botanist, or ecologist should prepare the HMP; additional expertise related to CMZs, unstable slopes, and wetlands may also be necessary. Additionally, an independent professional with similar qualifications should review the HMP. WDFW's regional habitat biologists can often serve in this role, especially for larger projects. USFWS or NOAA Fisheries should also review the HMP if the project might affect a federally listed fish or wildlife species.

3.3. Riparian Management in Urban Areas

Some people have raised questions about the applicability of RMZs to urban and urbanizing areas. These concerns generally fall into two categories: (1) the science on RMZs comes largely from agricultural and forestry settings, and so is perceived to be irrelevant to urban areas; and (2) there is a belief that the need to maximize density of development in urban areas is in direct conflict with the protection of riparian areas.

Concerns over the relevancy of literature on riparian functions to urban areas is largely unfounded. While most riparian ecosystem studies are from non-urban settings, the principles are the same. Functions of shade, bank stability, large wood recruitment, nutrient inputs, and pollutant removal operate similarly in urban areas as they do in other settings. However, within urban areas, these riparian ecosystem functions are often greatly diminished or even absent altogether.



Fish-bearing stream within an urban area of King County/Elizabeth Torrey, WDFW

The role that urban RMZs play in delivering habitat functions for aquatic and many terrestrial species is also like that in non-urban areas. Factors that may be different in urban areas are that urban riparian ecosystems may perform some functions at reduced levels due to their position in developed watersheds, which are often heavily degraded. However, intact RMZs in urban areas function as wildlife corridors that link habitat patches, which is critical for many species. In fact, sometimes RMZs in urban areas may be more important from a habitat standpoint, because within urban areas, adjacent uplands are often even more degraded than the RMZs, which then are often the only remaining areas where habitat functions are provided. Thus, a key element to maintain in urban RMZs is connectivity, both in and along streams.

Many Puget Sound salmon move through channelized streams, traversing heavily urbanized areas prior to reaching spawning grounds and as juveniles on a reciprocal journey to marine waters. Salmon must pass through a wide spectrum of development. For example, adults returning to spawn often start in urban cores (e.g., downtown Seattle), where streams are often channelized; then pass through areas with small lots and high urban density and into suburban

creeks where larger lots allow for more riparian protection; and finally, to rural lots with less development and better ecosystem health. When juveniles make their journeys in reverse, they generally spending more time in each of these areas than their parents did, and yet because of their small size, they are also at much greater risk of not surviving any of them. While the decades-long decline of many of our native salmon stocks illustrate just how challenging this is, their persistence—especially the subspecies which are showing signs of improvement—shows us what is possible. Therefore, it is critical that the urban environment maintain and enhance the ability of different species and ages of salmon to not just survive, but thrive, while in these disturbed areas.

Many of the actions we recommend urban communities focus on are the same or similar to those appropriate in less densely developed areas. For example, it is critical to maintain connectivity through properly sized culverts such that all fish can pass through at all relevant life stages. Additional riparian function can be achieved through revegetation efforts using native plants and by improving connectivity between habitat patches. A landscape analysis can help identify existing connections to protect, as well as areas where restoring connectivity is a priority. On the other hand, some actions are particularly well-suited to urban jurisdictions, like standards for Low Impact Development (LID) and state-of-the-art stormwater management. Further, when changes are made to urban infrastructure, this may create opportunities to improve riparian functions while contributing to new or improved public open spaces.

Recommendations for urban riparian ecosystems:

1. Delineate urban RMZs to protect what areas remain and to highlight lost or degraded areas to target for restoration.
2. Quantify current conditions, with a goal of maintaining and improving functions through regulatory and voluntary means.
3. Identify and prioritize restoration opportunities and projects within the RMZ:
    - Protect riparian functions that remain, especially in places that are relatively high functioning; implement actions that enhance degraded functions (see Chapter 4).
    - Prioritize opportunities to maintain and restore in-stream and riparian connectivity.
    - Adopt a stormwater design manual equivalent to Ecology's most current manual for western and eastern Washington.
    - Manage stormwater by adopting Ecology's latest manual regarding LID for new development, redevelopment and retrofit projects.

4. When replacing or removing existing infrastructure within an RMZ:
    - Map RMZ to pinpoint the best sites to restore – consider connectivity and adjacency to other Priority Habitats;
    - Improve aquatic connectivity by replacing culverts and removing barriers to movement;
    - Revegetate with native plants and consider improvements for wildlife by integrating structures necessary for nesting, breeding, and foraging;
    - As infrastructure is remodeled or replaced, incorporate additional setbacks from streams;
    - Control access to RMZ to limit soil compaction;
    - Avoid operating equipment near the stream to reduce sedimentation and soil compaction; and
    - Avoid using chemicals in the RMZ which are not approved for use there by Ecology.

3.4. Managing Watersheds



Tieton River on Oak Creek Wildlife Area in Yakima County, looking west toward the Cascade Mountains./Justin Haug, WDFW

As described in Chapter 8 of Volume 1, land use activities in a watershed can affect the stream network, even when the riparian ecosystem itself is relatively undisturbed. "Watershed management" is a land management approach that seeks to minimize negative effects of upland land uses on aquatic systems, which include riparian areas. The remainder of this chapter focuses on key watershed elements important to managing and protecting functional aquatic systems. Many of the approaches we outline here are non-regulatory and can complement regulatory efforts; as previously stated, we recommend cities and counties inventory current conditions of critical areas and, based on that inventory, develop watershed scale management plans accordingly.

Fully functional riparian ecosystems, in combination with targeted watershed protections, provide significant benefits to humans. These benefits, often described as ecosystem goods and services, include clean water; decreased flooding; increased nutrient cycling, sediment and pollutant filtering; reduced erosion; carbon sequestration; and cultural services such as recreational, spiritual, and other nonmaterial benefits. These services provide real but often unquantified economic benefits to individuals and society that largely go unnoticed until they are lacking.

3.4.1. Watershed-Scale Recommendations to Protect Aquatic Systems

To achieve desired ecosystem goods and services watershed managers should focus on influencing watershed processes that act upon water, wood, sediment, nutrients, vegetation, and pollutants at both the site- and watershed-scale. This section focuses on watershed-scale management.

Restore and Protect Watershed Processes – Efforts to improve watershed conditions should first focus on protecting and restoring watershed processes (e.g., natural disturbances) that create and retain habitat for fish and wildlife. Maintain the frequencies, magnitudes, and durations of natural disturbances (flood and fire being the most common) to the greatest extent that surrounding land uses can tolerate.

Manage Land for Stormwater – Stormwater runoff can change the timing, quality, and quantity of water provided to streams. Land uses should avoid/minimize changes to surface water flows. Protection and restoration efforts should focus on attenuating peak flows and reducing pollutants. Primary tools available to local governments include land use designations/zoning code, and stormwater regulations. See City of Redmond Watershed Management Plan (City of Redmond 2013).



Chum salmon gathered at a blocked culvert in Kitsap County./Brittany Gordon, WDFW

Manage Land for Stream Temperatures – Reduced riparian vegetation cover, decreased streamflow, and simplified stream channels (e.g., increased width-to-depth ratio and reduced groundwater exchange) can lead to increased water temperature (Volume 1, Chapter 4). Modifications like these are often the result of land use activities such as riparian vegetation removal; water diversions; unmanaged livestock grazing; and stream channelization associated with roads, levees, and other forms of development. Identify and restore thermally sensitive stream reaches at the watershed scale to maintain optimal stream temperatures for sensitive aquatic species such as salmonids.

Restore and Protect Connectivity – Manage watersheds to avoid creating longitudinal (e.g., dams, road crossings), lateral (e.g., levees and roads/buildings that cut off riparian areas and floodplains from their stream), and vertical (water withdrawals, reductions of floodplains) barriers to fish and wildlife movement and fragmentation of their habitat. This is especially important for highly mobile species that require a variety of habitat components across large areas. For example, where CMZs interact with floodplains, dikes and levees restrict the movement of the river or stream and also serve as a barrier for fish and many forms of wildlife.

Restoration to correct existing barriers to movement of water, wood, sediment, and species (e.g., removing blocking culverts) is a high priority with proven benefits for salmon. Connectivity to achieve nearly or completely contiguous RMZs is important to water quality and to achieve connectivity among patches. Ensuring connectivity both for terrestrial and aquatic wildlife works towards a more interconnected and healthy riparian system.

Plan for Climate Change – Impending changes to aquatic systems caused by climate change increases risk to species already threatened, and riparian ecosystem protection is one of the most useful responses to ameliorate those risks. For example, because more intense rainfall events will lead to wider streams, larger culverts will be necessary to support fish passage. WDFW, in collaboration with the University of Washington's Climate Impacts Group, created an online tool (UWCIG 2017) that estimates how much a stream's channel width will increase with climate change in the years 2040 and 2080. Connectivity within the RMZ allows voluntary migration for species and helps minimize temperature change and increase off-channel storage of water to reduce low flows.

Conduct Monitoring and Adaptive Management – Monitoring and adaptive management are important elements to both site-scale and watershed-scale; this is addressed further in Chapter 5.

3.4.2. Tools and Key References for Assessing Current Watershed Conditions

Washington's State agencies, including WDFW, have developed multiple tools to assist local government in assessing watershed conditions. Jurisdictions can utilize these resources—many available at no cost—to quantify changes in land cover, tailor planning for specific species, coordinate monitoring activities, inform restoration, and assess watershed health.

WDFW's High Resolution Change Detection (HRCD) is a spatial dataset that characterizes changes in land cover. This tool allows jurisdictions to evaluate in specific ways how watersheds are changing at a sub-parcel scale over 2- to 3-year intervals. This dataset is currently available throughout the entire Puget Sound basin and in some Eastern Washington watersheds. HRCD data is available at https://hrcd-wdfw.hub.arcgis.com/.

WDFW's Priority Habitats and Species program has several resources of interest to watershed planners. In addition to this two-volume document on riparian ecosystems, readers will find useful ideas in Land Use Planning for Salmon, Steelhead and Trout: A land use planner's guide to salmonid habitat protection and recovery (Knight 2009) and Landscape Planning for Washington's Wildlife: *Managing for Biodiversity in Developing Areas* (Azerrad et al. 2009).

Since 2004, the Pacific Northwest Aquatic Monitoring Partnership has collaborated with West Coast federal, state, and tribal agencies to coordinate monitoring activities and develop common approaches. This partnership provides best practices, mapping tools, and protocols, and serves as a voluntary clearinghouse for a wide variety of monitoring projects.

Since 2009, Ecology's Watershed Health Monitoring Project has been monitoring sites throughout the state to assess watershed health. This project's protocols can be adapted by jurisdictions and scaled to watersheds of various sizes. Data is stored in the Environmental Information Management database. This sophisticated database allows users to input and retrieve data via the web, reliably store it, and make it available for analysis. Quality assurance/quality control measures ensure data put into the database are of high quality.

Ecology's Puget Sound Watershed Characterization is a Puget Sound-wide tool that compares areas based on their suitability and value for restoration and protection. This tool informs two fundamental questions: (1) where to focus protection and restoration on the landscape first, and (2) what types of activities and actions (i.e., restoration, protection, conservation, or development) are most appropriate to that place. With insights gained by this tool, decision-makers can incorporate information regarding watershed processes to improve plans (e.g., comprehensive plans, subarea plans, CAOs, stormwater plans) and conservation efforts (e.g., in-lieu fee programs, open space tax credits, open space land acquisitions).

In 2016, the Washington Department of Commerce (Commerce) published Building Cities in the Rain (Ballash 2016) to help communities improve watersheds while redeveloping and revitalizing urban areas. The guidance describes an optional three-step process for prioritizing watersheds for stormwater retrofits in urban areas. Commerce's Puget Sound Mapping Project uses an interactive map to help users develop insights about how current and expected development patterns might affect the region's environmental health. The tool is designed to help decision makers consider information from the Puget Sound Watershed Characterization (described above) when making decisions regarding development projects, urban growth boundaries, and compensatory mitigation.

Finally, the University of Washington's Climate Impacts Group has developed a suite of tools, many in concert with WDFW, which may be useful for landowners and land use decision makers including climate trends, culvert design projections, and habitat connectivity.

Chapter 4. Restoring Riparian Ecosystems

4.1. Introduction

This chapter provides high-level guidance to landowners, land use decision makers, and conservation partners to promote restoration of riparian areas. Despite recent efforts to protect existing riparian systems, imperiled salmon stocks and other riparian dependent endangered species are not recovering as hoped (Table 4.1). Since non-indigenous settlement of Washington began in the 1800s, between 50 percent and 90 percent of riparian ecosystems have been lost or extensively modified (RCO 2019). While two subspecies (Hood Canal summer chum and Snake River fall Chinook) are moving towards recovery, most listed salmon in Washington are below recovery goals (Table 4.1).

The lack of recovery is also evidenced in the ongoing decline of salmon fishing, which affects the long-term health of Washington's tribes, Washington's economy, and our shared cultural heritage. The lack of salmon is one of the primary reasons Southern Resident Killer Whales are at risk of extinction, in addition to other impacts such as vessel disturbance and pollutants. (Lacy et al. 2017, Murray et al. 2019)

Table 4.1. Non-statistical evaluation of natural origin (wild) fish that returned to spawn with consideration for threats and factors affecting health including habitat, harvest, and hydropower. (Adapted from RCO 2019; Data sources: WDFW, Indian tribes, NOAA).

Below Goal (Endangered Species Act-Listed Salmon in Washington)			**Near Goal**
Getting Worse	*Not Making Progress*	*Showing Signs of Progress*	*Approaching Goal*
Upper Columbia River Spring Chinook	Upper Columbia River Steelhead	Mid-Columbia River Steelhead	Hood Canal Summer Chum
	Lower Columbia River Chum	Lake Ozette Sockeye	
	Lower Columbia River Coho	Lower Columbia River Steelhead	
Puget Sound Chinook	Lower Columbia River Fall Chinook	Snake River Steelhead	Snake River Fall Chinook
	Lower Columbia River Spring Chinook	Puget Sound Steelhead	
	Snake River Spring Chinook		
	Snake River Summer Chinook		



Former lake-bed above the area where the Glines Canyon Dam once stood on the Elwha River, Clallam County. Following dam removal, salmonids returned even faster than expected./Rachel Blomker, WDFW

Given the extent of historical loss, WDFW recognizes that protection alone of remaining riparian ecosystems, will not recover salmon or the Southern Resident Killer Whale population. Therefore, WDFW recommends restoring and enhancing riparian ecosystems to achieve healthy, intact, and fully functioning riparian systems statewide. Continued investments in restoration will be required at all levels of government and in concert with Washington tribes.

4.2. Restoration Actions

Although this section focuses on restoring riparian areas for the benefit of salmon, emulating historical conditions benefits many other aquatic and terrestrial species as well. WDFW is available to provide technical assistance and species-specific guidance for terrestrial species-focused restoration and recovery efforts. To recover salmon, we must protect all remaining existing riparian and watershed functions, while seeking opportunities to restore functions that have been lost over time. We provide the following information to assist the restoration community[10] in understanding what is important to restore.

4.2.1. Developing a Restoration Strategy

Aquatic restoration strategies typically start with a clear set of goals and objectives. The selection of appropriate restoration strategies is informed by the political, social, and ecological context of the watershed, and bounded by the extent of opportunities and constraints. It is important in ecosystem restoration to consider the habitat attributes and scale necessary for a desired suite of species, be they aquatic or terrestrial. At a watershed scale, restoration efforts should focus first on projects that offer the greatest potential for success. The Stream Habitat Restoration Guidelines (Cramer 2012) suggest the following prioritization of stream habitat restoration strategies that are specific to instream related activities most often geared at anadromous fish:

1. **Protect existing habitat.** Protect areas that provide healthy, high-quality habitat functions (strongholds, refugia, and key sub-watersheds) to prevent further degradation. Secure, expand, and link protected areas.

2. **Connect habitat.** Connect and provide access to isolated habitat, including instream, off-channel, and estuarine habitat made inaccessible by culverts, levees, fragmentation, or other man-made obstructions.

3. **Restore habitat-forming processes.** Employ land use recovery and watershed restoration techniques to restore processes that create, maintain, and connect habitats (including restoring sediment dynamics, large wood dynamics, and flow regimes; avoiding/removing manmade disturbances within the riparian ecosystem; and maintaining water quality, floodplain connectivity, and channel evolutionary processes). Employ a combination of active or passive restoration techniques, as necessary. Active restoration involves accelerating processes or attempting to change the trajectory of succession; passive restoration simply involves ceasing environmental stressors such as agriculture, grazing, or timber harvest, and then allowing nature to take its course.

10 Many watersheds in Washington have salmon recovery restoration goals that can be obtained from regional Salmon Recovery Boards or Lead Entities for Salmon Recovery. Lead Entities and Salmon Recovery Boards are in every region of the state, including those areas without salmon or other anadromous fish (https://www.rco.wa.gov/salmon_recovery/regions/regional_orgs.shtml).

4. **Create new or enhance existing habitat.** Improve existing or create new habitat for specific species by installing instream structures such as large woody debris; reconfiguring channel shape, cross-section, or profile to reduce incision or restore flow; or constructing one or more new side channels.

In conjunction with other state agencies and partners, WDFW provides multiple technical guidance documents to help design and implement riparian restoration projects that have proven successful in different types of landscapes, including on marine shorelines, and on river- and streambanks. These are part of a suite of Aquatic Habitat Guidelines found at https://wdfw.wa.gov/licenses/environmental/hpa/application/assistance. They include:

- Water Crossing Design Guidelines (Barnard et al. 2013)
- Stream Habitat Restoration Guidelines (Cramer 2012)
- Integrated Streambank Protection Guidelines (Cramer et al. 2002)
- Land Use Planning for Salmon, Steelhead and Trout: A land use planner's guide to salmonid habitat protection and recovery (Knight 2009)
- Draft Fishway Guidelines for Washington State (Bates 2000)
- Draft Fish Protection Screen Guidelines for Washington State (Nordlund and Bates 2000) Marine Shoreline Design Guidelines (Johannessen et al. 2014)
- Your Marine Waterfront (WDFW 2016)
- Protecting Nearshore Habitat and Functions in Puget Sound (AHGP 2010)

4.3. Implementing Riparian Strategies Through Incentives

There are several types of conservation incentives available to individuals and local governments:

- **Financial assistance:** grant programs that provide funding for conservation activities
- **Tax adjustment:** tax reductions for landowners undertaking conservation activities
- **Technical assistance:** advice and/or hands-on help for landowners on tools or techniques
- **Recognition:** promotion of landowners who undertake conservation actions

Each of these will be described (and examples provided) in more detail, below.

4.3.1. Financial Assistance

State and federal grant funds are available for riparian ecosystem conservation and restoration projects on public and private lands through the Recreation and Conservation Office (RCO) and Salmon Recovery Funding Board. To access these funds and to learn more, go to https://www.rco.wa.gov. Grant programs include:

- Aquatic Lands Enhancement Account
- Washington Wildlife and Recreation Program (Farmland, Forestland, Habitat, and Recreation categories)
- Estuary and Salmon Restoration Program—a program of WDFW
- Land and Water Conservation Fund
- Salmon Recovery and Puget Sound Acquisition and Restoration

Land trusts also help land owners conserve habitat for key aquatic and terrestrial species, often leveraging funds from foundations and other non-governmental sources; see www.walandtrusts.org for a county-specific list of land trusts.

For agricultural property owners, local conservation districts and the Washington State Conservation Commission (WSCC) can provide technical assistance to find an approach that works for the farmer and improves riparian ecosystem function. Technical assistance is also available from the federal Natural Resources Conservation Service (NRCS), Washington State University Extension, and WDFW. Additionally, a host of state and federal financial incentives to expand and maintain riparian functions within the riparian management zone (RMZ) are available, some of which are listed below. For example, the Conservation Reserve Enhancement Program (CREP) provides funding to landowners for riparian preservation and is the most successful riparian buffer program in Washington. Since CREP's 1999 inception in our state, more than 900 miles of stream buffers have been planted, and as of October 2020, producers had over 13,500 acres actively enrolled in CREP. Contact your local conservation district or the RCO to learn more.

- Conservation Reserve Enhancement Program (NRCS)
- Environmental Quality Incentives Program (NRCS)
- Conservation Stewardship Program (NRCS)
- Conservation Reserve Program (NRCS)
- Regional Conservation Partnership Program (NRCS)
- Agricultural Conservation Easement Program (NRCS)
- Agricultural Land Easements (NRCS)
- WWRP Farmland Preservation Grants (RCO)

Timber landowners have access to a variety of forestry-oriented conservation incentive programs (see list, below) and can also receive technical assistance from DNR's Forest Stewardship Program (foreststewardship@dnr.wa.gov, 360-902-1428):

- Forestry Riparian Easement (DNR)
- Rivers and Habitat Open Space Program (DNR)
- Healthy Forests Reserve Program (NRCS)
- Family Forest Fish Passage Program (DNR)
- Forest Legacy (USFS)
- WWRP Forestland Preservation Grants (RCO)



The federal Conservation Reserve Enhancement Program (CREP) funded this vegetation planting project along a stream in Skagit County./Wendy Cole, WDFW

4.3.2. Tax Reduction Incentives

Landowners can receive a substantial tax reduction by converting land into "open space" status because of the Open Space Taxation Act (WAC 458-30), enacted in 1970. Lands with riparian areas often qualify for this incentive; see your county assessor and local planning department for details.

4.3.3. Technical Assistance

Local governments and individual landowners who want to improve riparian habitat for a suite of species can request land use advice from a variety of sources, including:

- WDFW regional habitat and district wildlife biologists. Go to http://arcg.is/1SgsHqk to find the names and direct contact information for your local biologists, or call the regional office in your area:
  - Region 1 – Eastern: 509-892-1001
  - Region 2 – North Central: 509-754-4624
  - Region 3 – South Central: 509-575-2740
  - Region 4 – North Puget Sound: 425-775-1311
  - Region 5 – Southwest: 360-696-6211
  - Region 6 – Coastal: 360-249-4628
- Salmon Recovery Lead Entities or Regional Fisheries Enhancement Groups
- Tribal natural resource departments
- Local Conservation Districts



4.4. Suggested Restoration Practices

The following section provides a series of suggested restoration practices promoted by WDFW, other state and federal agencies, and conservation partners. We encourage consideration of these activities and others within and adjacent to the RMZ, as delineated in accordance with our recommendations in Chapter 2. Further, it is not unusual to find other types of Priority Habitats (e.g., wetlands, shrub-steppe) adjacent to riparian areas. In such cases, restoration practices should not degrade or disturb the adjacent habitat, but rather—if feasible—improve it in addition to improving the riparian habitat. The same approach should be used where riparian-adjacent Priority Species areas are present.

Like most restoration practices, the ones recommended below can range in complexity, both biologically and technically, so landowners are strongly encouraged to seek technical assistance from WDFW and other experts before taking any action: This will help save money, time, and greatly increase the likelihood of success for any restoration activity. Landowners should also be aware that many of these activities may require permits[11,12] issued by one or more

11 The Governor's ORIA Office provides additional assistance for general permitting questions (https://www.oria.wa.gov/site/alias__oria/347/Permitting.aspx)
12 Larger projects may also trigger permit requirements with federal agencies, such as the U.S. Army Corps of Engineers (USACE).

agencies such as WDFW for the Hydraulic Code rules, and DNR for the Forest Practices rules; as well as permits from the local jurisdiction.



Cooperative riparian enhancement project led by the Lower Columbia Fish Enhancement Group along the Toutle River, Cowlitz County/Josh Nicholas, WDFW

1. Improve quality of vegetation for both aquatic and terrestrial wildlife by removing invasive species wherever present. Further, to avoid the likely return of invasive species, cleared areas should be replaced with native riparian vegetation: specifically, native vegetation that provides needed ecosystem functions as described in Volume 1 and throughout this document (e.g., shade, large wood, pollution removal).

2. Where riparian areas already possess some native vegetation, enhance them with a greater mixture of native plants that provide necessary habitat components (forage, cover, breeding, roosting, etc.) for a diversity of species and multiple riparian functions (e.g., streambank stability, wood recruitment, organic litter input, and pollutant removal). The specific mix of vegetation will vary by ecoregion and local needs, but likely includes conifers, grasses, and herbaceous plants.

3. Increase off-channel habitat and improve natural flow regimes by removing dikes or levees and restoring access to and within the floodplain.

4. In areas of incised channels, reintroduce beaver or construct beaver dam surrogates to store sediments, raise streambed elevation, raise water table elevation, and restore riparian vegetation.

5. Remove reed canary grass, which can greatly inhibit channel morphology and aquatic species movement. (Management techniques for reed canary grass vary and are often site-specific: contact your local WDFW regional habitat biologist for technical assistance.)

6. Through proper consultation with WDFW and tribal biologists, increase the presence of large wood in streams and rivers to improve habitat for salmon, resident fish species, and aquatic amphibians.

7. Increase connectivity through removal of non-fish passing culverts. If replacement culverts are needed, ensure they are adequately sized and climate-change-resilient; see WDFW's online resource on Incorporating Climate Change into the Design of Water Crossing Structures (Wilhere et al. 2016).

8. Reduce soil erosion by increasing vegetation complexity and density, excluding (or substantially minimizing) soil compacting activities, and implementing upland soil management techniques where applicable.

9. For agricultural operators: add and/or improve fencing structures to increase the amount of riparian area acreage from which livestock are excluded to reduce compaction, erosion, and overgrazing.

Chapter 5. Improving Protection Through Adaptive Management

5.1. Introduction

Adaptive management is widely recognized as an essential component of effective natural resource management because it provides a systematic process for continually improving policies and management through outcome-based learning. The adaptive management process is a continual cycle of planning, acting, monitoring, evaluating, and adjusting (Figure 5.1). This feedback loop provides information for making adjustments that focus on improving decisions in all phases of resource management. The utility of adaptive management programs should be considered by conservation practitioners, landowners, and land use planners to ensure that conservation actions achieve desired outcomes: in the case of this document, that means preserving, protecting, and restoring healthy, intact, and fully functioning riparian areas. In addition to improving ecosystem outcomes, adaptive management should improve clarity of regulations–resulting in increased transparency to all stakeholders.

All cities and counties are currently protecting critical areas, including riparian ecosystems, through a variety of regulatory and non-regulatory mechanisms. One regulatory challenge is understanding how well these mechanisms meet their intent of protecting ecosystem functions and values and how to make improvements where they are falling short. This chapter was written in collaboration with the Washington Department of Commerce (Commerce) and relies heavily on the Commerce's 2018 update of the Critical Areas Ordinance Handbook (Bonlender 2018), with one exception, as noted.

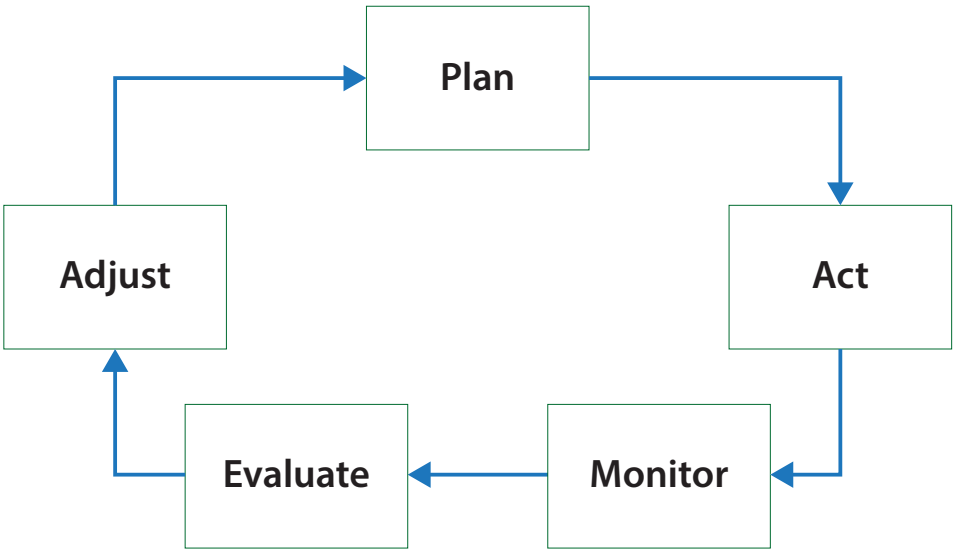


Figure 5.1. A simple depiction of the adaptive management cycle (modified from Bormann et al. 1994).

The process for monitoring we describe here supports both local and larger-scale actions that improve our collective efforts to protect riparian ecosystems throughout the state. For example, the Puget Sound Partnership (Partnership) uses "Vital Signs" of ecosystem health and recovery, such as riparian forest cover, to understand ecosystem condition, articulate shared goals and progress, and inspire action towards meeting those goals.

Adopting an adaptive management program can allow local governments to respond more quickly and meaningfully as new information become available. A willingness to address issues identified through this process is critical to the idea of adaptive management.

5.2. Common Questions Addressed by Adaptive Management

Adaptive management does not have to be expensive or complicated to be useful. We believe local jurisdictions can maximize their investment in adaptive management by focusing on two types of monitoring related to their own regulatory process (explained in more detail in the next section).

We begin by discussing three basic types of monitoring because we have found it instructive to understand how different monitoring types can be hierarchically or sequentially staged, based on the types of questions they seek to answer: implementation monitoring[13], effectiveness monitoring , and validation monitoring.

5.2.1. Implementation Monitoring

Implementation monitoring typically helps the permit issuer (permittor) answer the following questions about its permitting system, by looking at the outcomes of individual permits:

- Are permits consistent with regulations?
- Do permits contain all necessary conditions or provisions for a project?
- Does the permittor issue consistent permits (same requirements) for all permittees?

Implementation monitoring can also include:

- Permit *compliance monitoring,* which asks if the permitte followed or complied with each permit condition or provision and refrained from conducting unpermitted activities. Compliance monitoring usually takes place very soon after completion of permitted work.
- Keeping track of unpermitted activities; that is, finding changes in land use or management that require a permit but where no permit of any kind was issued.

13 As explained further in Section 5.2.2, we describe and use the term effectiveness monitoring somewhat differently than how it is described in Commerce's 2018 Critical Areas Handbook.



Fast-growing alder trees, like these shown in a low area along the Methow River in Okanogan County, can improve bank stability and increase summer shade more quickly than most conifers./Scott Fitkin, WDFW

5.2.2. Effectiveness Monitoring

In Commerce's 2018 Critical Areas Handbook, effectiveness monitoring is a form of long-term implementation monitoring. In other words, effectiveness monitoring looks at permit compliance as a while to determine whether permit conditions/provisions (e.g., buffer widths) are followed over time.

For the purposes of this document, we describe effectiveness monitoring a bit differently: Specifically, effectiveness monitoring is a way to determine whether permit conditions/provisions are working relative to intended environmental outcomes. For example, "Are permit conditions/provisions leading to the riparian function(s) (e.g., shade, bank stability) that they were intended to provide?" Effectiveness monitoring typically involves some on-the-ground measurement of environmental variables affected by land use activities.

5.2.3. Validation Monitoring

Research within the adaptive management framework is often referred to as validation monitoring. In the context of land use regulations, the questions relate to how management of critical areas (e.g., riparian) affects the specific environmental resource it was intended to protect (e.g., water quality, salmon). Validation monitoring may be beyond the fiscal means of most local governments. Moreover, it often involves questions that must be addressed over large spatial extents (e.g., at watershed or multi-watershed scale). In comparison, implementation and effectiveness monitoring are often tied to local jurisdiction's regulatory processes at the site scale: For these reasons, the next two sections focus more on these two types of monitoring.

5.3. Recommended Implementation Monitoring Efforts

We advise local governments to focus first on using implementation monitoring to evaluate their regulatory processes that affect riparian ecosystems. Implementation monitoring tracks execution of the permitting system from the perspective of both the permit issuer (permittor) and permit holder (permittee) (Figure 5.2). This effort can result in regular status reports that help demonstrate how well local governments and permittees are working together to meet resource objectives in a fair and consistent manner.

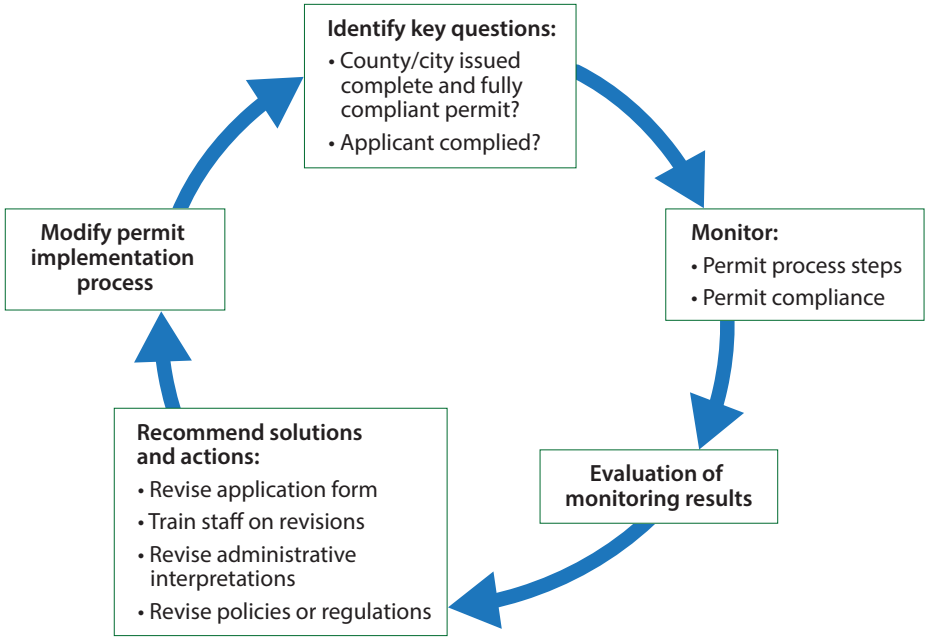


Figure 5.2. Depiction of the adaptive management cycle specific to permit compliance.

Implementation monitoring provides key information for permitting process improvement (5.2; Table 5.1). Even in situations where local governments cannot monitor all steps in their permitting process, monitoring any step—regulations to permit conditions/provisions, permit provisions to construction, construction to inspections, or inspections to enforcement—can provide valuable feedback about the quality of regulatory processes.

Monitoring does not have to be complicated. Even if a city or county chooses to do only permit implementation monitoring, this will provide key information that can improve the permit process, and an individual landowner can check whether choices like enhancing native plantings produce the desired results.

Table 5.1. Key questions for implementation monitoring during the Critical Areas permit review process.

Process Steps	Key study questions to evaluate permit implementation	Proposed metrics
Application	Was adequate information gathered from the permit applicant? Did the local government provide timely and necessary technical assistance to the permit applicant?	Number and percent of complete applications. i.e., include all information necessary to issue a permit. Number and percent by type of permit applications missing information.
Permit	Do permit provisions follow the local government code?	Number and percent of permit provisions by type consistent with code.
Permit	Do permit provision identify intent of protection and how it can be accomplished? (e.g., area of tree retention, distance of structure from stream, clearing, grading, or storm water provisions, replanting requirements, extent of impervious surface.)	Number and percent of (complete) permits (i.e., include all provisions that enable a permittee to be fully compliant with the permit). Number, percent, and type of missing provision/ information.
Permit (variance)	If a variance was granted, is the reason for the variance clearly stated?	Percent of variances by type justified by code or policy. Percent of permits with variances by type.
Permit (mitigation)	If compensatory mitigation was required, were the unavoidable impacts clearly identified/quantified? Was the rationale clearly stated?	Number and percent of permits by type with unavoidable impacts. Percent of permits by type with quantified mitigation requirements
Compliance	Post-Construction Visit: Did the permittee comply with the permit? (Requires field measurements of some or all the provisions in the permit. For riparian ecosystems, key provisions to inspect include RMZ width, retention of trees, replanting, structure distances from stream, area of impervious surface, and implementation of storm water provisions.)	Number and percent by type of provision that were out of compliance.
Enforcement	Are enforcement actions necessary to meet permit provisions and/or the regulations?	Number and percent by type of permit enforcement actions.

Because little or no fieldwork is required, the easiest and least expensive step to monitor is the link between regulations and permit provisions: that is, whether local land use regulations have been translated into permit provisions that can be understood easily by permittees. We recommend that some implementation monitoring become part of all local regulatory programs, even if it only on a relatively small subset of permits selected at random. A database for storing information on each step (i.e., a permit tracking system–see Table 5.1, Figure 5.3) is a critical tool for creating a complete system of accountability.

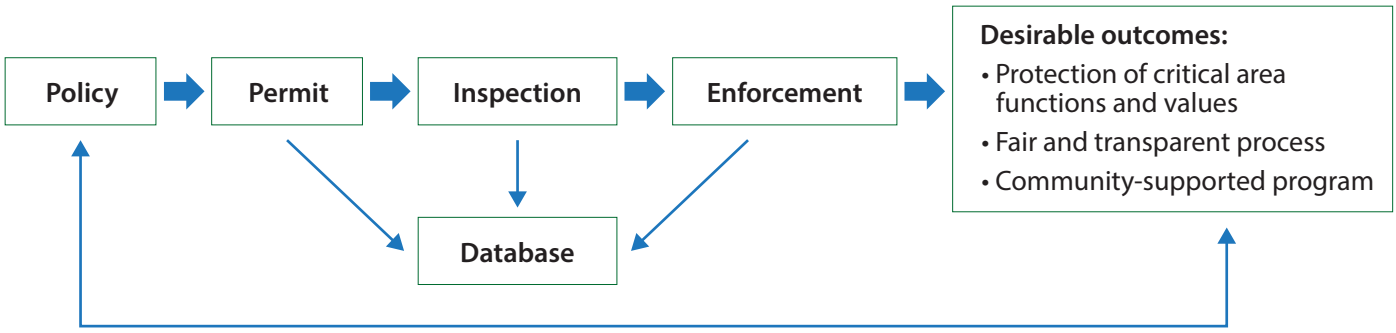


Figure 5.3. One system of permit accountability that includes implementation monitoring of internal permit processes, inspection for permit compliance, a database from which to judge outcomes, and a feedback loop connecting outcomes with policy intent.

Long-term implementation monitoring can help answer additional questions, such as: "Are rules/regulations intended to provide long-term protection of critical areas (e.g., RMZs) actually followed or maintained over time?" One way to answer this is by looking at changes in land cover, which describes the type and amount of vegetation, roads, and buildings occurring on the landscape. By comparing high quality aerial photographs taken of the same locations over time, change can be quantified and attributed to specific activities, both from natural disturbances (e.g., wildfires, river channel migration) and human activities (e.g., timber harvesting, residential subdivision construction, highway widening). In Section 5.5, we describe one such process WDFW developed and for which information for many parts of the state are already available.

5.4. Effectiveness of Regulatory Protections of Critical Areas

Where implementation monitoring has been successful, that is, either documenting a highly functional permitting process or improving poorly performing permitting process, we encourage additional effort on effectiveness monitoring. As described above, our primary goal for effectiveness monitoring would focus on understanding how well the permit conditions/provisions lead to measurable outcomes on the ground (e.g., protection/restoration of one or more riparian functions or values) over an extended period.

5.5. Using Land Cover Change to Understand Long-term Regulatory Protection

High Resolution Change Detection (HRCD) is a tool that is useful for detecting changes in two specific types of land cover (tree canopy and impervious surfaces) over set time periods. Land cover change analysis like HRCD can show jurisdictions the degree to which critical area regulations are maintaining RMZs as intended. This information can then help shape if, where, why, and how adjustments to permitting processes should occur. By combining land cover change analysis with targeted questions about permitting processes, jurisdictions can begin to adaptively manage changes to their overall regulatory system.

Adaptive Management Framework in the Voluntary Stewardship Program

The Voluntary Stewardship Program (VSP) was authorized by the Legislature in 2011 through RCW 36.70A.705. The goals of VSP are to protect and enhance critical areas where agricultural activities are conducted, maintain and improve the long-term viability of agriculture in the State of Washington, and reduce conversion of farmland to other uses. The program provides counties with an alternative approach from traditional development regulations that require protection (and encourage enhancement) of critical areas at the individual parcel scale. Instead, VSP relies upon voluntary practices and incentive programs to protect (and enhance) at a watershed scale. Counties "opted-in" to VSP, and as of 2019, 27 of the state's 39 counties are participating.

Under VSP, local workgroups created work plans that include benchmarks for protection and enhancement of critical areas designed to be achieved through voluntary and incentive-based actions. VSP requires monitoring and adaptive management to maintain and enhance critical areas, including riparian ecosystems, and directs workgroups to monitor at the watershed or sub-watershed scale. Key requirements for county-level programs include:

1. Establishing a durable system to track and report goals, benchmarks, and performance metrics.
2. Developing implementation and effectiveness monitoring programs and conducting monitoring on a pre-determined schedule.
3. Establishing an adaptive management program with (a) "triggers"; (b) subsequent actions to take; and (c) a process to review/update both the triggers and actions over time.
4. Reporting on the achievement of protection and enhancement goals and benchmarks at specified intervals.

Numerous counties have utilized WDFW's recommended VSP Adaptive Management Matrix in approved VSP Work Plans. Examples include:

- Chelan County, Appendix I (Approved April 2017)
- Grant County, Tables 5-7 through 5-10 (Approved June 2017)
- Asotin County, Tables 5-3 through 5-5 (Approved May 2018)
- Okanogan County, Chapter 6 (Approved September 2018)
- Spokane County, Section 4 (Approved November 2018)

Jurisdictions can adapt matrices as templates for connecting goals, benchmarks, performance metrics, monitoring, and adaptive management for other uses beyond VSP. These matrices can be modified as frameworks to identify specific elements of any adaptive management plan.

The example in the following section is adapted from Commerce's Critical Areas Handbook (Bonlender 2018). Chapter 7 of that document provides a number of similar monitoring program examples, nearly all of which were developed by cities or counties.

5.5.1. Example: WDFW/Thurston County Shoreline Master Program

In 2015, Thurston County and WDFW utilized a National Estuary Program grant to quantify shoreline vegetation, land cover change, and evaluate land use permit compliance. Specifically, Thurston County used WDFW's HRCD data to monitor compliance within the County's Shoreline Master Program (SMP) jurisdiction. This project developed a protocol manual for using HRCD for this purpose, available to all jurisdictions within the Puget Sound region.

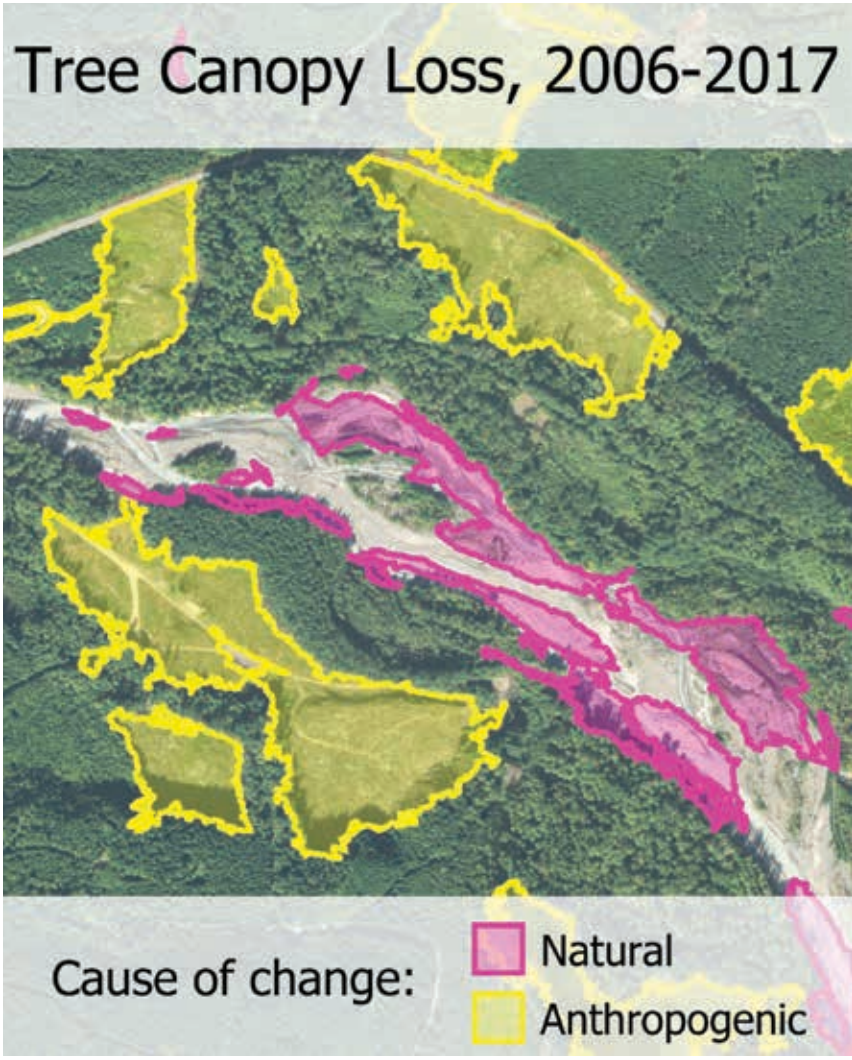
One goal of the pilot project was to answer several related sets of questions:

For Thurston County:

- What land cover change is happening within designated SMP areas? What change is happening throughout the Deschutes River watershed (WRIA 13)?
- How does change known by permit records compare with detected changes by HRCD?
- What changes, if any, can be made to the land use permits or permitting process that could increase the relevancy or efficacy in utilizing the HRCD in compliance monitoring?

For WDFW:

- How well can HRCD detect changes relative to land use permit records?
- Using Thurston County's SMP area as an example test area, what land cover changes are happening which HRCD is not capturing?
- With the development of a HRCD user manual, can HRCD be successfully utilized by other entities in the absence of direct assistance by WDFW?



High Resolution Change Detection (HRCD) analysis showing changes in tree canopy along and above a river in Thurston County. Pink polygons show where trees that existed prior to 2017 are no longer standing, apparently due to natural causes (e.g., where the river meandered). Yellow polygons show places where trees were removed as a result of timber harvesting./HRCD team, WDFW

The pilot quantified increases in impervious surfaces and decrease in tree canopy within marine areas of the SMP jurisdiction and checked for relevant permits issued. It consisted of five phases:

Phase 1: Initial SMP Change Analysis: Staff from WDFW's Habitat Program and the County's Long-Range Planning Department intersected the HRCD dataset with the County's SMP area and tax parcel data within ArcGIS for three time periods of HRCD availability (2006 to 2009, 2009 to 2011, and 2011 to 2013). Staff compared known areas of change to those locations with the county's land use permit records to find locations of observed change via HRCD without any permit record. During this phase, land cover change statistics were also produced, including total area of change and discrete occurrences of land cover change events.

Phase 2: Learning What the HRCD Misses: Using the SMP area in the County, WDFW staff manually looked for land cover changes not captured by the HRCD analysis, to understand how accurate HRCD was in capturing all land cover change situations (rates of omission error).

Phase 3: Developing a Standardized Method for Utilizing the HRCD: A major goal of this project was to develop support materials for others to be able to utilize HRCD to answer land use management questions independent of WDFW staff assistance. Using lessons learned in Phases 1 and 2, WDFW and the County agreed upon a recommended method for applying HRCD to a specific management question, and collaboratively developed a "how-to" manual. In this phase, WDFW staff also developed a web-based service (https://hrcd-wdfw.hub.arcgis.com) where users can download the HRCD dataset, detail the methodology of HRCD construction, find WDFW contact information, and more.

Phase 4: Testing the Manual through Remaining SMP Analysis in WRIA 13: Using only the HRCD dataset and the manual produced in Phase 3, County staff examined land cover change within the remaining SMP areas within WRIA 13 successfully for the same three time periods that HRCD data was available and utilized in the earlier phase.

Phase 5: Training and Outreach: With the lessons learned and products derived from Phases 1 through 4 of the project, staff worked in conjunction with the Coastal Training Program, managed by Ecology, to develop and deliver a workshop for planning staff within other state agencies, local governments, and some non-governmental organizations. WDFW also used this opportunity to train internal staff on the benefits, limitations, and uses of HRCD.

The evaluators analyzed land cover change within Thurston County's SMP area between 2006 and 2013, pulling permit records from timeframes that corresponded with the available HRCD datasets. The project's findings were very helpful, not only because of the information collected, but also in providing proof of concept for several of the steps/tools. For example: The utility of HRCD in analyzing patterns of land cover change in a specific geographic area of concern were well demonstrated. The HRCD analysis found that, from 2006 to 2013, less than half of one percent (0.39%) of the riparian area contained within the SMP had land cover change – approximately two-thirds of this was due to canopy loss, with one-third due to new impervious surfaces. The HRCD analysis did not find any permitted developments that were out of compliance, though it did find unpermitted events (e.g., tree removal) in each time period studied.

Furthermore, the HRCD dataset proved to be relatively simple to use. With the development of standard application methods, Thurston County was able to complete an analysis of their remaining SMP area without any further assistance from WDFW.

On the flip side, Thurston County found that comparing actual permit compliance with HRCD data was "tedious and difficult" because of limitations with the county's permit tracking database. For example, in many cases, land use permits did not include enough information to determine conclusively that a parcel with observed change via HRCD was out of compliance or determine that the parcel had a permit record during the study's timeframe in question.

Local governments can use HRCD analysis at the start to find land cover changes that are otherwise unknown; as they begin to understand patterns, HRCD analysis provides indications to identify locations that warrant closer investigation through other methods.

5.6. Conclusion

Implementation and effectiveness monitoring are important parts of adaptive management and can be undertaken relatively easily by local governments. Many of our riparian ecosystems are already degraded and stressed, so it is worth our while to investigate whether the actions put in place to protect them are being carried out as required and leading to the specific environmental responses that were intended. This is now more important than ever, because in spite of advances in science and efforts to improve regulatory processes, climate change and population pressures are increasingly confronting many parts of the state. Using monitoring and adaptive management to track successes and failures and then learning from both will make our challenges easier to overcome.



To install the lawn seen on the right of this photo, all vegetation was removed from the riparian area except a single row of cottonwood trees at the water's edge./Jennifer Nelson, WDFW

Literature Cited

Volume 1 serves as the primary source and citation for this document:

Quinn, T., G. Wilhere, and K. Krueger (managing editors). 2020. Riparian Ecosystems, Volume 1: Science Synthesis and Management Implications. Habitat Program, Washington Department of Fish and Wildlife, Olympia, Washington.

Anderson, P.S., S. Meyer, P. Olson, and E. Stockdale. 2016. Determining the ordinary high water mark for Shoreline Management Act compliance in Washington State. Publication No. 16-06-029. Washington State Department of Ecology, Olympia, Washington. (https://fortress.wa.gov/ecy/publications/documents/1606029.pdf)

Arid Lands Initiative. 2014. The Arid Lands Initiative: shared priorities for conservation at a landscape scale. Summary prepared by S.A. Hall and the Arid Lands Initiative Core Team. SAH Ecologia LLC, Wenatchee, Washington. Available at (https://www.sciencebase.gov/catalog/file/get/546d0a6ae4b0fc7976bf1db0?f=__disk__ab%2Fd6%2F7d%2Fabd67df8a73f48f87922d184ffec6e9b8dac635c)

Ashcroft, M.B. 2010. Identifying refugia from climate change. Journal of Biogeography 37:1407-1413.

Azerrad, J., J. Carleton, J. Davis, T. Quinn, C. Sato, M. Tirhi, G. Wilhere, and S. Tomassi. 2009. Landscape planning for Washington's wildlife: managing for biodiversity in developing areas. Habitat Program, Washington Department of Fish and Wildlife. Olympia, Washington. (https://wdfw.wa.gov/publications/00023)

Ballash, H. 2016. Building cities in the rain. Washington State Department of Commerce. Olympia, Washington. (https://www.ezview.wa.gov/site/alias__1780/overview/34828/overview.aspx)

Barnard, R. J., J. Johnson, P. Brooks, K. M. Bates, B. Heiner, J. P. Klavas, D.C. Ponder, P.D. Smith, and P. D. Powers. 2013. Water crossings design guidelines. Habitat Program, Washington Department of Fish and Wildlife, Olympia, Washington. (https://wdfw.wa.gov/publications/01501)

Bermingham, B., C. Douglas, B. Floyd, D. Koellmann, P. Mugunthan, and J. Small. 2013. Final draft semi-arid riparian functions and associated regulatory protections to support shoreline master program updates. Anchor QEA LLC., Kennewick, Washington.

Bonlender, B. 2018. Critical area handbook: A handbook for reviewing critical areas regulation. Washington State Department of Commerce, Olympia, Washington. (https://www.commerce.wa.gov/serving-communities/growth-management/growth-management-topics/critical-areas/)

Bormann, B.T., P.G. Cunningham, M.H. Brookes, V.W. Manning, and M.W. Collopy. 1994. Adaptive ecosystem management in the Pacific Northwest. PNW-GTR-341. U.S. Forest Service, Pacific Northwest Research Station, Portland, Oregon.

BLM (Bureau of Land Management). 2015. Riparian area management: proper functioning condition assessment for lotic areas. Technical Reference 1737-15. BLM, National Operations Center, Denver, Colorado.

City of Redmond. 2013. City of Redmond, Washington citywide watershed management plan. Prepared by Herrera Environmental Consultants, Inc. Seattle, Washington. (https://www.redmond.gov/DocumentCenter/View/11707/Watershed-Management-Plan-2013-PDF)

Cordell, H. K., D. Murphy, K.H. Ritters, and J.E. Harvard III. 2005. The natural ecological value of wilderness. Pages 205-249 in H.K. Cordell, J.C. Bergstrom, J. M. Bowker (editors). The Multiple Values of Wilderness. Venture Publishing, State College, Pennsylvania.

Cramer, M.L. (managing editor). 2012. Stream habitat restoration guidelines. Co-published by the Washington Departments of Fish and Wildlife, Natural Resources, Transportation, and Ecology, Washington State Recreation and Conservation Office, Puget Sound Partnership, and the U.S. Fish and Wildlife Service, Olympia, Washington.

Cramer, M., K. Bates, D. Miller, K. Boyd, L. Fortherby, P. Skidmore, and T. Hoitsma. 2002. Integrated streambank protection guidelines. Washington Department of Fish and Wildlife, Olympia, Washington. (https://wdfw.wa.gov/publications/00046)

DNR (Washington Department of Natural Resources). 2004. Forest Practices Board Manual, Section M2: standard methods for identifying bankfull channel features and channel migration zones. DNR, Forest Practices Division, Olympia, Washington. (https://www.dnr.wa.gov/publications/fp_board_manual.pdf?amcgpv)

EnviroVision, Herrera Environmental, and Aquatic Habitat Guidelines Working Group. 2010. Protecting nearshore habitat and functions in Puget Sound, revised edition. Washington State Department of Fish and Wildlife, Olympia, Washington. (https://wdfw.wa.gov/publications/00047)

Fetherston, K.L., R.J. Naiman, and R.E. Bilby. 1995; Large woody debris, physical process, and riparian forest succession in montane river networks of the Pacific Northwest. Geomorphology 13:133-144.

Fox, M.J. 2003. Spatial organization, position, and source characteristics of large woody debris in 2485 natural systems. Ph.D. Dissertation. University of Washington, Seattle, Washington.

Harris, R.R. 1987. Occurrence of vegetation on geomorphic surfaces in the active floodplain of a California alluvial stream. American Midland Naturalist 118:393-405.

Hilty, J.A., and A.M. Merenlender. 2004. Use of riparian corridors and vineyards by mammalian predators in northern California. Conservation Biology 18:126-135.

Johannessen, J., A. MacLennan, A. Blue, J. Waggoner, S. Williams, W. Gerstel, R. Barnard, R. Carman, and H. Shipman. 2014. Marine shoreline design guidelines. Washington Department of Fish and Wildlife, Olympia, Washington. (https://wdfw.wa.gov/publications/01583)

Johnson, D.H., and T.A. O'Neil. 2001. Wildlife Habitat Relationships in Oregon and Washington. Oregon State University Press, Corvallis, Oregon.

Keppel, G., K.P. Van Niel, G.W. Wardell-Johnson, C.J. Yates, M. Byrne, L. Mucina, A.G.T. Schut, S.D. Hopper, and S.E. Franklin. 2012. Refugia: identifying and understanding safe havens for biodiversity under climate change. Global Ecology and Biogeography 21:393-404.

Knight, K. 2009. Land use planning for salmon, steelhead and trout: a land use planner's guide to salmonid habitat protection and recovery. Habitat Program, Washington Department of Fish and Wildlife, Olympia, Washington. (https://wdfw.wa.gov/publications/00033)

Knutson, K.L., and V.L. Naef. 1997. Management recommendations for Washington's Priority Habitats: riparian. Habitat Program, Washington Department of Fish and Wildlife, Olympia, Washington. (https://wdfw.wa.gov/publications/00029)

Krosby, M., D.M. Theobald, R. Norheim, and B.H. McRae. 2018. Identifying riparian climate corridors to inform climate adaptation planning. PLOS ONE 13(11): e0205156.

Lacy, R.C., Williams, R., Ashe, E., Balcomb III, K.C., Brent, L.J., Clark, C.W., Croft, D.P., Giles, D.A., MacDuffee, M. and Paquet, P.C. (2017). Evaluating anthropogenic threats to endangered killer whales to inform effective recovery plans. Scientific reports, 7(1), 1-12.

Legg, N.T., and P.L. Olson. 2015. Screening tools for identifying migrating stream channels in western Washington – geospatial data layers and visual assessments. Publication No. 15-06-003. Washington State Department of Ecology, Olympia, Washington. (https://fortress.wa.gov/ecy/publications/documents/1506003.pdf)

Legg, N.T., and P.L. Olson. 2014. Channel migration processes and patterns in western Washington: A synthesis for floodplain management and restoration. Publication No. 14-06-028. Washington State Department of Ecology, Olympia, Washington. (https://fortress.wa.gov/ecy/publications/documents/1406028.pdf)

Lichvar, R.W., N.C. Melvin, M.L Butterwick, and W.N Kirchner. 2012. National wetland plant list indicator rating definitions. ERCD/CRREL TN-12-1. U.S. Army Corps of Engineers, Washington, D.C.

Murray, C.C., Hannah, L.C., Doniol-Valcroze, T., Wright, B., Stredulinsky, E., Locke, A., and R. Lacy. (2019). Cumulative Effects Assessment for Northern and Southern Resident Killer Whale Populations in the Northeast Pacific. Department of Fisheries and Oceans, Canadian Scientific Advisory Research Document 2019/056. x. + 88 pp.

Naiman, R. J., and R. E. Bilby. 1998. (editors) River ecology and management: lessons from the Pacific Coastal Ecoregion. Springer Science & Business Media, New York.

Naiman, R.J., H. Decamps, and M. Pollock. 1993. The role of riparian corridors in maintaining regional biodiversity. Ecological Applications 3:209-212.

Nordland, B., and K. Bates. 2000. Draft fish protection and screen guidelines for Washington State. Habitat Program, Washington Department of Fish and Wildlife, Olympia, Washington. (https://wdfw.wa.gov/publications/00050)

NRC (National Research Council). 2002. Riparian areas: functions and strategies for management. The National Academies Press, Washington, D.C. https://doi.org/10.17226/10327.

Olson, P. L., N. T. Legg, T. B. Abbe, M. A. Reinhart, and J. K. Radloff. 2014. A methodology for delineating planning-level channel migration zones. Publication No. 14-06-025. Washington State Department of Ecology, Olympia, Washington. (https://fortress.wa.gov/ecy/publications/documents/1406025.pdf)

Patten, D.T. 1998. Riparian ecosystems of semi-arid North America: diversity and human impacts. Wetlands 18:498-512. https://doi.org/10.1007/BF03161668.

Puget Sound Partnership. 2020. Puget Sound Vital Signs. Available: https://www.psp.wa.gov/evaluating-vital-signs.php (December 2020).

Quinn, T., et al. 1998. Habitat Associations of the riparian-dependent amphibian, reptile, mammals, and mollusks in commercial forest lands of Washington State: a report to the Timber, Fish & Wildlife policy committee. Washington Department of Natural Resources, Olympia, Washington.

Rapp, C.F., and T.B. Abbe. 2003. A framework for delineating channel migration zones. Publication No. 03-06-027. Washington State Department of Ecology, Olympia, Washington. (https://fortress.wa.gov/ecy/publications/documents/0306027.pdf)

RCO (Recreation and Conservation Office). 2019. State of Salmon. RCO, Olympia, Washington. https://stateofsalmon.wa.gov/exec-summary/ Retrieved July 23, 2019.

Richardson, J.S., R.J. Naiman, F.J. Swanson, and D.E. Hibbs. 2005. Riparian communities associated with Pacific Northwest headwater streams: assemblages, processes, and uniqueness. Journal of American Water Resources Association 41:935-947.

Rogers, L.E, R.E. Fitzner, L.L. Cadwell, and B.E. Vaughan. 1988. Terrestrial animal habitats and population responses. Pages 182-257 in W.H. Rickard, L.E. Rogers, B.E. Vaughan, and S.F. Liebetrau (editors). Shrub-steppe: balance and change in a semi-arid terrestrial ecosystem. Elsevier, New York.

Rosgen, D.L. 1996. Applied river morphology: Second edition. Wildland Hydrology Books, Fort Collins, Colorado.

Seavy, N.E., T. Gardali, G.H. Golet, F.T. Griggs, C.A. Howell, R. Kelsey, S.L. Small, J.H. Viers, and J.F. Weigand. 2009. Why climate change makes riparian restoration more important than ever: recommendations for practice and research. Ecological Restoration 27:330-338.

Shared Strategy Development Committee. 2007. Puget Sound salmon recovery plan. Shared Strategy for Puget Sound, Seattle, Washington.

Smith, D. 2005. Off-channel habitat inventory and assessment for the upper Skagit River basin. Report to non-flow coordinating committee of the Skagit River Hydroelectric Project (FERC No. 553). Skagit River System Cooperative, La Conner, Washington.

Thomas, F.M. 2014. Ecology of phreatophytes. Progress in Botany 75:335-375.

Thomas, J.W. (technical editor]). 1979. Wildlife Habitats in Managed Forests: The Blue Mountains of Oregon and Washington. Agriculture Handbook No. 553. U.S. Forest Service, Washington, D.C. (https://www.srs.fs.usda.gov/pubs/gtr/uncaptured/gtr_pnw080.pdf)

Thomas, J.W., J.F. Franklin, J. Gordon, and K.N. Johnson. 2006. The Northwest Forest Plan: Origins, components, implementation experience and suggestions for change. Conservation Biology 20:277-87.

USFS (U.S. Forest Service). 2008. Stream simulation: an ecological approach to providing passage for aquatic organisms at road-crossings. National Technology and Development Program, San Dimas, California.

USFS (U.S. Forest Service). 2001. Selway and Middle Fork Clearwater Rivers Subbasin Assessment. Nez Perce, Clearwater, and Bitterroot National Forests, Idaho. Retrieved August 26, 2019.

Vander Haegen, M.W. 2007. Fragmentation by agriculture influences reproductive success of birds in a shrub-steppe landscape. Ecological Applications 17: 934-947.

Ward, J.V., and J.A. Stanford. 1995. Ecological connectivity in alluvial river ecosystems and its disruption by flow regulation. Regulated Rivers: Research & Management 11:105-119.

Washington Sea Grant. 2009. Protection of marine riparian functions in Puget Sound, Washington. Washington Department of Fish and Wildlife, Olympia, Washington. (https://wdfw.wa.gov/publications/00693)

WDFW (Washington Department of Fish and Wildlife). 2005. Washington's comprehensive wildlife conservation strategy, final draft. WDFW, Olympia, Washington.

WDFW (Washington Department of Fish and Wildlife). 2016. Your marine waterfront: A guide to protecting your property while promoting healthy shorelines. WDFW, Olympia, Washington. (https://wdfw.wa.gov/publications/01791)

Williams, P.B., E. Andrews, J.J. Opperman, S. Bozkurt, and P.B. Moyle. 2009. Quantifying activated floodplains on a lowland regulated river: its application to floodplain restoration in the Sacramento Valley. San Francisco Estuary and Watershed Science 7(1).

Wolman, M.G., and L.B Leopold. 1957. River flood plains: some observations on their formation. Geological Survey Professional Paper 282-C. U.S. Government Printing Office, Washington, D.C.



Riparian area below the south slope of Mt. St. Helens. The area is still recovering from the mountain's volcanic eruption in May 1980. Skamania County/Brendan O'Doherty

Glossary of Terms

Active channel: The active channel is defined by the lower limit of continuous riparian vegetation (Naiman et al. 1998) and may be delineated by absence of both moss on rocks and rooted vegetation (USFS 2008). The upper most elevation of the active channel is sometimes equated with the ordinary high-water mark.

Active floodplain: Located between the active channel and adjacent terrace or hillslopes (Fetherston et al. 1995; Harris 1987). Depending on the watershed, the flood return interval of the active floodplain varies between 1 and 10 years (Wolman and Leopold 1957; Ward and Stanford 1995; Lichvar et al. 2006; Williams et al. 2009; BLM 2015).

Adaptive management: The systematic acquisition and application of reliable information to improve management over time. It often includes treating management decisions as experiments in order to address critical uncertainties and learn more quickly from experience. It involves setting objectives, monitoring conditions, and adjusting management based on results. Hallmarks of a sound adaptive management program include: (1) adequate funding for monitoring and research, (2) a willingness to change course when pre-established triggers are reached, and (3) a commitment to gather data and evaluate conditions at appropriate spatial extents and time scales. See Ecosystem-based management and WAC 365-195-920(2).

Anadromous fisheries: The commercial, recreational or subsistence harvest of fish that are born in freshwater, rear at sea, and return to freshwater to spawn. Anadromous fisheries of Washington include salmon (Chinook, coho, chum, sockeye, and pink), steelhead, bull trout, coastal cutthroat trout, green sturgeon, white sturgeon, eulachon, longfin smelt, and Pacific lamprey.

Aquatic species: Wildlife species that live in marine or freshwater including fish, shellfish (e.g., clams, snails, mussels), amphibians (e.g., frogs, salamanders), reptiles (e.g., turtles), crustaceans (e.g., crayfish), insects (e.g., larval mayflies, stoneflies, caddisflies, dragonflies) and various other invertebrates.

Best Available Science: Information produced through a valid scientific process that WDFW or another local, state or federal agency has determined represents the best available science consistent with criteria set out in WAC 365-195-900 through 365-195-925. (Volume 1 of this document is an example of Best Available Science regarding riparian ecosystems.)

Biota: The animal and plant life of a region, habitat, or geological period.

Buffer: The area around a critical area that separates the critical area from incompatible uses. For example, a 200m buffer may be established around a heron-nesting colony (the critical area) to keep suburban land uses from disrupting the colony. See WAC 365-190-130(3)(a). Riparian ecosystems are both buffers (for instream habitat) and critical areas on their own merit.

Channel Migration Zone: The area within which a river channel is likely to migrate and occupy over a specified time period (e.g., 100 years).

Channel slope or gradient: The average steepness of a stream segment measured as its change in elevation divided by its length. Typically, a segment's gradient is considered low if less than 2%, moderate between 2% and 4%, and high if greater than 4%.

Classification (critical area): Defining categories to which critical areas are assigned. The Priority Habitats and Species (PHS) program provides WDFW's recommended classification scheme for Fish and Wildlife Habitat Conservation Areas. Classification precedes designation in counties' and cities' effort to protect critical areas. *See* WAC 365-190-040(4).

Complexity: The complicated state seen in dynamic environments that contain multiple components and processes that interact with one another in a web of interactions whose outcomes are often unpredictable. Complexity can be described with conceptual models; outcomes of well-understood complex phenomena can be partially predicted using computer models.

Connectivity: Landscape connectivity is the physical relationship between landscape elements. Functional connectivity describes the degree to which landscapes facilitate or impede the movement of organisms between areas of habitat.

Critical Aquifer Recharge Area: Areas with an essential recharging effect on aquifers used for potable water. One of five types of Critical Areas identified in the Growth Management Act.

Critical Area(s): Places that the Growth Management Act requires all counties and cities to designate and protect, specifically, (1) Wetlands; (2) Critical Aquifer Recharge Areas; (3) Fish and Wildlife Habitat Conservation Areas (e.g., Riparian Management Zones); (4) Frequently Flooded Areas; and (5) Geologically Hazardous Areas. In developing policies and regulations to protect the functions and values of critical areas, counties and cities are required to include best available science and give special consideration to conservation or protection measures necessary to preserve or enhance anadromous fisheries. *See* RCW 36.70A.172(1). The presence of a critical area may limit some land development options. *See* WAC 365-190-040(6).

Delineation (critical area): The act of applying definitions or performance standards in the field to identify the boundary of a critical area.

Designation (critical area): Assigning critical areas into established categories and specifying their general distribution, location, and extent. Designation can be made by maps (which are useful for public awareness and for identifying if a proposal may affect a critical area) and by performance standards or definitions (which allow for specific identification and site-scale delineation during permit review). WDFW's Priority Habitats and Species (PHS) program provides the agency's recommended designation maps and performance standards/definitions for Fish and Wildlife Habitat Conservation Areas. Designation occurs after classification in counties' and cities' efforts to protect critical areas. *See* WAC 365-190-040(5).

Disturbance regime: The frequency, magnitude, and duration of disturbance events.

Disturbance: A pronounced, temporary change in environmental conditions within an ecosystem. Disturbances often act quickly and can alter ecosystem composition, structure, and function.

Ecological (biological) **integrity:** Ability of an ecological system to support and maintain a community of organism that has species composition, diversity, and functional organization comparable to those of natural habitats within a region. An ecological system has integrity when its dominant ecological characteristics (composition, structure, function, and processes) occur within their historical ranges of natural variability. See Historical condition and Range of natural variability.

Ecosystem(s): A spatially explicit unit of the Earth that includes all the organisms, along with all components of the abiotic (chemical and physical) environment. Ecosystems have composition, structure, and functions.

Ecosystem composition (or ecological composition): All living (biotic) and nonliving parts of an ecosystem.

Ecosystem function(ing) (or ecological function): (1) The process or cause and effect relationship underlying two or more interacting components, e.g., terrestrial plant material as food/substrate for aquatic invertebrates. (2) The sum of processes that sustain the system. (3) The capacity of natural processes and components to provide goods and services that satisfy human needs, either directly or indirectly. Ecosystem functions can be conceived as a subset of ecological processes (See *Ecosystem process*).

Ecosystem process (or ecological process): Interactions among components of an ecosystem, biotic (living organisms) and abiotic (chemical and physical) components. Many processes involve transfer, conversion, or storage of matter or energy (See *Ecosystem process*).

Ecosystem structure (or ecological structure): The arrangement of and relations among the parts or elements (components) of an ecosystem.

Ecosystem-based management (EBM): Management driven by explicit goals; executed by policies, protocols, and practices; and made adaptable by monitoring and research; based on our best understanding of the ecological interactions and processes necessary to sustain ecosystem composition, structure, and function. EBM acknowledges that humans are an important ecosystem component and focuses on managing human activities within ecosystems. EBM often involves balancing ecological, economic, and social objectives within the context of existing laws and policies.

Enhance: To improve a critical area's existing ecosystem processes, structure, and/or functions so that its ecological integrity is more like its historical condition.

Erosion: The loosening and transport of soil particles and other sediment by water. Terrestrial erosion includes raindrop splash erosion, overland flow sheet erosion, surface flow rill (shallow) and gully (deeper) erosion. Channel erosion includes streambank erosion and channel incision (gouging). Rill and gully erosion diminish the ability of the riparian area to trap sediment and pollutants and can often be avoided with intact riparian vegetation.

Fish and Wildlife Habitat Conservation Areas (FWHCA): A type of Critical Area specified in the Growth Management Act. The intent of FWHCAs are to maintain populations of species in suitable habitats within their natural geographic distribution so that (1) the habitat available is sufficient to support viable populations over the long term, and (2)

isolated subpopulations are not created. FWHCAs come in a variety of types including waters of the state, places with which listed species have a primary association, habitats and species of local importance, and riparian ecosystems. See WAC 365-190-130.

Flow regime (stream): The distribution of stream flow through space and time. Flow regimes can be described by their magnitude (e.g., mean annual, hourly maximum), timing, frequency or return periodicity, duration, spatial distribution, and rate of change. The pathways that water takes to reach a stream (e.g., surface runoff) and within a stream exert a strong influence on the flow regime.

Function: Physical, chemical, or biological processes that occur within an ecosystem. WAC 365-196-830 says, "Functions are the conditions and processes that support the ecosystem. Conditions and processes operate on varying geographic scales ranging from site-specific to watershed and even regional scales." See also *Ecosystem function(ing)* and *Ecosystem process.*

Habitat: The resources and conditions presented in an area that support the functional needs of a species (e.g., hiding, migration, resting, feeding, breeding, and rearing), and which are necessary for its survival and reproduction. Habitat is species-specific, scale dependent, and more than vegetation composition or structure.

Hazard Tree: A tree that a jurisdiction's building official or other recognized professional (e.g., certified arborist, registered landscape architect, or certified forester) has determined poses a near-term hazard to public safety or to an existing permanent structure or public utility.

Herbaceous: Non-woody plants such as grasses and ferns.

Historical condition: *See* Ecological integrity and Range of natural variability.

Hydrology: Description of the properties, distribution, movement, and storage of water on and below the Earth's surface.

Impervious surface: Ground surfaces that resist or prevent water infiltration, e.g., roofs of houses, roadways.

Imputed: Estimated; a value assigned to missing data by inference from the values of data within the same dataset.

Infiltration: The rate or process by which water on the ground enters the soil.

Instream: Within flowing freshwater; also, the area waterward of the Ordinary High-Water Mark.

Large Woody Debris: Large dead woody material (such as fallen trees and branches) in various stages of decomposition that provide nutrient capital to forest and aquatic resources and serve as habitat in forest and riparian ecosystems. Large wood is usually defined as having diameter greater than 4 in (10 cm) and length greater than 6 ft (≈ 2 m).

Low Impact Development (LID): A storm water and land-use management strategy that tries to mimic natural hydrologic conditions by emphasizing pre-disturbance hydrologic processes of infiltration, filtration, storage, evaporation, and transpiration.

Mitigation: General category of measures that a proponent may take to avoid, minimize, and compensate for impacts.

Mitigation sequence: The stepwise process of protecting a critical area through, first (1) avoiding harm to the critical area to the maximum extent practicable, then (2) minimizing unavoidable harm to the maximum extent practicable, and finally (3) providing compensation for all unavoidable harm by restoring, creating, enhancing, or preserving the critical area's ecological functions and values to replace those impacted or lost through permitted activities.

Monitoring: The process of observing and checking the progress or quality environmental conditions for the purposes of adaptive management. Often described as having three types – implementation, effectiveness, and validation.

Morphology (stream channel, aka fluvial geomorphology): A stream channel's shape and how it changes over time. Channel morphology is influenced by the abundance and variation in sediment sources, the ability of water to transport sediment downstream, and interactions of sediment with riparian vegetation and woody debris.

Off-Channel Habitat: Overflow channels, sloughs, alcoves, wetlands, and small streams found within the floodplains of larger river channels. Off-channel habitat consists of waters connected to and draining into rivers and streams by inundation during peak flow events (Smith 2005; WAC 222-16-031). Off-channel habitat provides habitat for salmonids and other aquatic species which often afford (1) spawning habitat that does not experience scouring high flows; and (2) summer rearing habitat that does not experience loss of stream flow.

Ordinary High Water Mark (OHWM): (1) That mark that will be found by examining the bed and banks and ascertaining where the presence and action of waters are so common and usual, and so long continued in all ordinary years, as to mark upon the soil a character distinct from that of the abutting upland (Washington Department of Ecology 2016). (2) That line on the shore established by the fluctuations of water and indicated by physical characteristics such as a clear, natural line impressed on the bank, shelving, changes in the character of soil, destruction of terrestrial vegetation, the presence of litter and debris, or other appropriate means that consider the characteristics of the surrounding areas (U.S. Army Corps of Engineers, 2014).

Organic litter: Plant, leaf, tree, or soil litter, and duff are dead plant materials that have fallen to the ground. In this document, organic litter is referenced as available for contributions to the stream system.

Passive Restoration: Allowing natural succession to occur in an ecosystem after removing a source of disturbance.

Population viability (local): The likelihood that a population of a species will persist for some length of time.

Precautionary principle: Erring on the side of not harming resources when faced with uncertainty, especially for potential harm that is essentially irreversible. Utilizing a precautionary approach in land use planning involves: (1) taking preventive action (avoiding impacts); (2) shifting the burden of proof to the project proponents; (3) exploring a wide range of potential alternatives; and/or (4) including multiple stakeholders and disciplines in decision making.

Priority Area: The area within a Priority Species' natural geographic distribution within which protective measures and/or management actions are needed to (1) support viable populations over the long term and (2) avoid creating isolated subpopulations.

Priority Habitat: A State of Washington habitat type with unique or significant value to many species; an area with one or more of the following attributes: (1) comparatively high fish and wildlife density; (2) comparatively high species diversity; (3) important breeding habitat; (4) important seasonal ranges; (5) important movement corridors; (6) limited availability; (7) high vulnerability to habitat alteration; or (8) unique or dependent species. Examples of Priority Habitats include but are not limited to instream, riparian, shrub steppe, Oregon white oak woodlands, freshwater wetlands, and marine nearshore.

Priority Habitats & Species (PHS): WDFW's primary means of transferring fish and wildlife information from resource experts to local governments, landowners, and others for the protection of fish, wildlife, and habitat. Includes endangered, threatened, sensitive, candidate, and vulnerable species and habitats deemed priorities of WDFW and reflective of best available science. See WAC 365-190-130.

Priority Species: A State of Washington fish or wildlife species requiring protective measures and/or management actions to ensure its survival. A Priority Species fits one or more of the following criteria: (1) is a state-listed endangered, threatened, sensitive, or candidate species, (2) has vulnerable aggregations, or (3) is of recreational, commercial, and/or tribal importance. Examples of Priority Species include but are not limited to steelhead/rainbow trout, bull trout/Dolly Varden, great blue heron, cavity-nesting ducks, sage grouse, fisher, orca, and elk.

Process: See *Ecosystem process.*

Protect: To prevent the degradation of existing ecosystem functions and values.

Range of natural variability (or Historical range of natural variability): Refers to the range of ecological conditions (components, structures and functions) in a time period before widespread anthropogenic changes.

Recruitment (wood): The process of wood moving from a riparian area to the stream channel. Sources of recruitment include bank erosion, windthrow, landslides, debris flows, snow avalanches, and tree mortality due to, for example, fire, ice storms, beavers, insects, or disease. Dominant factors include, but are not limited to, channel width, slope steepness, slope stability, forest composition and structure, and local wind patterns.

Refugia (singular Refugium): sites to which biota retreat, persist in and potentially expand from under changing environmental conditions (Keppel et al. 2012).

Riparian: An adjective meaning alongside a waterbody: stream, river, lake, pond, bay, sea, and ocean. Riparian areas are sometimes referred to by different names: riparian ecosystems, riparian habitats, riparian corridors, or riparian zones. Depending on the contexts, these terms may have somewhat different meanings.

Riparian area: A defined area encompassing both sides of a water body, composed of aquatic ecosystems (i.e., the river or stream), riparian ecosystem, and riverine wetlands. Riparian areas are three dimensional: longitudinal up and down streams, lateral to the width of the riparian ecosystem, and vertical from below the water table to above the canopy of mature site-potential trees (NRC 2002).

Riparian buffer: Buffer refers to its purpose, which is to reduce or prevent adverse impacts to water quality, fisheries, and aquatic biodiversity from human activities occurring upslope of the buffer. Riparian buffers managed specifically for pollutant removal may also be called a vegetated filter strip.

Riparian ecosystem: Riparian areas are transitional between terrestrial and aquatic ecosystems and distinguished by gradients in biophysical conditions, ecological processes, and biota. They are areas through which surface and subsurface hydrology connect waterbodies with their adjacent uplands. They include those portions of the ecosystem distinguished by gradients (i.e., riparian zones) and portions of terrestrial ecosystems that significantly influence exchanges of energy and matter with aquatic ecosystems (i.e., the Zone of Influence). Our definition of riparian ecosystem does not include adjacent waters (i.e., rivers or streams, but does include riverine wetlands) and recognizes the riparian zone as a distinctive area within riparian ecosystems.

Riparian Management Zone: A delineable area defined in a land use regulation; often synonymous with riparian buffer. For the purposes of this document, we define the RMZ as the area that has the potential to provide full riparian functions. In many forested regions of the state this area occurs within one 200-year site-potential tree height measured from the edge of the stream channel. In situations where a CMZ is present, this occurs within one site-potential tree height measured from the edges of the CMZ. In non-forest zones the RMZ is defined by the greater of the outermost point of the riparian vegetative community or the pollution removal function, at 100-feet.

Riparian values: The benefits that riparian ecosystems provide to society, including but not limited to flood damage reduction, water quality improvement, provision of harvestable populations of salmon, and provision of recreational opportunities. Riparian values have direct economic consequences to local communities through fishing opportunities, and flood and water quality protection, among others.

Riparian zone: A distinctive area within riparian ecosystems. The riparian zone contains wet or moist soils and plants adapted to growing conditions associated with periodically saturated soils. See *Riparian ecosystem.*

Risk: A situation involving exposure to danger, harm, or loss. Risk reflects the magnitude of the adverse impact and its probability of occurring. Risk is appropriately managed by applying the precautionary principle (especially for irreversible losses) and through adaptive management.

Salmonid: A family of fish comprised of salmon, trout and whitefish. Native salmonid species in Washington State include: Chinook Salmon (*Oncorhynchus tshawytscha*), Chum Salmon (*O. keta*), Coho Salmon (*O. kisutch*), Pink Salmon (*O. gorbuscha*), Sockeye Salmon/Kokanee (*O. nerka*), Steelhead/Rainbow Trout (*O. mykiss*), Cutthroat Trout (*O. clarki*), Bull Trout (*Salvelinus confluentus*), Dolly Varden (*S. malma*), Pygmy Whitefish (*Prosopium coulteri*), and Mountain Whitefish (*P. williamsoni*). This list does not include names of subspecies. (See *Anadromous* fisheries).

Site class: The classification of a site based on the productivity of its dominant tree species. Site classes vary based on local differences in soil nutrients and moisture, light and temperature regimes, and topography. Site classes are typically described as most productive (I) through least productive (V).

Site-Potential Tree Height: The average maximum height of the tallest dominant trees for a given age and site class.

Stronghold: Habitat strongholds are refugia watersheds that contain high quality habitat with depressed or weak populations. The habitat in these areas has a high to very high potential to support these species. The population level in these areas is not considered to be a function of habitat, but other factors (USFS2001).

Structure: See *Ecosystem structure.*

Succession: Ecological succession is the process by which the biological community composition recovers over time following a disturbance event.

Uncertainty (scientific): The absence of information about the state of something or a relevant variable. Sources of uncertainty include, but are not limited to natural variation (i.e., because outcomes vary in difficult-to-predict ways through time and space), model uncertainty (i.e., we do not understand how things interact with each other), systematic error (e.g., poorly designed experiments or calibrated instruments), or measurement error. See *Risk*.

Values: The level of benefits that the space, water, minerals, biota, and all other factors that make up a natural ecosystem provide to support native life forms, including humans (Cordell et al. 2005).

Vegetative filter strips: A riparian buffer designed to capture nutrients, contaminant compounds, and sediment transported by run-off. Filter strips are sometimes synonymous with riparian buffers.

Water quality: Physical, chemical, and biological characteristics of water that describe its suitability to meet human needs or habitat requirements for fish and wildlife.

Watershed processes: The fluxes of energy (e.g., sunlight, wildfire) and materials (particularly water and sediment) that interact with biota (e.g., vegetative cover, salmon, beavers, soil microbes) to form a watershed's physical features and characteristics, which give rise to its instream physical and ecological conditions. These processes occur within a context that reflects the watershed's climate, geology, topography, and existing human land use. See *Ecosystem process.*

Watershed: A land area that drains to a common waterbody.

Wetland: Those areas that are inundated or saturated by surface or ground water at a frequency and duration sufficient to support—and that under normal circumstances do support—a prevalence of vegetation typically adapted for life in saturated soil conditions. Examples include but are not limited to swamps, marshes, and bogs.

Zone of Influence: The portions of terrestrial ecosystems that significantly influence exchanges of energy (e.g., sunlight) and matter (e.g., large wood, sediment, nutrients) with aquatic ecosystems.

Appendix. Site-Potential Tree Height Mapping Tool

The Site-Potential Tree Height (SPTH) Mapping Tool helps users find information they need to conserve, protect, and restore riparian ecosystems within a project site. The SPTH mapping tool works on personal computers (PCs) and mobile devices (tablets and smartphones).

Site-Potential Tree Height Map Data

The SPTH mapping tool contains several GIS data layers, explained below:

1. Site-potential Tree Height at 200 Years ($SPTH_{200}$),
2. Imputed[14] $SPTH_{200}$ Values for Urban areas,
3. Dryland Ecosystems – No SPTH Values, and
4. Other Lands – No SPTH Values.

Site-potential Tree Height at 200 Years ($SPTH_{200}$)

WDFW derived the $SPTH_{200}$ values from forest productivity site index information using Natural Resource Conservation Service (NRCS) soil polygons and its Soil Data Viewer tool for ArcGIS. The NRCS-provided forest productivity site index values, in feet, were for ages 50 years in Western Washington and typically 100 years in Eastern Washington. WDFW determined $SPTH_{200}$ values using tree site index equations. Each soil polygon has one or more tree species records with associated $SPTH_{200}$. When multiple tree species records with associated $SPTH_{200}$ are available, WDFW recommends using the largest $SPTH_{200}$ value of the tree species historically present at the site (such trees may currently be found on the site, but also may not). For example, if a project site contains mostly red alder but Douglas-fir is present (or was present prior to modern human alterations), use the Douglas-fir $SPTH_{200}$ for that soil polygon.

Imputed $SPTH_{200}$ Values

Four large urban areas (Seattle, Spokane, Tacoma, and Bellingham) lacked NRCS soil polygons; therefore, forest productivity information could not be mapped for most locations within those areas. Similarly, numerous soil polygons labelled as "Urban Land" lacked forest productivity information. For each of these four urban areas, WDFW calculated an imputed $SPTH_{200}$ by using an area-weighted average for 200-year site index values within a two-mile buffer around the perimeter. WDFW recommends the use of this imputed $SPTH_{200}$ as a guide for delineating RMZs in these urban areas. At the time of publication, WDFW had calculated imputed $SPTH_{200}$ information for those large urban areas. WDFW expects to continue to update the map.

[14] Imputed: estimated; a value assigned to something by inference from the value of the products or processes to which it contributes.

Dryland Ecosystems and Other Lands

Not all soil polygons are forested, or have forest productivity information from NRCS; therefore, not all of them have associated $SPTH_{200}$ values. In addition, Benton, Franklin, Grant, and Adams counties had no forest productivity information in their NRCS soil polygons. These areas without $SPTH_{200}$ values were classified in one of two ways: as "dryland ecosystems", or "other lands."

- WDFW approximated the area contained within "dryland ecosystems" using the Arid Lands Initiative study area boundary (Arid Lands Initiative, 2014) and have developed associated process steps that we recommend be used to derive RMZ widths (Volume 2, Section 2.2.3).

- The "other lands" comprise the remaining soil polygons and are small and dispersed across the landscape. These polygons include the NRCS soil map unit name, if applicable, and often represent soils that do not support tree growth, such as beaches and wetlands, as well as certain types of heavily modified sites like gravel pits. Please consult with a WDFW regional habitat biologist on deriving RMZs for "other lands" and consider following a similar process for delineation in dryland ecosystems.

Using the Site-Potential Tree Height Mapping Tool

The mapping tool can be accessed from several locations:

- WDFW website (https://wdfw.wa.gov/species-habitats/at-risk/phs/recommendations),
- Washington Geospatial Open Data Portal (http://geo.wa.gov/), and
- ArcGIS Online (AGOL) (https://wdfw.maps.arcgis.com/apps/MapSeries/index.html?appid=919ea98204eb4f5fa70eca99cd5b0de1).

The mapping tool consists of the statewide map with the four riparian datasets described above; user tools; and a sidebar explaining map contents, how to use the map, and links to supporting documents.

The four riparian datasets have unique colors indicating where the information occurs.

- **Green:** Area where $SPTH_{200}$ has been calculated.
- **Orange:** Areas where $SPTH_{200}$ values have been imputed.
- **Pale brown:** Dryland ecosystems where there is no tree height information.
- **Beige:** Places for which no SPTH site index information is available.

Tribal and publicly owned/managed lands federal and tribal lands are typically subject to different riparian regulations. Tribal, federal, and state lands are displayed in shades of grey. County-owned lands are shown in lavender, and city-owned lands are light blue.

The mapping tool contains the following tools (Figure A1):

- **Zoom slider:** zoom in or out on the center of the map.
- **Address search tool:** zooms to a street address, place name, or latitude and longitude.
- **Legend:** displays the map layers currently visible. For example, map layers displayed at a site-specific scale will not appear in the legend when zoomed out to the statewide extent.
- **Home icon:** resets map to statewide extent.
- **Target icon:** allows the user to zoom directly to their current location.
- **Measurement tool:** use this to measure the distance between objects (e.g. edge of stream to another point), or to measure an area (square feet of an area surrounding a project site).
- **Basemap selector:** change the basemap to show a different view of the landscape: aerial imagery (default), topographic map, open street map, terrain with labels, and USGS national map.
- **Scale bar:** shows the scale that the map is zoomed to. At a statewide extent, the scale bar will show 0 to 60 miles. When zoomed to a scale where you can view the project area, the scale bar will show 0 to 100 feet or 200 feet.
- **Coordinates:** latitude and longitude (decimal degrees) are shown where the cursor is located on the map.
- **Panning:** move the map by placing the cursor over a desired location and dragging it to the center of the map display.

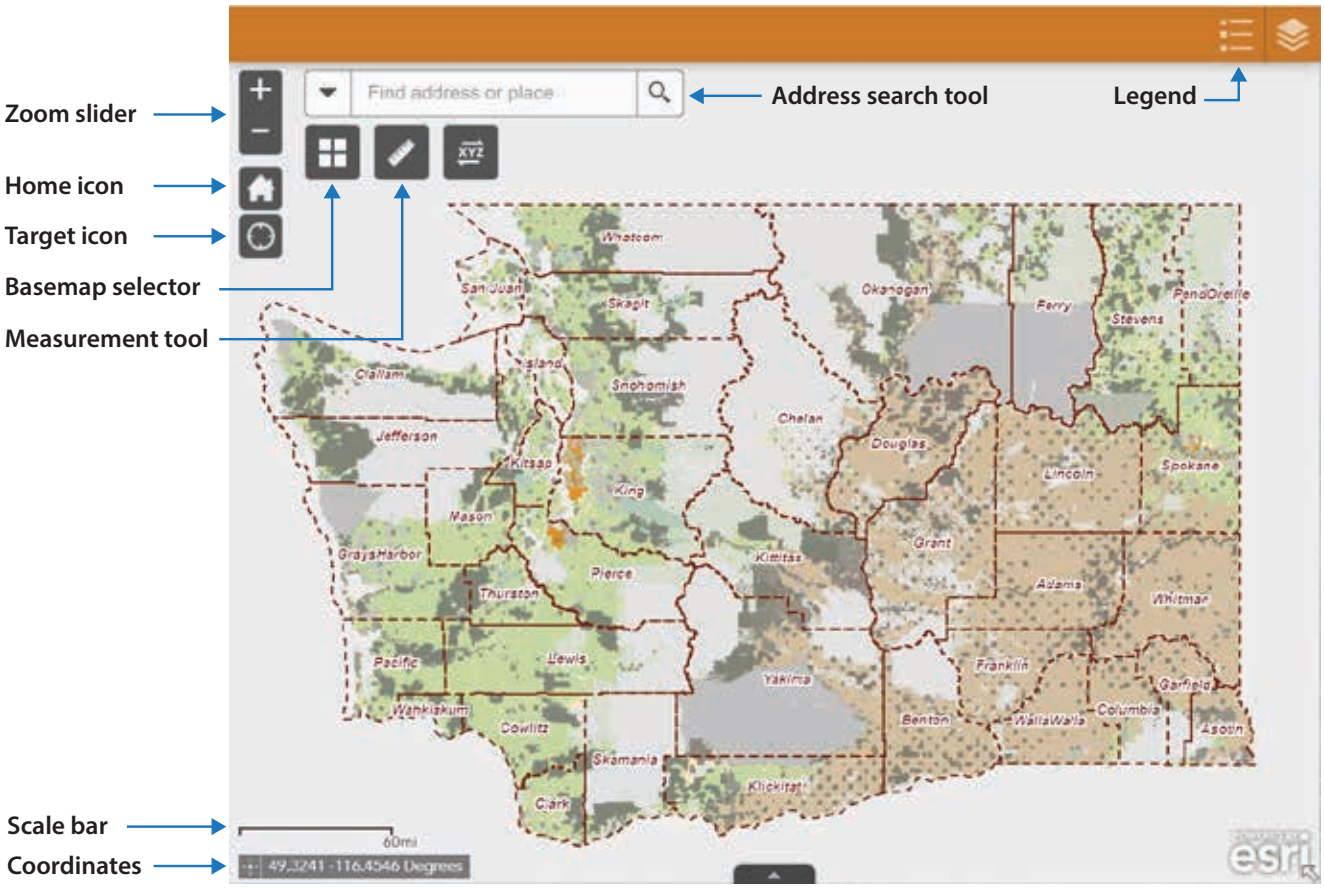


Figure A1. Tools available on the SPTH200 and RMZ Online Map.

To zoom to a site location, use the Address Search tool or use a combination of the Zoom Slider and panning. (If using the Address Search tool, select the "ArcGIS World Geocoding Service" from the dropdown menu to the left of the search field for faster results.) Once the site is located, a click (on PCs) or tap (on mobile devices) of the cursor will open a popup window with information about that location. Be sure to review each window if multiple records are selected.

The NRCS soil polygons form a complex mosaic across the landscape, so you must zoom in close enough to clearly see your project site. Clicking (or tapping, on mobile devices) on the map when it is zoomed out will result in erroneous returns of the $SPTH_{200}$ values. Below is an example of using these tools to obtain riparian information at a project site.

Mapping Tool Example #1

1. Start up the Online Map.

2. Type the project location into the Address Search tool (Figure A2). If the address is unknown, use a nearby place name or latitude and longitude. This example uses 16018 Mill Creek Boulevard, Mill Creek, Washington.

3. Select the correct address from the drop-down menu or continue to enter manually. Click (on a **PC**) or tap (on a **mobile device**) the search button. The map will zoom to that location, shown as a small blue box and a popup titled "Search result" (Figure A3).

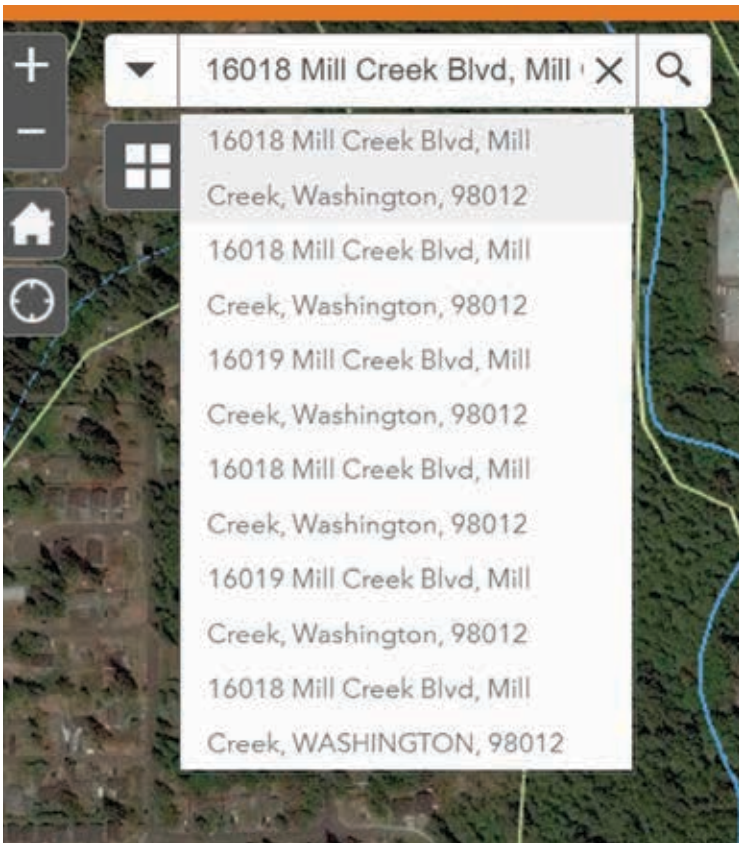


Figure A2. Using the Address Search tool.

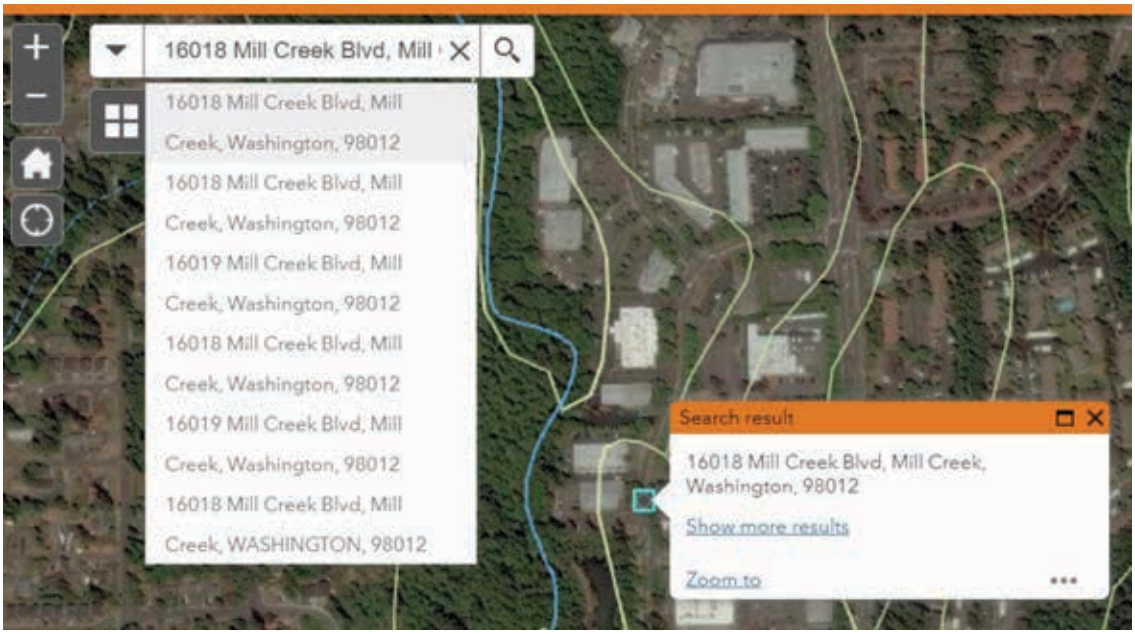


Figure A3. Zoomed in aerial image of the site address.

4. Click (or tap) on the "X" in the Address Search tool to close the popup. Zoom and pan until you can clearly see where the project site is on the landscape (Figure A4).

   In this example, the project site lies in a wooded area to the west of the address selected in the previous screen. We panned west to center the map display over the project site. In this screen, you can see outlines of the soil polygons.



Figure A4. Adjusting the map display over the project site.

5. Click (or tap) near a stream on the project site. The outline of the soil polygon selected will turn blue, and a popup window will provide information about the $SPTH_{200}$ (Figure A5). On a PC, the popup should automatically show (1) the $SPTH_{200}$ in feet, (2) the species of tree it is based on, and (3) the reference study used to derive the height value. On a mobile device, tap the arrow on the right side of the popup to display this information.

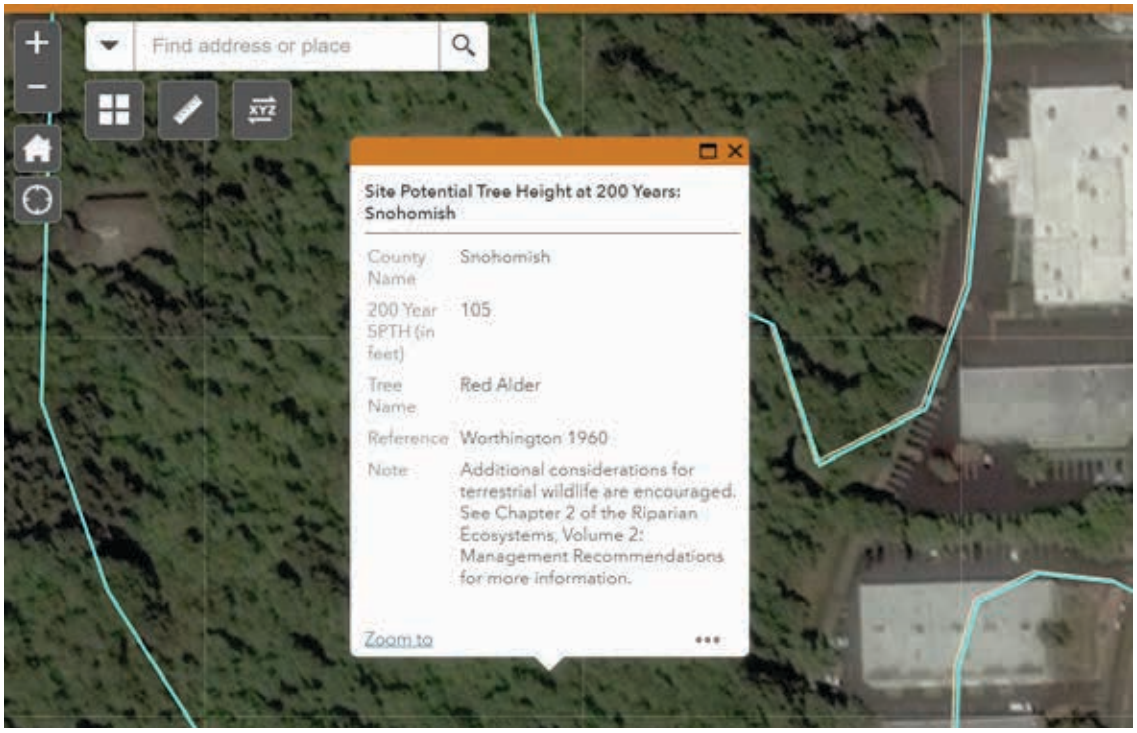


Figure A5. Bringing up the $SPTH_{200}$ information at the project site.

In Example #1, the soil polygon for the project site only showed one tree species: Red Alder. Sometimes soil polygons will list more than one tree species, as shown in Example #2.

Mapping Tool Example #2

Example #2, the project site was at a different location. Steps 1-3 in Example #1 were repeated to zoom to the project site. For this site, the popup window for the selected soil polygon looked different:

- The upper left corner of the popup window says "(1 of 2)"; and
- There is a small arrow near the upper right corner of the popup window.

This means that this soil polygon has two different associated tree species. The first is Douglas-fir (see Figure A6a).

To view the information for the second tree species, click on the small arrow. The second tree species is western hemlock (see Figure A6b).

For project locations with multiple tree species, WDFW recommends using the largest $SPTH_{200}$ value, even if the largest tree species is not the most numerous (or even currently present) onsite.

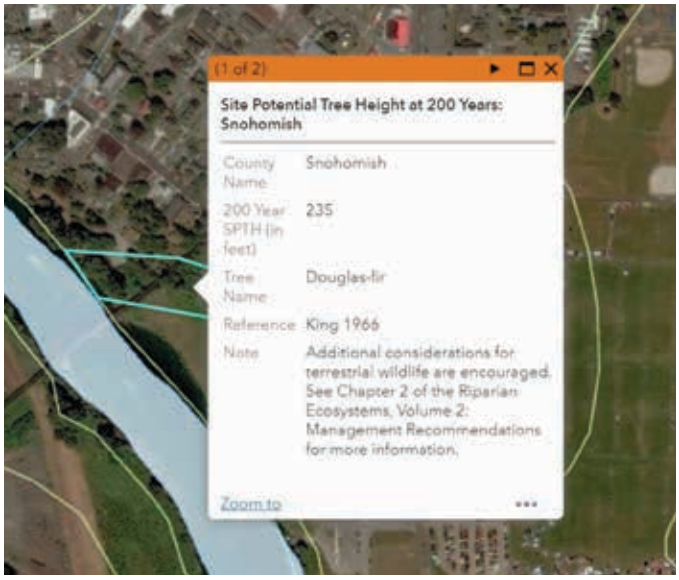


Figure A6a. SPTH information for the first of multiple tree species at a given site.

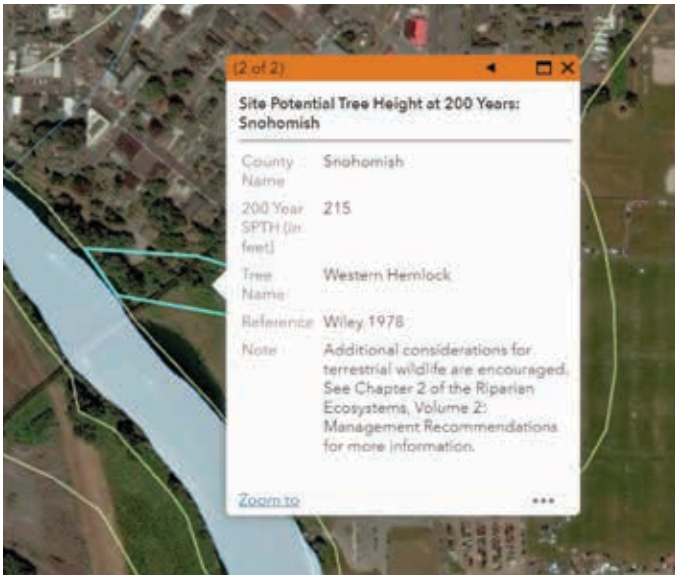


Figure A6b. SPTH$_{200}$ information for the second of multiple tree species at a given site.

Appendix References: Tree Site Index Curves

The following studies were used to determine SPTH$_{200}$ throughout the state:

Alexander, R.R. 1966. Site indexes for lodgepole pine, with corrections for stand density: instructions for field use. Research Paper RM-24. U.S., Forest Service, Rocky Mountain Forest and Range Experiment Station, Fort Collins, Colorado.

Alexander, R.R. 1967. Site indexes for Engelmann spruce. Research Paper RM-32. U.S., Forest Service, Rocky Mountain Forest and Range Experiment Station, Fort Collins, Colorado.

Baker, F.S. 1925. Aspen in the Central Rocky Mountain Region. Bulletin 1291. United States Department of Agriculture, \Washington, D.C.

Barnes, G.H. 1962. Yield of even-aged stands of western hemlock. Technical Bulletin 1273. U.S. Forest Service, Pacific Northwest Forest and Range Experiment Station, Portland, Oregon.

British Columbia Forest Service (BCFS). 1977. Site index curves for cottonwood (as adapted by W.J. Sauerwein). pp. 852-853 *in* Pocket Woodland Handbook. U.S. Department of Agriculture, Soil Conservation Service, Portland, Oregon.

Cochran, P.H. 1979a. Gross yields for even-aged stands of white or Douglas-fir and white or grand fir east of the Cascades in Oregon and Washington. Research Paper PNW-263. U.S. Forest Service, Pacific Northwest Forest and Range Experiment Station, Portland, Oregon.

Cochran, P.H. 1979b. Site index and height growth curves for managed, even-aged stands of Douglas-fir east of the Cascades in Oregon and Washington. Research Paper PNW-251. U.S. Forest Service, Pacific Northwest Forest and Range Experiment Station, Portland, Oregon.

Cochran, P.H. 1985. Site index, height growth, normal yields, and stocking levels for larch in Oregon and Washington. Research Note PNW-424. U.S. Forest Service, Pacific Northwest Forest and Range Experiment Station, Portland, Oregon.

Haig, I.T. 1932. Second-growth yield, stand, and volume tables for the western white pine type. Technical Bulletin 323. United States Department of Agriculture, Washington, D.C.

Hegyi, F., J.J. Jelinek, J. Viszlai, and D.B. Carpenter. 1979. Site index equations and curves for the major tree species in British Columbia. Forest Inventory Report No. 1. Ministry of Forestry, Victoria, British Columbia.

Herman, F.R., R.O. Curtis, and D.J. Demars. 1978. Height growth and site index estimates for noble fir in high-elevation forests of the Oregon-Washington Cascades. Research Paper PNW-243. U.S. Forest Service Pacific Northwest Forest and Range Experiment Station, Portland, Oregon.

Hoyer, G.D., and F.R. Herman. 1989. Height-age and site index curves for Pacific silver fir in the Pacific Northwest. Research Paper RP-418. U.S., Forest Service. Pacific Northwest Research Station, Portland, Oregon.

King, J.E. 1966. Site index curves for Douglas-fir in the Pacific Northwest. Forestry Paper 8. Weyerhaeuser Company, Forestry Research Center, Centralia, Washington.

Kurucz, J.F. 1978. Preliminary, polymorphic site index curves for western red cedar (*Thuja plicata Donn*) in coastal British Columbia. Forest Research Note No. 3. MacMillan Bloedel, Nanaimo, British Columbia.

Meyer, W.H. 1961. Yield of even-aged stands of ponderosa pine. Technical Bulletin 630 (revised 1961). United States Department of Agriculture, Washington, D.C.

Meyer, W.H. 1937. Yield of even-aged stands of Sitka spruce and western hemlock. Technical Bulletin 544. United States Department of Agriculture, Washington, D.C.

Monserud, R.A. 1985. Applying height growth and site index curves for inland Douglas-fir. Research Paper INT-347. U.S. Forest Service. Intermountain Research Station, Ogden, Utah.

Schmidt, W.C., R.C. Shearer, and A.L. Roe. 1976. Ecology and silviculture of western larch forests. Technical Bulletin 1520. U.S. Forest Service, Washington, D.C.

Wiley, K.N. 1978. Site index tables for western hemlock in the Pacific Northwest. Forestry Paper No. 17. Weyerhaeuser Company, Western Forestry Research Center, Centralia, Washington.

Worthington, N.P., F.A. Johnson, G.R. Staebler, and W.J. Lloyd. 1960. Research Paper No. 36. Normal yield tables for red alder. U.S. Forest Service, Pacific Northwest Forest and Range Experiment Station, Portland, Oregon.













Washington Department of FISH and WILDLIFE

Frontiers in Ecology and the Environment

Forecasting the effects of accelerated sea-level rise on tidal marsh ecosystem services

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Forecasting the effects of accelerated sea-level rise on tidal marsh ecosystem services

Christopher Craft[1], Jonathan Clough[2], Jeff Ehman[3], Samantha Joye[4], Richard Park[5], Steve Pennings[6], Hongyu Guo[6], and Megan Machmuller[4]

We used field and laboratory measurements, geographic information systems, and simulation modeling to investigate the potential effects of accelerated sea-level rise on tidal marsh area and delivery of ecosystem services along the Georgia coast. Model simulations using the Intergovernmental Panel on Climate Change (IPCC) mean and maximum estimates of sea-level rise for the year 2100 suggest that salt marshes will decline in area by 20% and 45%, respectively. The area of tidal freshwater marshes will increase by 2% under the IPCC mean scenario, but will decline by 39% under the maximum scenario. Delivery of ecosystem services associated with productivity (macrophyte biomass) and waste treatment (nitrogen accumulation in soil, potential denitrification) will also decline. Our findings suggest that tidal marshes at the lower and upper salinity ranges, and their attendant delivery of ecosystem services, will be most affected by accelerated sea-level rise, unless geomorphic conditions (ie gradual increase in elevation) enable tidal freshwater marshes to migrate inland, or vertical accretion of salt marshes to increase, to compensate for accelerated sea-level rise.

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Tidal wetlands such as salt, brackish, and freshwater marshes provide essential ecosystem services to society. Such services include functions associated with regulation, habitat, and production (de Groot *et al.* 2002; Daily *et al.* 1997).

Positioned at the interface between land and sea, tidal marshes are uniquely suited to provide ecosystem services associated with waste treatment, biological productivity, and disturbance regulation. These services are especially important to the 53% of the US population that lives in the coastal zone (Boesch *et al.* 2000). Tidal marshes are susceptible to climate change, especially accelerated sea-level rise (SLR). Sea level is predicted to increase by 30–100 cm by 2100, based on the Intergovernmental Panel on Climate Change (IPCC) Special Report on Emissions Scenarios (SRES; Meehl *et al.* 2007). The vulnerability of tidal wetlands to accelerated SLR depends on geologic factors, such as tectonic uplift and glacial isostatic adjustment, which buffer shorelines from SLR, and subsidence, which accelerates it. Tide range also affects marsh vulnerability, as macro- (> 4 m) and meso-tidal (2–4 m) marshes are less susceptible to SLR than are micro-tidal (< 2 m) marshes (Stevenson and Kearney in press).

In some coastal areas, rising sea level may result in tidal marsh submergence (Moorhead and Brinson 1995) and habitat migration, as salt marshes transgress landward and replace tidal freshwater and brackish marshes (Park *et al.* 1991). Declining tidal marsh area and habitat conversion may lead to changes in delivery of ecosystem services provided by these wetlands.

We used field and laboratory measurements, geographic information systems, and simulation modeling to predict the effects of accelerated SLR on tidal marsh area and delivery of select ecosystem services along the Georgia coast. Our goal was to predict how tidal marsh area and delivery of ecosystem services would respond to different scenarios of sea-level rise during the 21st century.

Methods

Ecosystem services related to production (macrophyte biomass) and waste treatment (nitrogen [N] accumulation in soil, potential denitrification) were measured in two salt marshes, two brackish marshes, and two tidal freshwater marshes on each of three rivers along the Georgia coast: the Ogeechee, the Altamaha, and the Satilla. Marshes were chosen for this study by examination of their dominant vegetation, which correlates strongly with salinity: on the southeastern and Gulf coasts of the US, *Spartina alterniflora* dominates in salt marshes (20–35 ppt [parts salt per thousand parts water]), *Juncus roemerianus* dominates in brackish marshes (5–20 ppt), and *Zizaniopsis mileacea* dominates in tidal freshwater marshes (< 0.5 ppt). *Spartina* spp and *Juncus* spp are also common genera of salt and brackish marshes, respectively, in the temperate zone.

Aboveground biomass of macrophytes was measured by harvesting vegetation from 0.25-m^2 quadrats (n = 12 per marsh) at the end of the season (October 2006). Nitrogen accumulation in soil was determined by collect-

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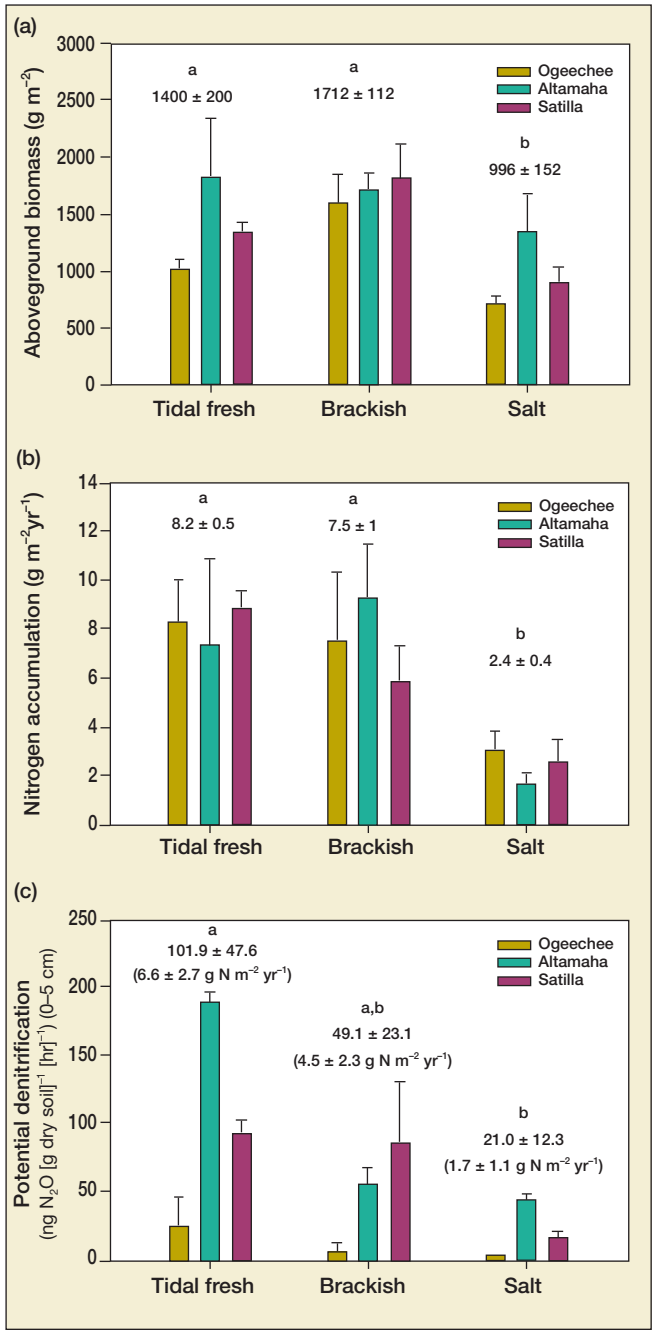


Figure 1. *(a) Aboveground biomass, (b) N accumulation in soil, and (c) potential denitrification in tidal fresh, brackish, and salt marshes of three Georgia river systems (Ogeechee, Altamaha, and Satilla). Means sharing the same letter are not significantly different according to the Ryan–Einot–Gabriel–Welsch multiple range test ($p \leq 0.05$).*

ing two soil cores (8.5-cm diameter by 50 cm deep) from each marsh. Cores were sectioned into 2-cm increments and each increment was analyzed for bulk density, N concentration, and cesium-137 (^{137}Cs; Craft 2007). Potential denitrification was measured in laboratory (sediment slurry) incubations of soil (n = 4 cores in each marsh, taken May 2007) as described by Joye and Paerl (1994).

Changes in tidal marsh area and habitat type in response to accelerated SLR were modeled using a "sea-level affects marshes model" (SLAMM version 5), which simulates the dominant processes involved in wetland conversions and shoreline modifications during long-term sea-level rise (Park *et al.* 1989; www.warrenpinnacle.com/prof/SLAMM). SLAMM5 integrates elevation–submergence and wave action–erosion. SLAMM5 also incorporates a salinity algorithm, based on freshwater discharge and cross-sectional area of the estuary, to model saltwater intrusion in river-dominated estuaries of our study domain. Model inputs included the USGS National Elevation Dataset (NED; http://ned.usgs.ov), NOAA tidal data, and USFWS National Wetlands Inventory (NWI) data (http://wetlandsfws.er.usgs.gov). SLAMM5, a cell-based model, was run at 28-m resolution based on NED characteristics within the study region; however, it simulates finer-scaled spatial features, such as the tall *Spartina* marsh.

Model simulations were based on the SRES A1B mean (39 cm) and maximum (69 cm) increase in SLR over the next 100 years, with a time step of 25 years. Because the measured rate of SLR is greater along the Georgian coast (2.5 mm per year) and the southeastern coast of the US in general, relative to the global average of 1.8 mm per year (Church *et al.* 2001; Peltier 2001), our simulations are based on mean and maximum increases of 52 cm and 82 cm, respectively, by 2100. The SRES A1 scenario assumes rapid economic growth, low population growth, and rapid introduction of new and more efficient technology (Church *et al.* 2001; Meehl *et al.* 2007). The SRES A2 scenario, which assumes a lower rate of economic growth and fewer technological advances, but greater population growth, predicts a similar increase in sea-level rise during the next century (Church *et al.* 2001).

Delivery of ecosystem services was scaled up by multiplying the habitat-specific, plot-based measurements (ie amount of macrophyte biomass, N accumulation in soil, or potential denitrification per unit area for tidal freshwater, brackish, or salt marsh) by the total area of the habitat types predicted by the model. Changes in a particular service are the difference between the totals for two different times (ie initial condition versus 2100 for the scenarios simulated).

Results

Ecosystem services of tidal freshwater, brackish, and salt marshes

The various habitats of tidal marshes provide different quantities of ecosystem services. For example, aboveground biomass was 40–70% greater in tidal freshwater and brackish marshes than in salt marshes (Figure 1). Biomass quality, based on leaf C:N, was also greater in the tidal freshwater marsh (34.5 ± 2.8) than in the brackish marsh (40.9 ± 1.3) and salt marsh (36.4 ± 1.8). Reduced aboveground biomass in salt marshes is linked to greater

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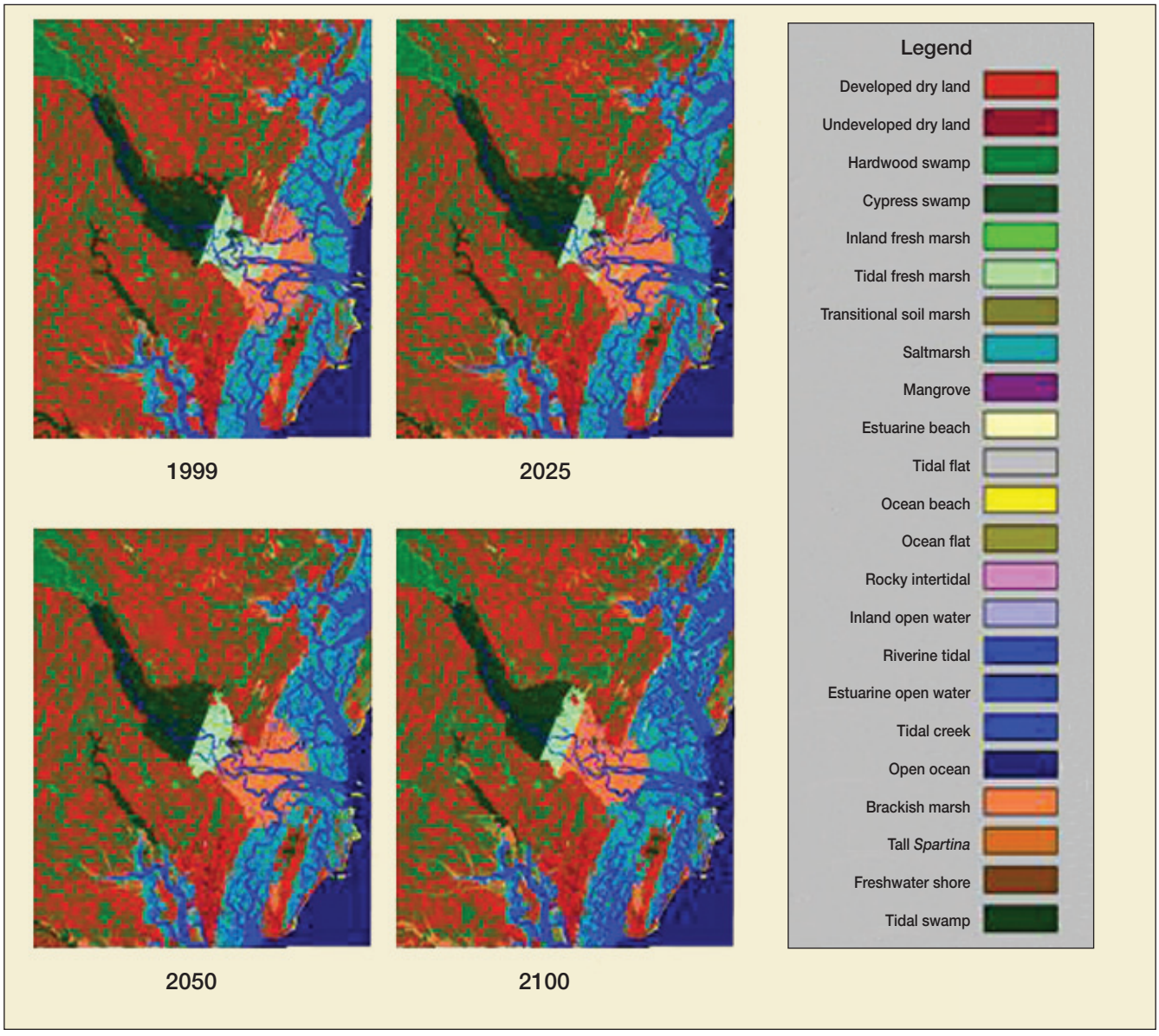


Figure 2. *SLAMM simulation of effects of accelerated SLR on tidal marshes of the Altamaha River, Georgia. The simulation was run using the SRES A1B scenario that assumes a 52-cm increase in sea level by 2100. The coarse vertical resolution of the NED dataset results in the linear pattern (ie striping) of wetland migration observed during the simulation.*

salinity and sulfide stress, which inhibits N uptake and reduces plant growth (Odum 1988; Mendelssohn and Morris 2000).

Tidal freshwater and brackish marshes also provided greater waste treatment per unit area than did salt marshes (Figure 1). These marshes sequestered three times more N in soil and supported two to three times greater potential denitrification than salt marshes. Greater N accumulation and potential denitrification in tidal freshwater and brackish marsh soils is linked to low levels of salinity. In tidal marsh soils, decomposition is positively related to salinity, such that organic matter and N accumulation are reduced in salt marsh soils relative to brackish and tidal freshwater marshes (Craft 2007). Salinity also hinders denitrification by inhibiting nitrifying bacteria that convert ammonium to nitrate (Joye and Hollibaugh 1995) and by favoring sulfate-reducing bacteria that may outcompete denitrifiers for available labile carbon substrates (Weston *et al.* 2006).

Effect of accelerated SLR on tidal marsh area and ecosystem services

Simulation modeling predicts that a 52-cm increase in sea level will lead to a decline in tidal marsh area and delivery of ecosystem services along the Georgia coast during this century. To illustrate, Figure 2 depicts SLAMM simulation results for the Altamaha River. For this river system, the model predicts a large decline in area of tidal freshwater marsh (–38%) and swamp (–24%), a smaller decline of salt marsh (–8%), and a small increase in brackish marsh habitat (+4%). A corre-

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Table 1. Predicted change in area (km^2) of selected land-cover types along the Georgia coast, in response to the A1B SRES sea-level rise scenario as modeled by SLAMM

	A1B mean = 52 cm			*A1B max = 82 cm*		
	1999	*2100*	*% change*	*1999*	*2100*	*% change*
Dry land	5008	4385	–12	5006	4265	–15
Non-tidal swamp	1838	2089	+14	1837	2106	+15
Tidal swamp	413	316	–24	407	267	–34
Inland fresh marsh	64	65	+2	64	63	–2
Tidal fresh marsh	79	80	+1	82	50	–39
Brackish marsh	417	458	+10	416	412	–1
Salt marsh	1116	890	–20	1106	610	–45
Transitional salt marsh[1]	32	254	+694	34	306	+800
Tidal flat	11	26	+136	11	177	+1510
Estuarine open water	742	1091	+47	756	1401	+85

Notes: The simulation was run assuming the mean (52 cm) and maximum (82 cm) increase in sea level between 1999 and 2100. Differences in the initial areas of land-cover types between the A1B mean and max simulations are the result of using IPCC projections that begin in 1990 and, thus, lead to small differences in the initial conditions based on the scenario (mean versus max) chosen. [1]High marsh shrub vegetation flooded only during spring tides and storm tides.

sponding increase in transitional salt marsh (+780%, from 8 to 68 km^2), tidal flat (+400%, from 1 to 5 km^2), and estuarine open water (+52%, from 176 to 268 km^2) also occurs as sea level rises (Figure 2).

For the entire Georgia coast, a 52-cm increase in sea level causes overall reduction in salt marsh (–20%), along with a small increase in tidal freshwater marsh (+2%) and a larger increase in brackish marsh (+10%; Table 1). The decline in salt marsh is attributed to submergence and replacement by tidal flats and estuarine open water (Table 1). The increase in tidal freshwater marsh and brackish marsh occurs at the expense of tidal swamp, which declines by 24% as these marshes migrate up-river in response to sea-level rise and saltwater intrusion. Overall, there is a net loss of tidal marsh habitat (184 km^2), as salt marsh habitat declines by 226 km^2, while brackish marsh and tidal freshwater marsh increase by 41 km^2 and 1 km^2, respectively (Table 2).

By combining measurements of ecosystem services with the change in tidal marsh habitat, we can predict how delivery of ecosystem services is affected by accelerated SLR. As tidal marsh habitat declines, delivery of ecosystem services related to productivity and N retention and removal are reduced. Aboveground biomass of macrophytes is reduced by more than 150 000 metric tons (t) per year under the A1B mean scenario (Table 2). Nitrogen sequestration in soil is reduced by 227 t per year, whereas potential denitrification is reduced by 193 t per year. The cumulative reduction in delivery of ecosystem services is attributed mostly to loss of salt marsh habitat, even though tidal freshwater marsh and brackish marsh provide greater delivery of ecosystem services than do salt marshes on a per-unit-area basis.

An 82-cm increase in sea level, predicted by the A1B maximum scenario, leads to even greater reduction in tidal marsh area and delivery of ecosystem services. Based on this scenario, tidal freshwater, brackish, and salt marshes decline by 39%, 1%, and 45%, respectively, by 2100. Delivery of ecosystem services is also dramatically reduced under the A1B maximum scenario, as macrophyte biomass

Table 2. Predicted change in tidal marsh area and delivery of select ecosystem services along the Georgia coast between 1999 and 2100 in response to a 52-cm and 82-cm increase in sea level

	Habitat change (km^2)		*Macrophyte biomass (t yr^{-1})*		*N sequestration in soil (t yr^{-1})*		*Potential denitrification (t yr^{-1})*	
	52 cm	*82 cm*	*52 cm*	*82 cm*	*52 cm*	*82 cm*	*52 cm*	*82 cm*
Tidal fresh marsh	+1	–32	+1400	–44 800	+8	–262	+7	–211
Brackish marsh	+41	–4	+70 200	–6 800	+307	–30	+184	–18
Salt marsh	–226	–496	–225 100	–494 000	–542	–1188	–384	–843
Cumulative (km^2)	–184	–532	–153 500	–545 600	–227	–1480	–193	–1072
Cumulative (%)	–11%	–33%	–8%	–28%	–4%	–23%	–4%	–25%

Notes: Change in delivery of ecosystem services was calculated by multiplying the change in habitat area by the mean ecosystem service values for each marsh type in Figure 1. Negative values denote a reduction in marsh area and delivery of ecosystem services.

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decreases by nearly 550 000 t per year, N accumulation in soil decreases by 1482 t N per year, and potential denitrification declines by 1072 t N per year (Table 2).

Under the A1B mean and maximum SLR scenarios, cumulative tidal marsh area declines by 12% and 33%, respectively, while cumulative reduction in delivery of ecosystem services is 4– 28% lower (Table 2). Delivery of ecosystem services is less affected by accelerated SLR than is tidal marsh area, because brackish marsh area, which has high delivery of services per unit area, does not change substantially (–1% to +10%) relative to salt marshes that decline in area by 20–45%. This result highlights an unappreciated value of brackish marshes: because they support high levels of ecosystem services and do not decline as much as other tidal marsh types, they may buffer some of the negative impacts of SLR.

Sensitivity analysis of model parameters

We conducted a sensitivity analysis by varying model parameters, historic rate of SLR, site-specific accretion rates for salt marsh, brackish marsh, and tidal freshwater marsh, and erosion rates for tidal flat and salt marsh by plus or minus 15%, to determine which parameters most affect model output when comparing results after 69 cm of eustatic (worldwide) SLR (82 cm for Georgia). Model results were most sensitive to changes in the historic rate of local SLR, which affects long-term projections of local SLR. Increasing this parameter by 15% decreased salt marsh and tidal freshwater marsh area by 7.3% and 13%, respectively, and tidal flat area increased by 12%. Model output was less sensitive to site-specific accretion and erosion rates. Decreasing accretion rates by 15% resulted in a 7% decrease in salt marsh area and a 5% decrease each in brackish marsh and tidal freshwater marsh area. Increasing tidal flat erosion rate by 15% resulted in an 18% decrease in this habitat type.

Discussion

Limitations of the approach

Several caveats associated with the tools and approaches we used deserve mention. First, uncertainties exist with scaling results from laboratory and plot measurements to the landscape level. Second, there are limitations associated with the data inputs used in the SLAMM5 SLR simulations. For example, NED elevation data covering the entire coast have only moderate resolution. Third, the SLAMM5 model lacks feedback mechanisms that may come into play as SLR accelerates. For example, increasing inundation of salt marshes may increase macrophyte production and lead to increased vertical accretion (Morris *et al.* 2002). Conversely, increasing saltwater intrusion into tidal freshwater marshes may accelerate decomposition (Weston *et al.* 2006), leading to reduced vertical accretion. Despite these caveats, our approach provides important insights into how accelerated SLR may affect tidal marshes and their delivery of ecosystem services in the future.

Beyond the southeast coast

Although our simulation focuses on the Georgia coast, we speculate that, elsewhere, tidal freshwater and salt marshes will also be most affected by SLR. Tidal freshwater marshes will decline in area as saltwater intrudes and brackish marshes migrate inland to replace them. Salt marshes will convert to open water because their low rate of vertical accretion relative to brackish and tidal freshwater marshes (Craft 2007) may prevent them from keeping pace with accelerated SLR.

Declining area of tidal freshwater wetlands, marshes, and swamp forests (Table 1) may be problematic for the American alligator (*Alligator mississippiensis*), wood stork (*Mycteria americana*), and other species that depend on freshwater aquatic habitats. On a per-unit-area basis, tidal freshwater wetlands provide higher levels of ecosystem services than do salt marshes, so their decline will lead to a disproportionate decrease in delivery of ecosystem services. In the 21st century, these problems will probably be compounded by reduced river discharge caused by the greater climate variability (eg droughts) that will accompany global warming (Meehl *et al.* 2007), and by increased demand for freshwater by a growing human population. At the same time, declining area of salt marsh may lead to reduced shoreline protection and habitat support for marsh nekton (free swimming aquatic animals; Kneib 2000), although increasing marsh edge may enhance nekton access to the remaining marsh (Zimmerman *et al.* 2000).

Our predictions of the effects of accelerated SLR on the delivery of tidal marsh ecosystem services of the Georgia coast should be viewed with caution, because the drivers of climate change, greenhouse gases (and temperature), will also increase. Increasing CO_2 and temperature over the next century may alter plant physiological processes that affect the distribution and productivity of plant communities. For example, increasing CO_2 may favor increased productivity and water-use efficiency, especially by C_3 vegetation, which may lead to changes in plant community composition and productivity (Körner 2006). Nitrogen accumulation in soil may be altered by increased temperature and lower N demand from vegetation as a result of higher CO_2 (Curtis *et al.* 1990).

Forecasted changes in tidal marsh area and delivery of ecosystem services are applicable to other temperate areas, where tidal marshes experience meso-tidal inundation and where rates of SLR are comparable (ie 2–3 mm per year). Some coastal regions experience tectonic uplift and there, tidal marshes are not as vulnerable. Worldwide, there is evidence that tidal marshes in flood-dominated estuaries, or those that receive high sediment loads, may be better buffered against SLR than marshes in ebb-dominated or low sediment supply estuaries (Morris

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et al. 2002; Stevenson and Kearny in press). In regions where subsidence is occurring, tidal marshes are at greater risk. Marshes exposed to micro-tidal (< 2 m) inundation are also likely to suffer greater declines in area and delivery of ecosystem services than are meso-tidal (2–4 m inundation) marshes, because they rely more on organic matter accumulation to support vertical accretion and, thus, may not be able to compensate for accelerated SLR (Stevenson and Kearney in press). On a positive note, Georgia's tidal marshes experience meso-tidal inundation (tide range = 2.3 m), which buffers them against moderate increases in sea level, as they may be able to increase their rate of vertical accretion to compensate (Morris *et al.* 2002). Thus, the decline in salt marsh habitat may not be as great as predicted by our model simulations.

In summary, our results suggest that salt, brackish, and tidal freshwater marshes of the Georgia coast will respond differently to a 52-cm increase in SLR, with fresh and salt marshes suffering greater losses than brackish marshes. Because brackish marshes provide ecosystem services at a rate greater than that of other marsh types, and because brackish marshes are predicted to undergo less precipitous declines in area than other marsh types, the predicted loss of ecosystem services along the Georgia coast is less than would be forecast based solely on losses in total marsh area.

Acknowledgements

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References

Boesch DF, Field JC, and Scavia D (Eds). 2000. The potential consequences of climate variability and change on coastal areas and marine resources. Washington, DC: US Department of Commerce. NOAA's Coastal Ocean Program, Decision Analysis Series No 21.

Church JA and Gregory JM. 2001 Changes in sea level. In: Houghton JT, Ding Y, Griggs DJ, *et al.* (Eds). Climate change 2001: the scientific basis. Contribution of Working Group I to the third assessment report of the Intergovernmental Panel on Climate Change. Cambridge, UK: Cambridge University Press.

Craft CB. 2007. Freshwater input structures soil properties, vertical accretion and nutrient accumulation of Georgia and United States (US) tidal marshes. *Limnol Oceanogr* **52**: 1220–30.

Curtis PS, Balduman LM, Drake BG, and Whigham DF. 1990. Elevated atmospheric CO_2 effects on belowground processes in C_3 and C_4 estuarine marsh communities. *Ecology* **71**: 2001–06.

Daily GC, Alexander S, Ehrlich PR, *et al.* 1997. Ecosystem services: benefits supplied to human societies by natural ecosystems. *Issues Ecol* **2**: 1–16.

de Groot RS, Wilson MA, and Boumans RJM. 2002. A typology for the classification, description and valuation of ecosystem functions, goods and services. *Ecol Econ* **41**: 393–408.

Joye SB and Hollibaugh JT. 1995. Influence of sulfide inhibition of nitrification on nitrogen regeneration in sediments. *Science* **270**: 623–25.

Joye SB and Paerl HW. 1994. Nitrogen cycling in microbial mats: rates and patterns of denitrification and nitrogen fixation. *Mar Biol* **119**: 285–95.

Kneib RT. 2000. Salt marsh ecoscapes and production transfers by estuarine nekton in the southeastern United States. In: Weinstein MP and Kreeger DA (Eds). Concepts and controversies in tidal marsh ecology. Dordrecht, Netherlands: Kluwer Academic Publishers.

Körner C. 2006. Plant CO_2 responses: an issue of definition, time and resource supply. *New Phytol* **172**: 393–411.

Meehl GA, Stocker TF, Collins WD, *et al.* 2007. Global climate projections. In: Solomon S, Qin D, Manning M, *et al.* (Eds). Climate change 2007: the physical science basis. Contribution of Working Group I to the fourth assessment report of the Intergovernmental Panel on Climate Change. Cambridge, UK: Cambridge University Press.

Mendelssohn IA and Morris JT. 2000. Ecophysiological controls on the productivity of *Spartina alterniflora* Loisel. In: Weinstein MP and Kreeger DA (Eds). Concepts and controversies in tidal marsh ecology. Dordrecht, Netherlands: Kluwer Academic Publishers.

Moorhead KK and Brinson MM. 1995. Response of wetlands to rising sea level in the lower coastal plain of North Carolina. *Ecol Appl* **5**: 261–71.

Morris JT, Sundareshwar PV, Nietch CT, *et al.* 2002. Response of coastal wetlands to rising sea level. *Ecol Appl* **83**: 2869–77.

Odum WE. 1988. Comparative ecology of tidal freshwater and salt marshes. *Annu Rev Ecol Syst* **19**: 147–76.

Park RA, Lee JK, Mausel PW, and Howe RC. 1991. Using remote sensing for modeling the impacts of sea level rise. *World Resour Rev* **3**: 184–220.

Park RA, Trehan MS, Mausel PW, and Howe RC. 1989. The effects of sea level rise on US coastal wetlands. In: Smith JB and Tirpak DA (Eds). The potential effects of global climate change on the United States. Appendix B – sea-level rise. Washington, DC: US Environmental Protection Agency.

Peltier WR. 2001. Global glacial isostatic adjustment and modern instrumental records of relative sea level history. In: Douglas BC, Kearney MS, and Leatherman SP (Eds). Sea-level rise: history and consequences. San Diego, CA: Academic Press.

Stevenson JC and Kearney MS. Impacts of global climate change and sea level rise on tidal wetlands. In: Silliman BR, Bertness MD, and Strong D (Eds). Anthropogenic modification of North American salt marshes. Berkeley, CA: University of California Press. In press.

Weston NB, Dixon RE, and Joye SB. 2006. Ramifications of salinity intrusion in tidal freshwater sediments: geochemistry and microbial pathways of organic matter mineralization. *J Geophys Res-Biogeosci* **111**: G0100. doi:10.1029/2005JG000071.

Zimmerman RJ, Minello TJ, and Rozas LP. 2000. Salt marsh linkages to productivity of penaeid shrimps and blue crabs in the northern Gulf of Mexico. In: Weinstein MP and Kreeger DA (Eds). Concepts and controversies in tidal marsh ecology. Dordrecht, Netherlands: Kluwer Academic Publishers.

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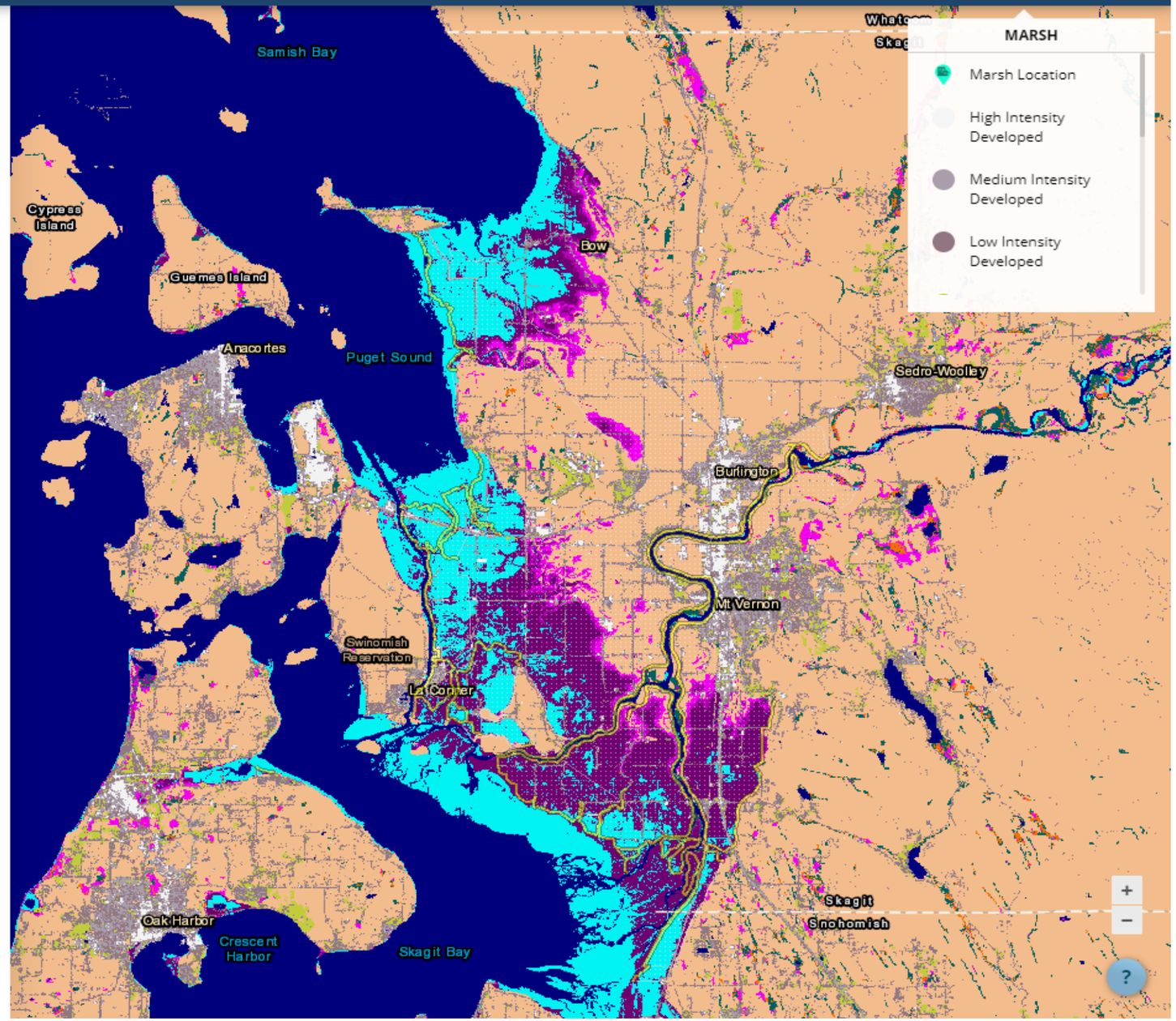
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Five local sea level rise scenarios can be displayed either by year or by individual scenario.

Customize the scenarios and accretion rate to compare to the half foot marsh increments (using sliders) and view how accretion can offset sea level rise.

Marsh Migration Tutorial





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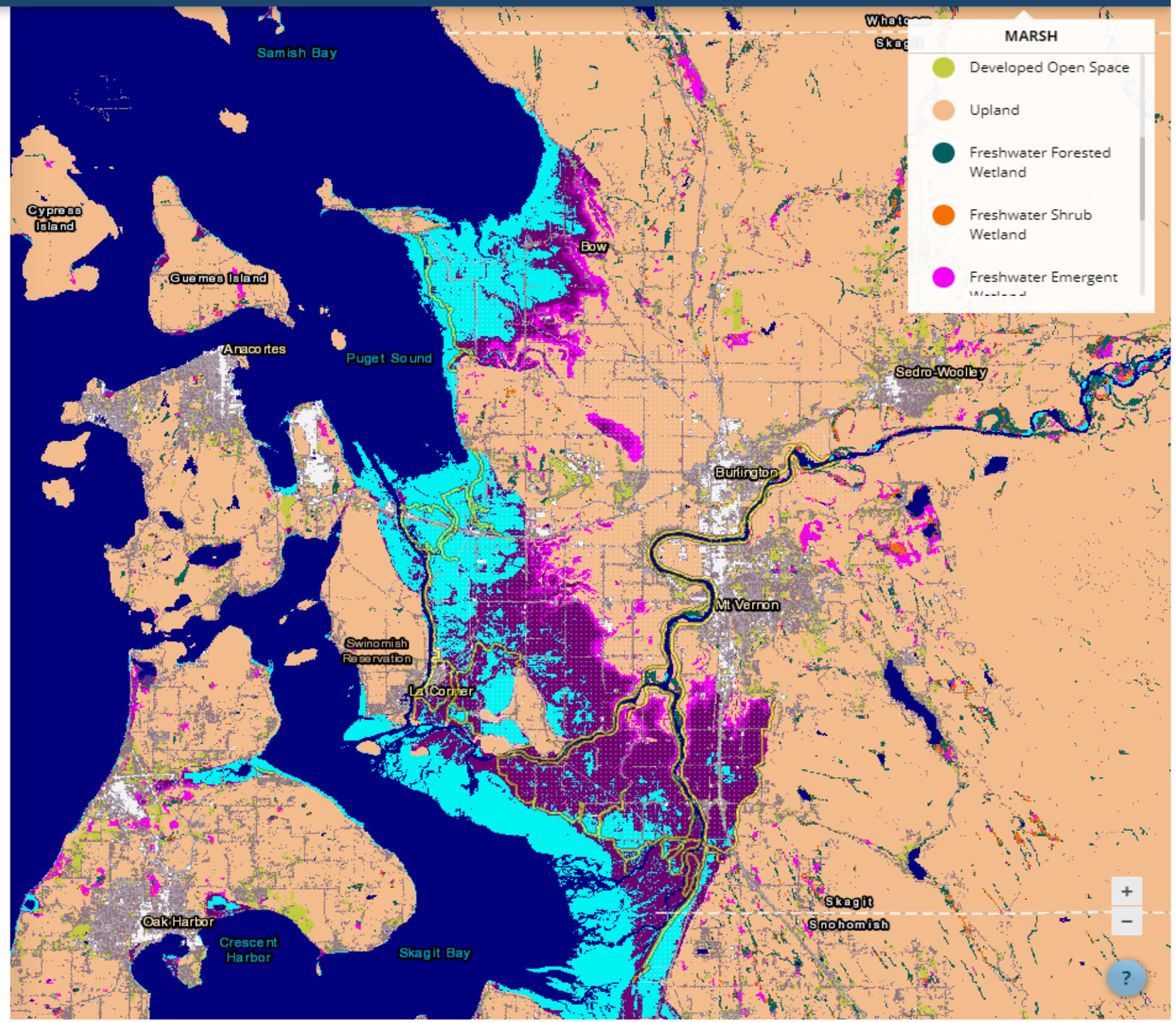
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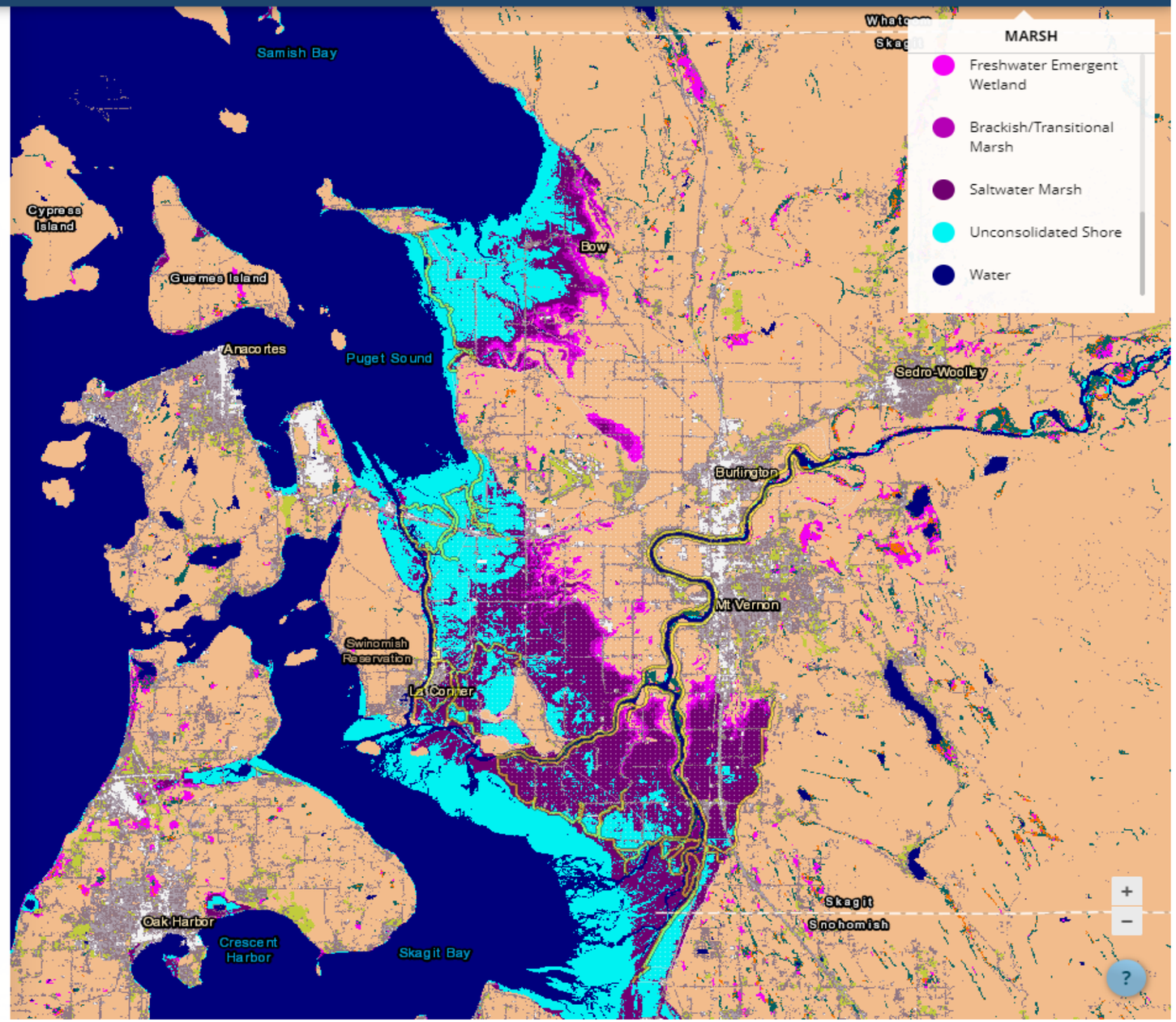
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Padilla Bay National Estuary Research Reserve
The City of Tacoma
The Nature Conservancy
U.S. Geological Survey
University of Oregon
University of Washington Climate Impacts Group
University of Washington Department of Earth and Space Sciences
University of Washington School of Marine and Environmental Affairs
Washington Department of Fish and Wildlife
Pacific Northwest National Laboratory

WASHINGTON **COASTAL** **RESILIENCE** PROJECT

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Prepared for the Washington Coastal Resilience Project

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Purpose of this Report

One of the objectives of the WCRP is to develop an updated assessment of projected sea level change for coastal Washington State and its relationship to coastal hazards such as flooding and erosion. Washington State has two previous assessments of sea level rise; one published in 2012 by the National Academies of Science (NRC, 2012), and another in 2008 (Mote et al., 2008). This report provides an updated set of sea level rise projections that incorporates the latest science, provides community-scale projections, and is designed for direct application to risk management and planning. Subsequent reports will describe new findings related to storm surge, waves, and efforts to integrate sea level rise in coastal planning and management.

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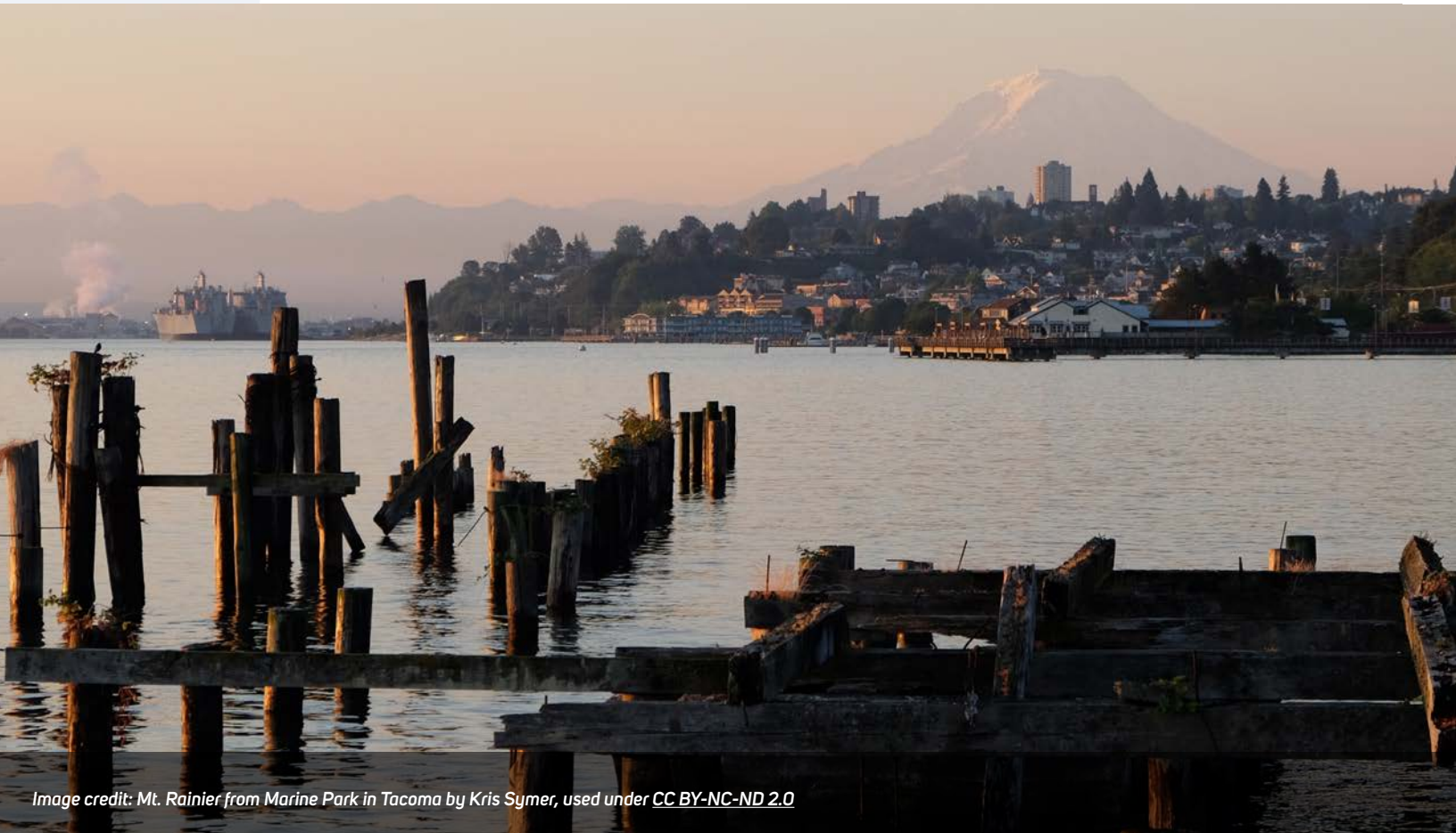


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EXECUTIVE SUMMARY

Washington's coastal areas and marine waters are not only an important economic engine for the state but also provide an important sense of place and figure irreplaceably in the traditions and cultures of tribal communities. The state's coastlines also provide valuable ecosystem services that support human and natural communities alike. Sea level rise will exacerbate existing risks and vulnerabilities, such as shoreline and coastal bluff erosion, storm surge, flooding, and groundwater intrusion. This assessment provides new up-to-date projections for use in coastal habitat restoration, community and land-use planning, and infrastructure design and operations.

Washington State is due for a new assessment of sea level rise. The science has advanced significantly since the last assessment (NRC, 2012), in particular suggesting the potential for higher rates of sea level rise this century. In addition, previous assessments did not adequately account for differences in the rate of vertical land movement across the state, which affects how sea level rise is experienced on land. Finally, past studies have typically provided a low, middle, and high projection, with little guidance on how to interpret these in the context of sea level rise planning. We have developed a new set of projections that address each of these issues. Specifically, there are three distinguishing features of the new projections:

(1) **New Science.** Our projections are primarily drawn from a recent comprehensive assessment of global and regional sea level rise (Kopp et al., 2014). The new projections incorporate recent research indicating the potential for higher sea level rise in the 21st century.

(2) **Community-scale.** Projections are developed for 171 locations distributed along Washington's coastline. These account for variations in the rate of vertical land movement across the state.

(3) **Probabilistic.** We assess the likelihood, for a given greenhouse gas scenario, that sea level rise will reach or exceed a certain level relative to the present. This probabilistic approach may be better suited for application to risk management and planning.

Our study begins with a new set of projections for **absolute sea level rise** (the height of the ocean surface relative to a fixed, unmoving reference point, such as the center of the earth). However, the impacts of sea level rise will be felt via a

change in height of the ocean surface relative to land. To estimate relative sea level rise, we combine separate estimates of absolute sea level rise and vertical land movement (uplift or subsidence), bringing them together to create the **relative sea level rise projections** described below.

Whereas we produce a single set of absolute sea level rise projections for the entire state of Washington (**Table 1**), there are important differences in vertical land movement along the state's coastlines. As a result, we produce local estimates of vertical land motion for 171 locations along Washington's coastline (**Figure 1**). Our relative sea level rise projections reflect these distributed estimates of vertical land motion, showing higher sea level rise in some places than in others. Although the rate of vertical land movement is generally small compared to absolute sea level rise projections – especially later in the 21st century – it can have a noticeable impact on observed and projected sea level in some locations.

TABLE 1: Absolute sea level rise projections, in feet, for Washington State. Projections are expressed in terms of the "probability of exceedance" for three different time periods (2050, 2100, and 2150) and two different greenhouse gas scenarios (RCP 4.5 ["Low"] and RCP 8.5 ["High"]; van Vuuren et al., 2011). Projected changes are assessed relative to contemporary sea level, which we define as the average sea level over the 19-year period from 1991-2009. Projections for 2050 and 2100 the High greenhouse gas scenario (RCP 8.5, highlighted below) are also shown in **Figure 2. Examples of *location-specific* relative sea level rise projections are available in Table 2.**

PROJECTED ABSOLUTE SEA LEVEL CHANGE

(feet, averaged over each 19-year time period)

Time Period	Greenhouse Gas Scenario	Central Estimate (50%)	Likely[5] Range (83-17%)	Higher magnitude, but lower likelihood possibilities		
				10% probability of exceedance	1% probability of exceedance	0.1% probability of exceedance
2050 (2040-2059)	Low	0.6	0.4 - 0.8	0.9	1.2	1.8
	High	0.7	0.5 - 0.9	1.0	1.3	2.0
2100 (2090-2109)	Low	1.6	1.0 – 2.2	2.5	4.1	7.2
	High	2.0	1.4 - 2.8	3.1	4.8	8.3
2150 (2140-2159)	Low	2.5	1.5 - 3.8	4.4	8.5	16.2
	High	3.4	2.3 - 4.9	5.6	10.0	18.3

Future sea level depends on how much and how quickly atmospheric greenhouse gases cause the earth system to warm, as well as how sensitive each process contributing to sea level rise is to that warming. As a result, we develop a separate set of projections for two greenhouse gas scenarios, which can be thought of as representing "low" and "high" trajectories of future greenhouse gas emissions.

The projections are probabilistic. For each greenhouse gas scenario, a set of probabilities describe the likelihood that sea level rise will meet or exceed a particular amount (i.e.: our likelihoods refer to the "probability of exceedance" of a given amount of sea level rise). Even for a single greenhouse gas scenario, there is often a wide range among projections; this primarily reflects the uncertainty in the observed and modeled response of sea level rise to climate change. The primary contributor to this range is the large uncertainty in the rate and magnitude of ice melt from Antarctica and, to a somewhat lesser extent, Greenland. The likelihoods allow users to select probabilities to align with a particular decision context or risk management approach.

As an example, our absolute sea level rise projections suggest a central estimate – corresponding to a 50% chance that absolute sea level will rise by at least that amount – of 1.6 ft for a low greenhouse gas scenario and 2.0 feet for a high greenhouse gas scenario, by 2100.[1] At the low end, the projections give an 83% probability that sea level will rise by at least 1.0 or 1.4 feet, again for a low and a high greenhouse gas scenario, respectively. At the high end, the projections suggest a rapid acceleration in the rate of sea level rise over the 21st century: the projections give a 1% probability, for example, that absolute sea level rise will reach or exceed 4.1 feet for a low greenhouse gas scenario, and 4.8 feet for a high greenhouse gas scenario, by 2100.

Recent research has led to an increase in the high-end projections for sea level rise, and it is possible that future research could do the same (e.g., Kopp et al., 2014). Given the difficulties that this would cause for planners, we have also provided an extreme high-end projection, which we consider to represent an approximate physical upper limit for sea level rise. In our probabilistic framework we derive this from the 0.1% probability of exceedance for the high greenhouse gas scenario, which we find is consistent with other assessments of the maximum possible change in sea level by the end of the 21st century. We project an upper limit of 8.3 feet of absolute sea level rise by 2100.

1. All projections are given relative to the average sea level for 1991-2009.

Our results differ from past projections. Comparing the projections for 2100, our central estimate (1.6-2.0 ft) is lower than the central estimate from the last regional report on sea level rise (2.3 ft; NRC, 2012). Previous studies did not include an estimate of likelihoods, but the high end from the NRC - (2012) report (4.5 ft) is much lower than in the new projections (7.2-8.3 ft), and instead corresponds to about the 1% probability of exceedance in our current study (4.1-4.8 ft). A more in-depth review of the science, including comparisons with previous work, can be found in **Appendix B**.



Image credit: Hoh River mouth by Sam Beebe, used under CC BY 2.0

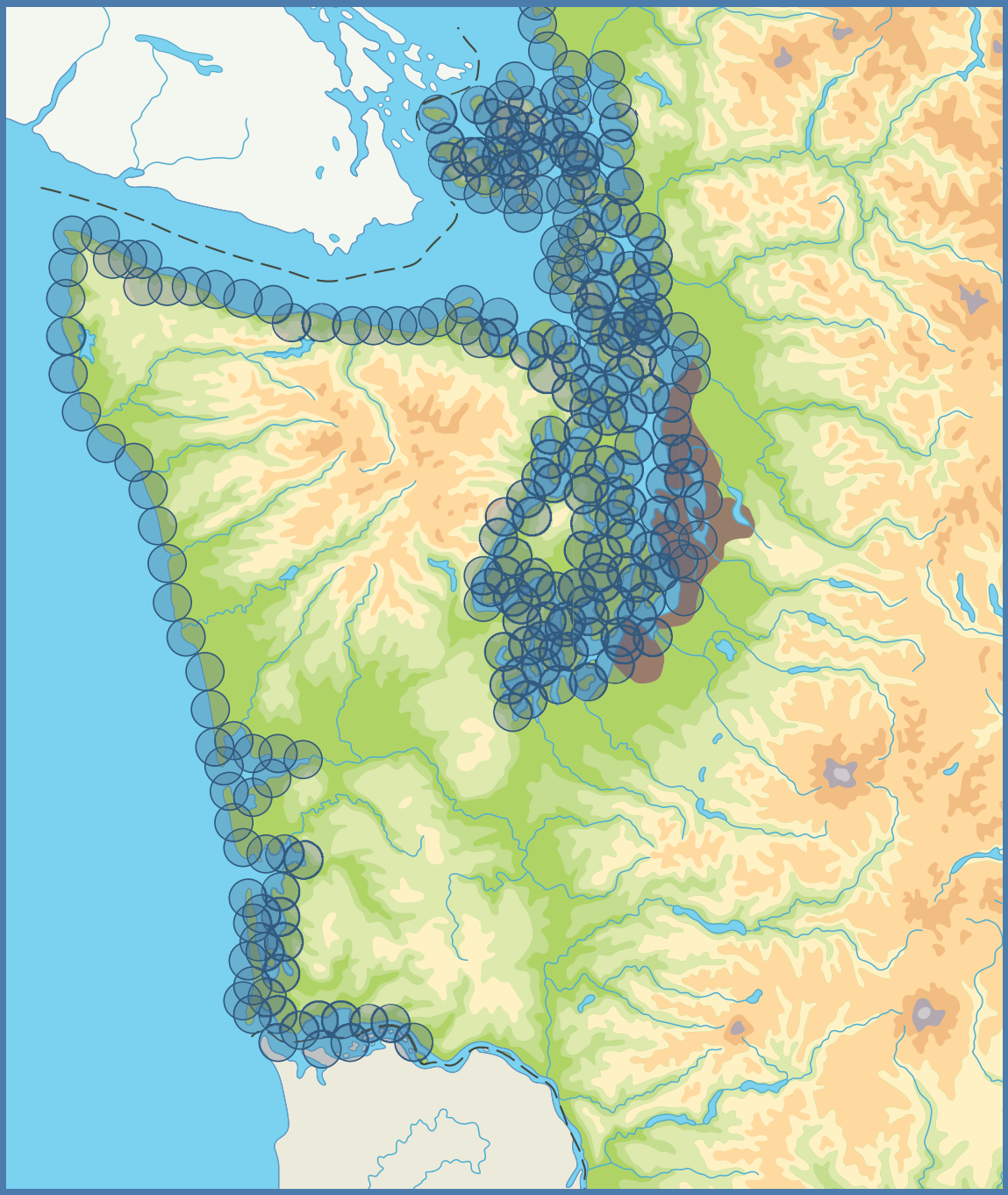
The projections cited above refer to absolute sea level rise, and do not account for vertical movement of the land surface. Our relative sea level rise projections track with these absolute sea level rise projections but are modulated by the local rates of vertical land motion. For example, on the northwest Olympic Peninsula near Neah Bay, where the land is uplifting rapidly, the relative sea level rise projections are lower than the absolute sea level rise projections. In areas where the land is subsiding, such as central Puget Sound, the relative sea level rise projections are slightly higher than the absolute sea level rise projections. We provide relative sea level rise projections for 171 individual locations along the Washington coastline that account for these local changes under the two greenhouse gas scenarios. Projections for each location can be downloaded from the project website: www.wacoastalnetwork.com/wcrp-documents.html

Although we assume that our assessed rates of vertical land motion remain constant over time, a large Cascadia earthquake could suddenly reverse the estimated trend in some parts of Washington State. Although not incorporated quantitatively in our relative sea level rise projections, we provide information about the potential change in land elevation associated with such an event.

Finally, it is worth emphasizing that sea level rise projections are different from Federal Emergency Management Agency (FEMA) flood insurance studies, because (1) FEMA studies only consider past events , and (2) flood insurance studies only consider the 100-year event, whereas sea level rise affects coastal water elevations at all times.

Our new projections reflect the latest science on sea level rise and are an improvement over previous assessments (**see Appendix B**). Over time, these will undoubtedly be updated as new science becomes available. Until that time, we recommend using these new projections for coastal impacts assessments within the state of Washington.

FIGURE 1: Map showing the 171 locations along Washington's coastline for which relative sea level projections are provided. At each location, a different estimate of vertical land movement and associated uncertainty is combined with the statewide projections for absolute sea level to produce a locally-specific set of projections for relative sea level rise. Projections for each location can be downloaded from the project website: www.wacoastalnetwork.com/wcrp-documents.html.



INTRODUCTION

This report provides a summary of new projections of sea level rise for Washington State. These projections improve on previous estimates (NRC, 2012 ;, Mote et al., 2008) by:

- Incorporating new science about the processes contributing to global sea level rise, including new understanding of the dynamics of melt for the Greenland and Antarctic ice sheets,
- Accounting for community-scale differences in vertical land movement along Washington's coastlines, and
- Estimating the probabilities that various amounts of sea level rise will occur for a given greenhouse gas scenario.

These projections can be used to inform coastal risk assessments, planning, decision making and ongoing management for Washington's coastal communities.

Future greenhouse gas emissions depend on human behavior: technological innovation, geopolitics, population growth, etc. As a result, there is no reliable way to estimate the probability of following a particular emissions trajectory. Instead, we have developed a separate set of probabilistic projections for both a low and a high greenhouse gas scenario.[2]

We present our projections in terms of the probability of exceedance, or the likelihood that sea level rise will meet or exceed a particular elevation relative to contemporary sea level. Recent research has emphasized the potential for large amounts of sea level rise, and today's high-end projections are much higher than those of previous studies. In order to minimize the chance that our high-end projections are similarly revised upward in the future, we have also included a very high magnitude projection, which multiple studies indicate is a likely upper bound for future sea level rise by 2100 (**Appendix B**).

The probabilities associated with our projections are fundamentally different from the probability associated with a coastal flood event, for example, a 100-year flood. The 100-year flood – defined as the level of flooding having a 1%

2. For more on greenhouse gas scenarios, see Section 1 of Mauger et al., 2015. Note two other greenhouse gas scenarios are omitted: RCP 2.6 and RCP 6.0. Recent research suggests that it is no longer feasible to achieve the dramatic reductions required under RCP 2.6 (e.g., Davis and Socolow, 2014; Pfeiffer et al., 2016). RCP 6.0 is not included because of a limited amount of projections that continue past 2100.



Image credit: King Tide Nov 29, 2014 Southworth by Fletcher Sandbeck, used under CC BY 2.0

chance of occurring in any given year – is derived from historical observations, and is calculated based on the frequency with which past high-water events, or the meteorological drivers of those events (e.g., high winds), have occurred. Our sea level rise projections, in contrast, are derived using models to project changes over time into the future. As a result, our sea level rise projections incorporate uncertainties in models as well as in the observations used to adjust and refine those models.[3]

Finally, we emphasize that sea level rise projections are different from the coastal flood risk assessments performed in a typical Federal Emergency Management Agency (FEMA) study. Specifically: (1) The current study concerns future changes in sea level, whereas FEMA flood maps are based on historical observations and assume no long-term change in risk, and (2) FEMA studies are focused on one specific event – the 100-year coastal flood – and do not address water levels during normal tides or other storm intensities. Our projections, in contrast, concern the long-term change in sea level, affecting the height of the water surface at all tidal elevations as well as during storm events.

This report begins by introducing our projections of absolute sea level change (the height of the ocean surface relative to a fixed, unmoving reference point, such as the center of the earth). Because sea level rise will be experienced as a change in the height of the ocean surface relative to land, we then estimate relative sea level change, which combines separate estimates of absolute sea level rise and vertical land movement (uplift or subsidence).

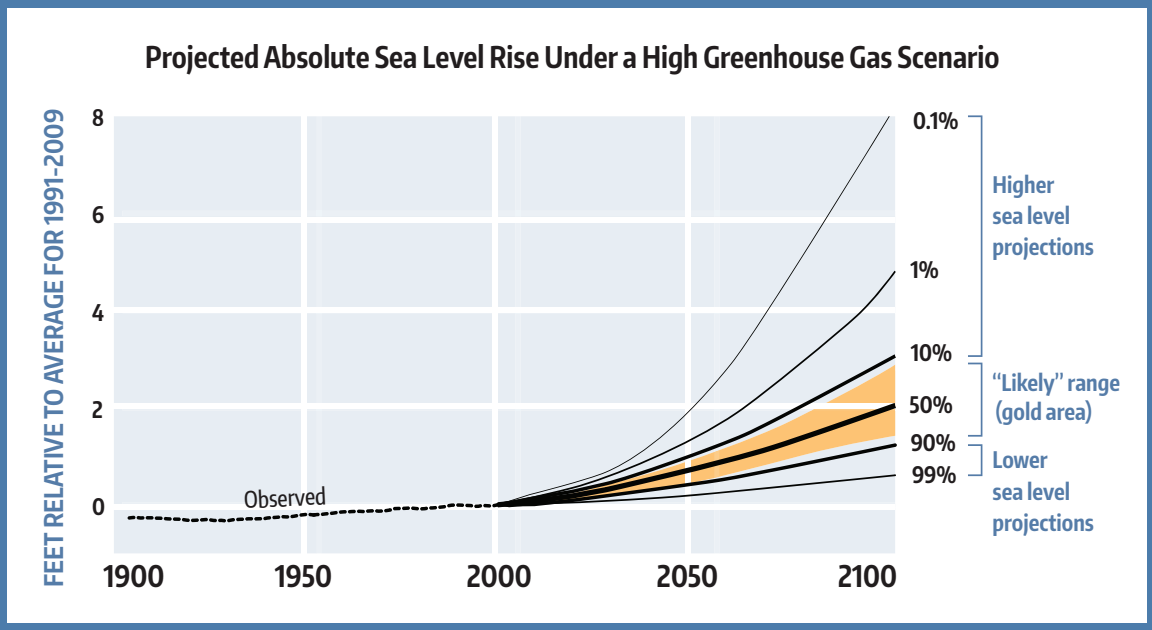
3. In statistical terms, this is the distinction between "Frequentist" vs. "Bayesian" approaches. We adopt a Bayesian approach to projecting future sea level after Kopp et al. (2014).

ABSOLUTE SEA LEVEL PROJECTIONS

Overview

This section describes our new projections of absolute sea level rise for Washington State (**Figure 2**). Absolute sea level refers to the height of the ocean surface, irrespective of any movement of the land. Changes in absolute sea level are evaluated relative to a "geocentric" reference frame – i.e., relative to the center of the earth – as opposed to the elevation of the land surface. Absolute sea level change can be combined with estimates of vertical land movement (e.g., uplift and subsidence) to project changes in "relative" sea level. Relative sea level rise is more applicable to community planning, since ultimately it is the relative change in sea level that will determine impacts on land.[4]

FIGURE 2: Absolute sea level rise projections, through 2100, for a high greenhouse gas scenario (RCP 8.5), for Washington State. Projections are based on Kopp et al. (2014) and observed variations in absolute sea level are shown for 1907-2007.[4] All results are shown relative to the average for 1991-2009. The probability values are "probabilities of exceedance", i.e., the current best assessment of the likelihood that absolute sea level will rise by at least a given change in elevation.



4. The observed absolute sea level change estimates in **Figure 2** were obtained by removing our estimate of vertical land movement (**Appendix C**) from the observed relative sea level trends, averaged over seven Washington State tide gauges. The resulting time series of monthly absolute sea level was then smoothed with a 19-year moving average.

Although there is potential for different rates of absolute sea level rise across Washington's coast, these differences are very small (generally less than 0.3 feet, about 4 inches, by the end of the century; **Appendix A**) and are not well resolved by current modeling. As a result, we produced a single set of absolute sea level rise projections for all of Washington State.

Our projections describe potential changes in long-term average absolute sea level (i.e., over multiple years or decades), relative to 1991-2009. Short-term water level variability – e.g., due to storms, El Niño, and other processes – can temporarily add to or reduce the rate of sea level change, and will continue to do so into the future.

The new projections are probabilistic, in that they describe the full range of possible future sea level changes for a given greenhouse gas scenario, with associated probabilities of exceedance within that range. Probabilities were determined based on the current science concerning each individual component of sea level rise (Kopp et al., 2014, see discussion below). This new approach is different from previous assessments for Washington State (Mote et al., 2008; NRC, 2012), which presented future ranges, but without a comprehensive assignment of likelihood.

SEA LEVEL AND DATUMS

Sea level typically refers to the long-term (i.e., over multiple years or decades) average sea surface height relative to land (often described as "Mean Sea Level", or MSL). In our study, projections are intentionally averaged over a 19-year period, since this encompasses the 18.6-year lunar cycle in tidal range. At any given time, the actual sea level could be lower or higher than this average due to tides, storms, or changes in wind and ocean currents. These short-term variations will continue into the future, and may be important to consider in planning. In the current study we average over these short-term influences on sea level in order to emphasize the long-term rise in sea level due to climate change.

Tide gauge observations are always reported relative to some common baseline, or "datum". This is a critical detail in coastal project planning and design, since the use of an incorrect datum can lead to an erroneous assessment of risk. Our results, however, are not tied to any particular datum. This is because we assess the ***change*** in absolute and relative sea level over time, which could be applied to any water surface elevation.



It is possible that tidal ranges may be influenced by sea level rise, as has been demonstrated for other locations around the globe at relatively high sea level rise magnitudes (e.g., Idier et al., 2017). However, this is very likely a minor effect, and it has not been quantified for the State of Washington. As a result, our projections assume that tidal ranges remain the same in the future.

Results

Our new absolute sea level rise projections are summarized in **Table 1** and **Figure 2**; the complete set of projections can be found in Appendix A. Whereas **Figure 2** shows results for just one greenhouse gas scenario (the high RCP 8.5 scenario), **Table 1** summarizes the absolute sea level rise projections for both a low and a high greenhouse gas scenario. In both, projections are averaged over the 19-year period indicated in the table, are shown in feet relative to contemporary sea level for Washington State, and are evaluated for a range of probabilities of exceedance.

By 2100, projections for all scenarios indicate a high likelihood (~50% probability or greater) of at least 1.5 feet of sea level rise, with the potential for more than 8 feet at the upper end of the distribution. At the low end, there is an 83% probability that sea level will rise by at least one foot by 2100, for a low greenhouse gas scenario (RCP 4.5).

TABLE 1: Absolute sea level rise projections, in feet, for Washington State. Projections are expressed in terms of the "probability of exceedance" for three different time periods (2050, 2100, and 2150) and two different greenhouse gas scenarios (RCP 4.5 ["Low"] and RCP 8.5 ["High"]; van Vuuren et al., 2011). Projected changes are assessed relative to contemporary sea level, which we define as the average sea level over the 19-year period 1991-2009. Projections for 2050 and 2100 for RCP 8.5 (highlighted below) are also shown in **Figure 2. Examples of *location-specific* relative sea level rise projections are available in Table 2.**

PROJECTED ABSOLUTE SEA LEVEL CHANGE
(feet, averaged over each 19-year time period)

Time Period	Greenhouse Gas Scenario	Central Estimate (50%)	Likely[5] Range (83-17%)	Higher magnitude, but lower likelihood possibilities		
				10% probability of exceedance	1% probability of exceedance	0.1% probability of exceedance
2050 (2040-2059)	Low	0.6	0.4 - 0.8	0.9	1.2	1.8
	High	0.7	0.5 - 0.9	1.0	1.3	2.0
2100 (2090-2109)	Low	1.6	1.0 – 2.2	2.5	4.1	7.2
	High	2.0	1.4 - 2.8	3.1	4.8	8.3
2150 (2140-2159)	Low	2.5	1.5 - 3.8	4.4	8.5	16.2
	High	3.4	2.3 - 4.9	5.6	10.0	18.3

The projected rise in sea level for 2050 is essentially the same for all greenhouse gas scenarios, since both scenarios show a similar amount of warming by that time. In contrast, future emissions make a big difference in the amount of sea level rise projected for 2100 and 2150. By 2100, for example, the median projection (50% probability of exceedance) is nearly a half foot lower for the low greenhouse gas scenario than it is for the high greenhouse gas scenario.

Our results differ from past projections. Comparing the projections for 2100, our central estimate (1.6-2.0 ft) is lower than the central estimate from the last regional report on sea level rise (2.3 ft; NRC, 2012). Previous studies did not include an estimate of likelihoods, but the high end from the last report (4.5 ft) is much lower than in the new projections (7.2-8.3 ft), and instead corresponds to about the 1% probability of exceedance in our current study (4.1-4.8 ft). A more in-depth review of the science, including comparisons with previous work, can be found in **Appendix B**.

Approach

This section briefly describes our approach to estimating future absolute sea level rise in Washington State; a broader literature review discusses the components of sea level rise in greater detail and can be found in **Appendix B**. Our approach makes use of tools and methods developed by Kopp et al. (2014), who estimate full probability distributions of each of the "climatically-controlled" components of sea level change, as follows:

- **Ocean Processes.** Warming waters cause sea level to rise ("thermal expansion"), while shifting winds and ocean currents can cause sea level to rise in some places and fall in others. In both cases, changes are assessed using global climate model projections from Phase 5 of the Coupled Model Intercomparison Project (CMIP5, Taylor et al., 2012).
- **Land-Based Glaciers and Ice Caps.** Melting land ice contributes to sea level rise. This category includes all land ice except the Greenland and



Image credit: Taylor Glacier, McMurdo Dry Valleys, Antarctica by Heidi Roop, Climate Impacts Group.

Antarctic ice sheets. Projections of land-based ice melt and its contribution to sea level rise are based on the model of Marzeion et al. (2012). As above, changes are assessed using climate projections from CMIP5.

- **Ice Sheets.** Changes in the size of the Greenland and Antarctic ice sheets also affect sea level. Ice sheets are treated separately from other land-based ice because the dynamics of ice movement are complex and are particularly important in Greenland and Antarctica. The median and likely[5] range among the projections of future ice sheet melt stem from the IPCC (2013) report, while the upper extremes are obtained from the expert elicitation results of Bamber and Aspinall (2013).

Other smaller contributors are also included in the Kopp et al. (2014) analysis. For example, they apply a model based on the approach of Mitrovica et al. (2011), to account for the change in gravitational pull of glaciers and ice sheets as they shrink in size. This is often referred to as "sea level fingerprinting", and can cause sea level to rise more rapidly in some places than others, and even cause sea level to fall in a few isolated areas very close to the ice sheets. There are also other factors that are not directly influenced by climate change, including retention of water behind man-made reservoirs (which lowers sea level), groundwater extraction (which raises sea level once the extracted water reaches the ocean), and even the ongoing response of the Earth's crust to the last ice age, a process known as "Glacial Isostatic Adjustment" (GIA). These processes are also accounted for in our projections.

We depart from the Kopp et al. (2014) approach in our estimates of the influence of GIA on absolute sea level rise. Because GIA concerns movement of the earth's crust and underlying mantle, it affects both vertical land motion and – via changes in the shape of ocean basins – absolute sea level. Kopp et al. (2014) developed a combined estimate that includes both consequences of GIA along with other influences on local relative sea level, such as plate tectonics. In our analysis, we develop separate estimates of the effects of GIA on vertical land movement and absolute sea level rise. This allows us to develop detailed, spatially varying estimates of vertical land movement along all of Washington's coastline, beyond simply the locations of high quality tide gauge records (**Appendix C**). Since our vertical land movement estimates do not include the influence of GIA on absolute sea level rise, these were obtained separately from **Appendix B** of NRC (2012, **Table B.2**).

5. We have adopted the IPCC terminology that relates likelihood statements to specific probabilities. In this case, "likely" refers to a confidence level of 66% or above. See www.ipcc.ch/pdf/supporting-material/uncertainty-guidance-note.pdf.

Future sea level rise estimates are produced using a "Monte Carlo" approach, in which the probability distribution for each component of sea level rise (ocean processes, land-based glaciers and ice caps, ice sheets, sea level fingerprinting, GIA, etc.) is sampled randomly, then added together to develop one estimate of future sea level rise. This process is repeated 10,000 times, each time producing a new estimate of future sea level rise. The result is a probability distribution of sea level rise for a particular time period and scenario, from which we can estimate the amount of sea level rise associated with specific probabilities of exceedance. This approach is repeated for each decade (from 2000 to 2150) and for a low and a high greenhouse gas scenario (Kopp et al., 2014).

For the purpose of this assessment we chose the 99% and 1% probability of exceedance levels as the bounds of possible future sea level rise. However, processes that could lead to extreme high-end sea level rise are currently an area of intense scientific and planning interest. In particular, recent modeling of the Antarctic Ice Sheet suggests that the best estimate for 21st century sea level rise may be higher than previously estimated (DeConto and Pollard, 2016). Although this study highlights important mechanisms that may lead to accelerated Antarctic melt, the authors note that their results are preliminary and "should not be viewed as actual predictions." Nonetheless, it is possible that future research could shift future projections upward. As a result, we have also included an upper limit or very high magnitude sea level rise projection, associated with an extremely low probability of exceedance (0.1%). The inclusion of this low probability, high impact sea level rise projection is in keeping with recent sea level rise planning work in other regions (e.g., Griggs et al., 2017; Sweet et al., 2017; Kopp, personal communication). This high-end projection is discussed in more detail in **Appendix B**.

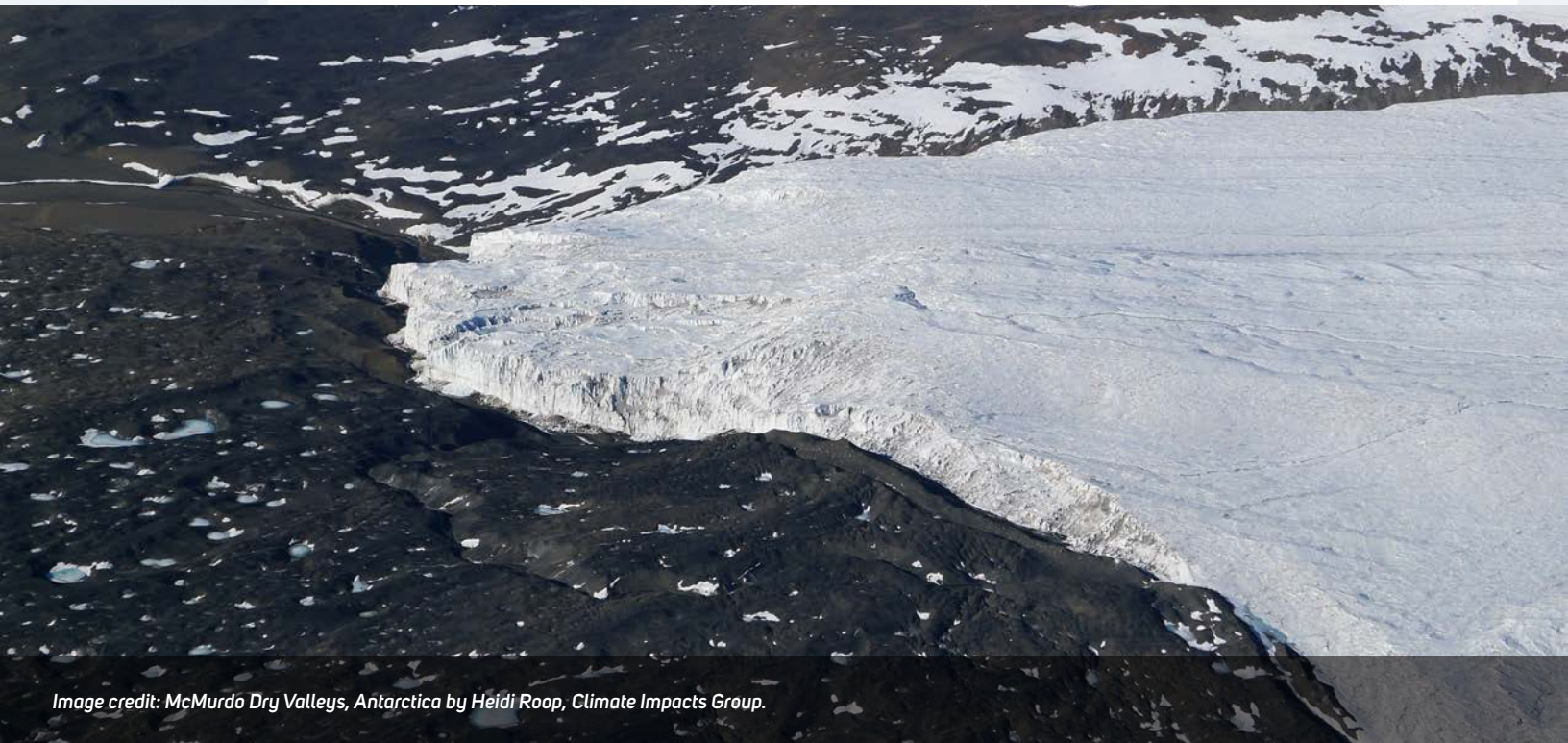


Image credit: McMurdo Dry Valleys, Antarctica by Heidi Roop, Climate Impacts Group.

RELATIVE SEA LEVEL PROJECTIONS

Overview

Relative sea level is the long-term (over multiple years or decades) average sea surface height relative to a fixed point on land. Relative sea level changes reflect both changes in absolute sea level and vertical movement of the land surface (i.e., subsidence or uplift). In Washington State, vertical land movement can have a non-negligible impact on near-term changes in observed and projected relative sea level rise (Mazotti et al., 2008).

As with the absolute sea level rise projections, our relative sea level rise projections (**Table 2**) describe potential changes in long-term average sea level (i.e., over

TABLE 2: Relative sea level projections, in feet, for three of the 171 locations along Washington's coastline. Example locations in Washington include the Taholah, Neah Bay, and Long Beach. Projections are expressed in terms of the "probability of exceedance" for 2100 (2090-2109) under two different greenhouse gas scenarios (RCP 4.5 ["Low"] and RCP 8.5 ["High"]; van Vuuren et al., 2011). Projected changes are assessed relative to contemporary sea level, which we define as the average sea level over the 19-year period 1991-2009. Data for all 171 locations are available at www.wacoastalnetwork.com/wcrp-documents.html.

PROJECTED RELATIVE SEA LEVEL CHANGE FOR 2100
(feet, averaged over a 19-year time period)

Location	Vertical Land Movement Estimate	Greenhouse Gas Scenario	Central Estimate (50%)	Likely Range (83-17%)	Higher magnitude, but lower likelihood possibilities		
					10% probability of exceedance	1% probability of exceedance	0.1% probability of exceedance
Tacoma (47.3N, 122.4W)	-0.5 ± 0.2	Low	2.1	1.5-2.7	3	4.6	7.9
		High	2.5	1.9-3.3	3.6	5.3	8.8
Neah Bay (48.4N, 124.6W)	1.1 ± 0.3	Low	0.5	-0.1 - 1.2	1.5	3.1	6.3
		High	1	0.3 - 1.7	2	3.8	7.4
Taholah (47.4N, 124.3W)	0.3 ± 0.5	Low	1.3	0.6-2.1	2.4	3.9	7.1
		High	1.7	1.0-2.6	2.9	4.6	8.1

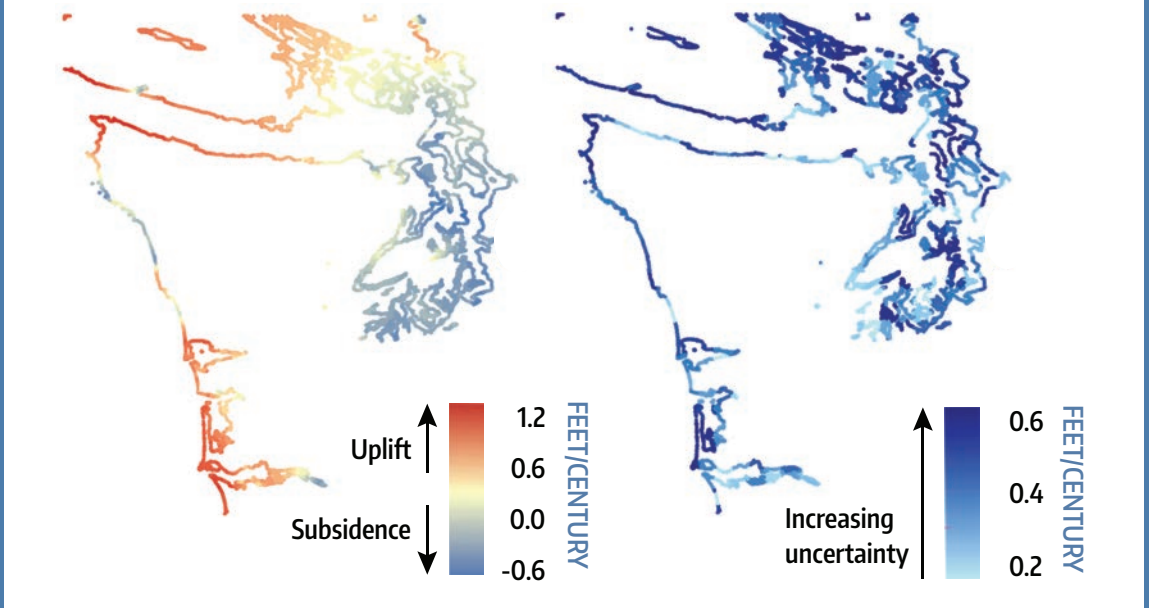
multiple years or decades), relative to 1991-2009. Our projections are probabilistic: for each greenhouse gas scenario, the range among projections is expressed as the probability that sea level rise will reach or exceed a particular change in elevation (this is often referred to as the "probability of exceedance").

Results

Coastal vertical land movement varies in Washington State (**Figure 3**), which translates into variations in relative sea level. Our vertical land movement estimates were produced on a 0.1-degree grid (equivalent to roughly 5-7 miles). The same resolution is used for our relative sea level rise projections. The projections are summarized in a series of excel files, produced for each of the 171 coastal locations that correspond to the 0.1-degre grid, each with a separate worksheet for each greenhouse gas scenario ("Low": RCP 4.5 and "High": RCP 8.0; **Figure 4**). All projections can be found on the WCRP project website: www.wacoastalnetwork.com/wcrp-documents.html.

By construction, the relative sea level rise projections reflect variations in the estimated rate of vertical land movement along Washington's coastline (e.g. **Table 2**). Areas that are estimated to be uplifting rapidly (e.g., the northwest tip of the Olympic Peninsula) have lower projected changes in relative sea level

FIGURE 3: Vertical land movement best estimate rates (left) expressed in rates of feet/century, and their uncertainties (1 standard deviation, right) as estimated for Washington's coastline.



when compared to areas (e.g., parts of central Puget Sound) that are estimated to be subsiding (**Table 2 and Figure 3**). The uncertainty in coastal vertical land movement estimates can also be seen in the relative sea level rise projections. For example, the large uncertainty in vertical land movement for the Long Beach peninsula leads to a larger difference between the 17 and 83% probability of exceedance projections than in adjacent areas.

A key assumption in our analysis is that our assessed rates of vertical land motion will continue, uninterrupted, through 2150. Seismic activity can cause sudden changes in land elevation, thus altering sea level. Although earthquakes are difficult to predict, modeling suggests that a large earthquake, occurring along the Cascadia subduction zone fault, could result in a sudden change in land elevation along large swaths of Washington's coast. This "co-seismic" land level change on the coast is not built into our relative sea level rise projections. Given its potential importance for planning, we obtained model estimates of land level changes for an earthquake with a return frequency of 500 years.[6] This information is included in our relative sea level rise tables for Washington's coast (**Figure 4**, see **Appendix C** for a more in-depth discussion).

Smaller earthquakes, such as on the Seattle fault, can also cause sudden changes in land elevation. However, these changes occur over a much smaller area. It is beyond the scope of this assessment to estimate these smaller potential changes for all of coastal Washington. Communities that are adjacent to crustal faults[7] may choose to undertake a more detailed and localized analysis to take into account possible relative sea level changes associated with local faults.

Approach

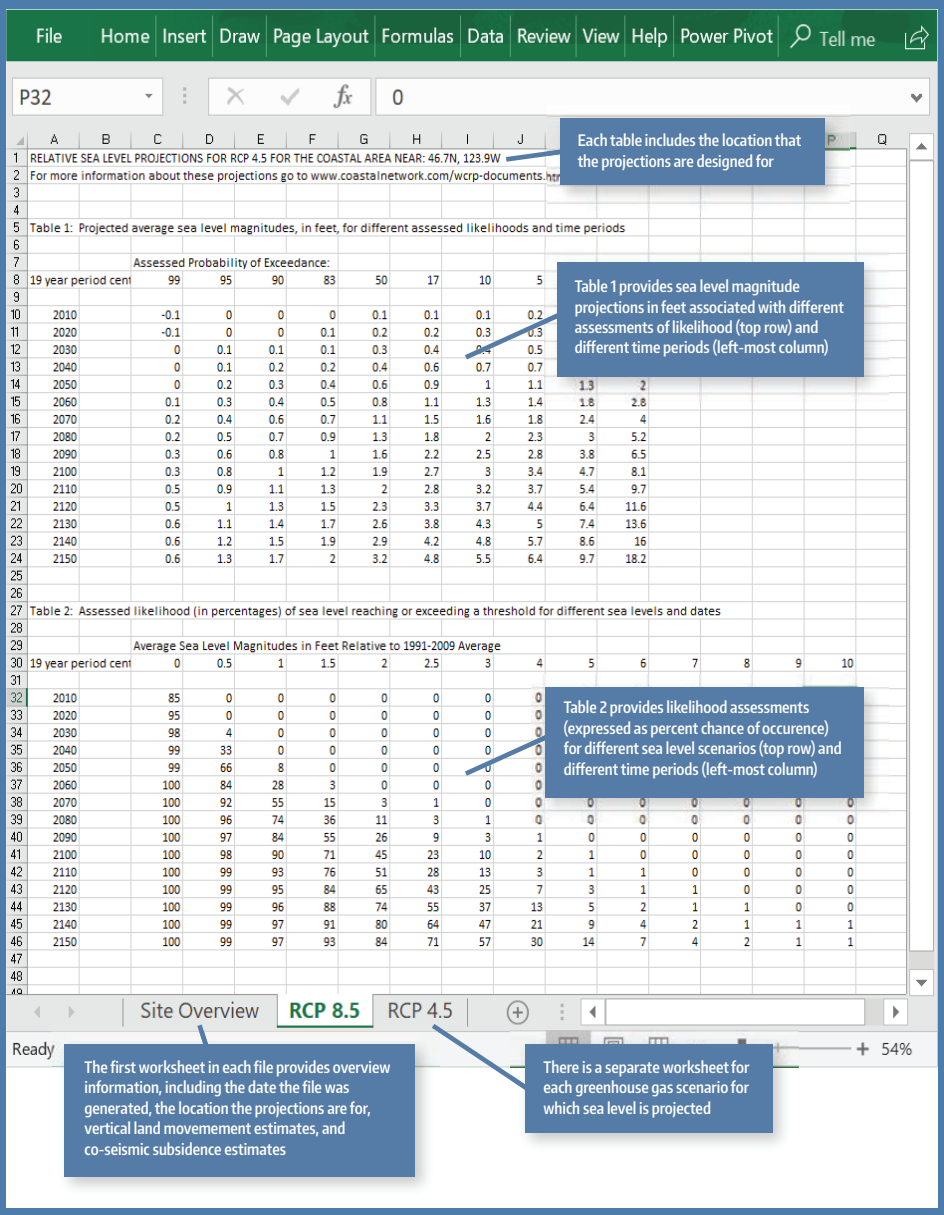
We developed relative sea level rise projections by incorporating our assessment of absolute sea level change, and its uncertainty, with our estimated rates of coastal vertical land movement and their uncertainties. As noted in the previous section, variations in absolute sea level across Washington State are small and are not well characterized by current modeling. As a result, we produce a single set of absolute sea level rise projections for all of Washington State. In contrast, our vertical land movement estimates are spatially distributed, with notable variations along the state's coastline (**Figure 3**).

6. The geologic record indicates that there have been seven large subduction zone earthquakes in the Cascadia subduction zone over the last 3500 years, yielding a return interval of 500 years.

7. See https://geologyportal.dnr.wa.gov/#natural_hazards

Previous investigations have estimated the rate of vertical land movement for Washington State (Mote et al., 2008; NRC, 2012). However, there are a number of limitations to these previous assessments – in particular, previous studies either assumed the same rate for the entire state, or limited their assessment to a very small number of locations along the coastline. As a result, we opted to conduct our own vertical land movement assessment that made use of over 500

FIGURE 4: Example relative sea level table, with descriptions showing how the data are organized.



individual vertical land movement observations along Washington's coast, as well as modeled estimates of likely bedrock movements associated with tectonic processes. A detailed description of our vertical land motion estimates can be found in **Appendix C**.

Notably, our approach also assessed the uncertainty in the vertical land movement estimates, so that we could estimate a probability distribution for the rate of vertical land movement. This made it straightforward to combine the absolute sea level rise and vertical land movement estimates to develop probabilistic projections of relative sea level rise at discrete locations on Washington's coastline.

CONCLUSIONS

This report provides an updated set of sea level rise projections for Washington State. The projections improve on previous work by incorporating the latest science, providing community-scale projections, and assessing the probability that sea level rise meets or exceeds a particular change in elevation.

The probabilistic projections are intended to better align with coastal risk management and planning. By providing likelihoods, users can select probabilities to align with a particular decision context or risk management approach. For example, planners might want to consider high-impact low-probability projections for decisions regarding critical infrastructure (e.g., a hospital), whereas the low-end or middle projections might be the best approach for situations where management can easily be adapted in the future (e.g., vegetation management).



Image credit: Fisherman in stormy weather in Ocean Shores, WA.
Photo by: Bernd Thaller, used under CC BY 2.0

Our new projections reflect the latest science on sea level rise and are an improvement over previous assessments. Over time, these will undoubtedly be updated as new science becomes available. Until that time, we recommend using these new projections for coastal impacts assessments within the state of Washington.

REFERENCES

Bamber, J. L., & Aspinall, W. P. (2013). An expert judgment assessment of future sea level rise from the ice sheets. Nature Climate Change, 3(4), 424. www.nature.com/nclimate/journal/v3/n4/full/nclimate1778.html

Davis, S. J., & Socolow, R. H. (2014). Commitment accounting of CO2 emissions. Environmental Research Letters, 9(8), 084018.

DeConto, R. M., & Pollard, D. (2016). Contribution of Antarctica to past and future sea-level rise. Nature, 531(7596), 591.

Griggs, G., Árvai, J., Cayan, D., DeConto, R., Fox, J., Fricker, H.A., Kopp, R.E., Tebaldi, C., Whiteman, E.A. (California Ocean Protection Council Science Advisory Team Working Group). Rising Seas in California: An Update on Sea-Level Rise Science. California Ocean Science Trust, April 2017.

Idier, D., Paris, F., Le Cozannet, G., Boulahya, F., & Dumas, F. (2017). Sea-level rise impacts on the tides of the European Shelf. Continental Shelf Research, 137, 56-71.

IPCC, 2013: Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 1535 pp.

Kopp, R. E., Horton, R. M., Little, C. M., Mitrovica, J. X., Oppenheimer, M., Rasmussen, D. J., ... & Tebaldi, C. (2014). *Probabilistic 21st and 22nd century sea-level projections at a global network of tide-gauge sites. Earth's Future, 2(8), 383-406.* https://doi.org/10.1002/2014EF000239

Marzeion, B., Jarosch, A. H., & Hofer, M. (2012). Past and future sea-level change from the surface mass balance of glaciers. The Cryosphere, 6(6), 1295. https://doi.org/10.5194/tc-6-1295-2012

Mauger, G.S., Casola, J.H., Morgan, H.A., Strauch, R.L. Jones, B., Curry, B., Busch Isaksen, T.M., Whitely Binder, L., Krosby, M.B., & Snover, A.K. (2015.) State of Knowledge: Climate Change in Puget Sound. Report prepared for the Puget Sound Partnership and the National Oceanic and Atmospheric Administration. Climate Impacts Group, University of Washington, Seattle.

Mitrovica, J. X., Gomez, N., Morrow, E., Hay, C., Latychev, K., & Tamisiea, M. E. (2011). On the robustness of predictions of sea level fingerprints. Geophysical

Journal International, 187(2), 729-742. https://doi.org/10.1111/j.1365-246X.2011.05090.x

Mote, P.W., Petersen, A., Reeder, S., Shipman, H., & Whitely Binder, L., (2008). Sea Level Rise in the Coastal Waters of Washington State. Report prepared by the Climate Impacts Group, University of Washington and the Washington Department of Ecology. www.cses.washington.edu/db/pdf/moteetalslr579.pdf

National Research Council (NRC). 2012. Sea-Level Rise for the Coasts of California, Oregon, and Washington: Past, Present, and Future. Committee on Sea Level Rise in California, Oregon, Washington. Board on Earth Sciences Resources Ocean Studies Board Division on Earth Life Studies The National Academies Press. http://nap.edu/13389#

Pfeiffer, A., Millar, R., Hepburn, C., & Beinhocker, E. (2016). The '2 C capital stock'for electricity generation: Committed cumulative carbon emissions from the electricity generation sector and the transition to a green economy. Applied Energy, 179, 1395-1408.

Van Vuuren, D. P., Edmonds, J., Kainuma, M., Riahi, K., Thomson, A., Hibbard, K., ... & Masui, T. (2011). The representative concentration pathways: an overview. Climatic change, 109(1-2), 5. https://doi.org/10.1007/s10584-011-0148-z

Witter, R. C., Zhang, Y. J., Wang, K., Priest, G. R., Goldfinger, C., Stimely, L., ... & Ferro, P. A. (2013). Simulated tsunami inundation for a range of Cascadia megathrust earthquake scenarios at Bandon, Oregon, USA. Geosphere, 9(6), 1783-1803. https://doi.org/10.1130/GES00899.1

Wang, K., & Tréhu, A. M. (2016). Invited review paper: Some outstanding issues in the study of great megathrust earthquakes—The Cascadia example. Journal of Geodynamics, 98, 1-18. https://doi.org/10.1016/j.jog.2016.03.010

Comment #29

Robby Eckroth

From: Kaia Hayes <kaiah@re-sources.org>
Sent: Thursday, May 8, 2025 5:35 PM
To: PDS comments
Cc: Eddy Ury
Subject: 2025 Update to Critical Areas Ordinance

Honorable Planning Commissioners,

RE Sources is a non-profit organization founded in 1982. We work to protect the health of northwest Washington's people and ecosystems through the application of science, education, advocacy and action.

Please accept our comments below on the 2025 update to the Critical Areas Ordinance:

Critical Areas Ordinance
Effectively Implementing No Net Loss

For the past few decades, No Net Loss (NNL) of habitat and ecosystem function has been the adopted standard for growth in Washington state, particularly in the context of mitigating development and other use impacts within Critical Areas. **When considering the scope and nature of impacts to these areas, it's critical to distinguish what exactly is at risk of being lost.** More than individual components like trees, acres of wetland vegetation, acres of pervious surface, etc, No Net Loss asks us to view these within the larger context of a functioning natural system or critical habitat for species of interest.

Certain proposed "1:1" mitigation strategies such as replanting can fail to address this larger context, and become ineffective in truly mitigating an activity's impact on ecological function. As a simple example, we know that young trees require significant time investment and water resources to establish and mature before they can offer a net-benefit via the many ecosystem services that older trees provide. If we remove four long-established trees from a parcel in favor of replanting four young trees in a more convenient location, this action will not even begin to mitigate the loss of ecosystem function maintained by the original stand of older trees for many years. The complexity of this accounting increases with scale, and when we consider the hydrologic nuances balanced by functioning riparian and wetland ecosystems.

Existing Critical Areas Ordinance language should be reviewed to ensure that policies reflect a true No Net Loss of ecological function and critical habitat.

Climate Change and Critical Areas

We now also better understand the role of climate change in exacerbating many of the landscape-level challenges that communities prepare for through long-range planning efforts like the Comprehensive Plan update. **At all levels, planning for climate impacts like drought, wildfire, flooding, and sea level rise has established itself as the new and necessary baseline.** We see this at the state and local level with the GMA's mandate that climate data and GHG emissions projections be integrated into comprehensive planning for the first time. The Critical Areas Ordinance (CAO) is perhaps an even more

important opportunity to do so, as the foundation for implementation of the Comp Plan's high level policies.

How does this reality impact the No Net Loss standard? We can think of NNL as shoveling a fixed amount of dirt to fill a hole. With the addition of the exacerbating lens of climate change, the depth of this hole is no longer static– it's getting deeper. **To practice a static No Net Loss approach today is to lose ground and net significant loss tomorrow.** We need to instead adopt a "two step forward, one step back" approach to mitigating ecological function and habitat loss to keep pace with this widening impact gap.

A New Baseline for Building Resilience

Net Ecological Gain (NEG) embodies exactly this – and in the face of climate change, can be considered the "new No Net Loss." The Net Ecological Gain standard for mitigation in Critical Areas is not only to account for use impacts, but to restore or enhance the net function or habitat value to a higher level than existed prior to the mitigated activity.

In Washington state, efforts to formally establish and adopt the NEG standard into law have been in process since 2019. The most recent 2024 WDFW report to the WA legislature (following two NEG-focused provisos in 2019 and 2023) details next steps for stronger enforcement of existing NNL regulations, as well as a plan for developing and implementing a Net Ecological Gain framework through a number of regulatory and incentive-based strategies. A followup report is due to the legislature June 30, 2025.

The County should adopt Net Ecological Gain (NEG) as a standard for both the Critical Areas Ordinance and the 2025 Comprehensive Plan in order to keep abreast of evolving planning standards, and to leverage the greatest benefit from efforts to build resilience for the dynamic conditions of the decades ahead.

Thank you for the opportunity to comment,
--
Kaia Hayes
(she / her / hers)
Land & Water Policy Manager
RE Sources
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We are on the ancestral homelands of the Coast Salish Peoples, whose tribal treaty rights we support and for whose enduring care of the lands and waters we are deeply grateful.

Comment #30

Robby Eckroth

From: Eddy Ury <eddyu@re-sources.org>
Sent: Thursday, May 8, 2025 6:09 PM
To: PDS comments
Cc: Kaia Hayes; Ander Russell
Subject: 2025 Skagit Co. Code update proposal

Honorable Planning Commissioners,

We appreciate your consideration of these comments on the proposed code reorganization, in addition to our comments on Critical Areas from my colleague, Kaia Hayes.

The proposal includes several changes for compliance with new state requirements, and a significant code-scrub intended for clarity. While the proposal is an improvement, in our assessment the County should go further to improve SCC Title 14 for clarity, consistency and to better align with the goals and policies of the 2025 Comprehensive Plan. In particular, the updated goal and policies of 9A-5 (Utilities) cannot be implemented unless Skagit County amends Title 14 to clarify the parameters for utility development in various zones.

The rules for "utility development" in Title 14 are exceptionally vague, ambiguous, inconsistent and unnecessarily confusing. The utility development definition *"includes, but is not limited to, facilities and services that generate, transport, process, or store water, sewage, solid waste, electrical energy, communications and pipelines for fuel, oil, natural gas, and petroleum products."* Tree types are delineated : minor, major, and major regional.

SCC 14.10.060 lists utility development (apparently of all types) to be allowed in all zones. In contradiction, Chapter 14.18 Part VIII (Utility uses) specifies limitations in the Ag-NRL zone, including a prohibition on major utility developments for generation and storage of electricity. Under SCC 14.13 (Natural Resource Zones and Uses) however there are no prohibited uses listed. What's more puzzling, in 14.10.070 major regional utility development is listed as a marijuana use prohibited in all zones. If this is not an outright error in the draft and there is a particular sort of marijuana facility that could meet the definition of major regional utility, that could be more clearly specified. This all underscores the problem of lumping vastly disparate uses into a singular category.

The definition of utility development in 14.18 seems to encompass oil refineries and chemical manufacturing, which are existing uses at March Point in the unincorporated Anacortes UGA. It is thus implied by SCC 14.10.060 that oil refineries are allowed in all zones. Confusingly, the extensive list of categorized uses for the Anacortes UGA Urban Development District (A-UD) in Chapter 14.16 (Municipal UGA Zones and Uses) does not include industrial uses, and utility development is not listed as an allowed use. However, in the Anacortes Municipal Code (AMC 19.45.010), oil refining and chemical manufacturing are both explicitly permitted. Permitting authority still rests with Skagit County, which defers to the city rules. As it happens, the Comprehensive Plan 2025 Draft for the City of Anacortes includes an updated Economic Development policy ED-4.7 : *Coordinate with Skagit county to anticipate and plan for potential future desired uses at the March Point refineries as product types, manufacturing processes, economic competitiveness, and transportation methods change.* Consistency between the City and County development regulations could improve the predictability of the permitting process.

We encourage Skagit County to engage with the City of Anacortes and, following adoption of the 2025 Comp Plan update, resolve to further amend SCC Title 14 in 2026 with a land use ordinance that sets clear parameters around industrial development for both new and existing facilities. With clear and specific rules in place, concerned parties could be better assured of conditions upfront, while project applicants would gain more predictable and expeditious outcomes. All involved — businesses, government administrators, project proponents and opponents alike — should benefit from transparent rules and guidelines that clarify expectations.
Thanks again for your service and inclusion of public participation in these consequential decisions to shape our shared future.

Sincerely,
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Eddy Ury
Climate & Energy Policy Manager
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