From:	Krueger, Morgan (DFW)
To:	Chris Pasinetti
Cc:	Berejikian, Marian (DFW); Douglas, Julian K (DFW); Cathy Burbank; Whittaker, Kara A (DFW); Stapleton, Timothy R (DFW); Reinbold, Stewart G (DFW); Douglas, Julian K (DFW); Pate, Nathan (COM)
Subject:	RE: Comp Plan and CAO comments
Date:	Friday, August 30, 2024 11:35:44 AM
Attachments:	image001.png Vol.1. Science Synthesis.pdf Vol.2. Management Recommendations.pdf 08.30.2024 case #2022-C-195, WDFW comments regarding Enumclaw's draft Comp Plan.pdf 08.30.2024 Submittal ID 2024-S-7309, WDFW comments Enumclaw draft CAO.pdf

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Hi Chris,

I wanted to be sure to provide you with WDFW's final Comprehensive Plan and CAO comment letters. Kindly include these comment letters in the official record, along with the attached documents detailing WDFW's best available science. Please let me know if you have any questions or comments.

Have a great weekend!

Best,

Morgan Krueger (she/her)
Regional Land Use Lead, Habitat Division
Washington Dept. of Fish and Wildlife
Region 4

Morgan.Krueger@dfw.wa.gov
425-537-1354

From: Krueger, Morgan (DFW)
Sent: Friday, August 23, 2024 2:52 PM
To: Chris Pasinetti <CPasinetti@ci.enumclaw.wa.us>
Cc: Berejikian, Marian (DFW) <Marian.Berejikian@dfw.wa.gov>; Douglas, Julian K (DFW) <Julian.Douglas@dfw.wa.gov>
Subject: RE: Comp Plan and CAO comments

Hi Chris,

Thank you for the opportunity to offer our draft comment letters regarding Enumclaw's draft Comprehensive Plan and CAO. Once we receive confirmation from your team, we will finalize our draft comments and upload them to PlanView. If we do not receive confirmation, we will upload these comments in one week from today. If you have any comments, questions, require technical assistance, or would like to schedule a time to chat about these comments, please feel free to reach out to me.

All the best,

Morgan Krueger (she/her)
Regional Land Use Lead, Habitat Division
Washington Dept. of Fish and Wildlife
Region 4

Morgan.Krueger@dfw.wa.gov
425-537-1354

From: Chris Pasinetti <CPasinetti@ci.enumclaw.wa.us>
Sent: Monday, July 29, 2024 12:09 PM
To: Krueger, Morgan (DFW) <Morgan.Krueger@dfw.wa.gov>
Cc: Berejikian, Marian (DFW) <Marian.Berejikian@dfw.wa.gov>; Douglas, Julian K (DFW) <Julian.Douglas@dfw.wa.gov>
Subject: RE: Discuss BAS Document

External Email

That would be fine

From: Krueger, Morgan (DFW) <Morgan.Krueger@dfw.wa.gov>
Sent: Monday, July 29, 2024 11:43 AM
To: Chris Pasinetti <CPasinetti@ci.enumclaw.wa.us>
Cc: Berejikian, Marian (DFW) <Marian.Berejikian@dfw.wa.gov>; Douglas, Julian K (DFW) <Julian.Douglas@dfw.wa.gov>
Subject: RE: Discuss BAS Document

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Hi Chris,

Thank you for getting this to me. I will be sure to get comments back on the draft Comprehensive Plan elements and draft CAO update by 8/30. Please let me know if this timeframe will work for you and your team.

All the best,

Morgan Krueger (she/her)
Regional Land Use Lead, Habitat Division
Washington Dept. of Fish and Wildlife
Region 4

Morgan.Krueger@dfw.wa.gov
425-537-1354

From: Chris Pasinetti <CPasinetti@ci.enumclaw.wa.us>
Sent: Monday, July 29, 2024 9:54 AM
To: Krueger, Morgan (DFW) <Morgan.Krueger@dfw.wa.gov>
Cc: Berejikian, Marian (DFW) <Marian.Berejikian@dfw.wa.gov>; Douglas, Julian K (DFW) <Julian.Douglas@dfw.wa.gov>
Subject: RE: Discuss BAS Document

External Email

Morgan,

Here is a first draft. I'm meeting with our consultant tomorrow so there will likely be some changes. Any comments would be great, again, sooner would be better than later.

We encourage applicants to apply for permits electronically. Instructions on how to apply online can be found here: https://tinyurl.com/478ez6a7. If you have questions about how to apply for permits electronically please email permits@ci.enumclaw.wa.us.

Chris Pasinetti, AICP
Community Development Director
City of Enumclaw | 1309 Myrtle Avenue | Enumclaw, WA 98022
Office 360-615-5726 | Email: cpasinetti@ci.enumclaw.wa.us
Hours: Mon – Fri 8:00am – 4:30pm

From: Krueger, Morgan (DFW) <Morgan.Krueger@dfw.wa.gov>
Sent: Tuesday, July 9, 2024 1:20 PM
To: Chris Pasinetti <CPasinetti@ci.enumclaw.wa.us>

Cc: Berejikian, Marian (DFW) <Marian.Berejikian@dfw.wa.gov>; Douglas, Julian K (DFW) <Julian.Douglas@dfw.wa.gov>
Subject: RE: Discuss BAS Document

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That would be wonderful Chris! The earlier the better.

All the best,

Morgan Krueger (she/her)
Regional Land Use Lead, Habitat Division
Washington Dept. of Fish and Wildlife
Region 4

Morgan.Krueger@dfw.wa.gov
425-537-1354

From: Chris Pasinetti <CPasinetti@ci.enumclaw.wa.us>
Sent: Tuesday, July 9, 2024 1:02 PM
To: Krueger, Morgan (DFW) <Morgan.Krueger@dfw.wa.gov>
Subject: RE: Discuss BAS Document

External Email

Also, as a side note. My consultants are working on a DRAFT critical area ordinance amendment as well. As soon as I have that available I will send that you

---

From: Krueger, Morgan (DFW) <Morgan.Krueger@dfw.wa.gov>
Sent: Tuesday, July 9, 2024 8:58 AM
To: Chris Pasinetti <CPasinetti@ci.enumclaw.wa.us>
Cc: Berejikian, Marian (DFW) <Marian.Berejikian@dfw.wa.gov>; Douglas, Julian K (DFW) <Julian.Douglas@dfw.wa.gov>; 'Shook, Erika' <Erika.Shook@jacobs.com>
Subject: RE: Discuss BAS Document

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Perfect. We will have comments back to you by then.

All the best,

Morgan Krueger (she/her)
Regional Land Use Lead, Habitat Division
Washington Dept. of Fish and Wildlife
Region 4

Morgan.Krueger@dfw.wa.gov
425-537-1354

From: Chris Pasinetti <CPasinetti@ci.enumclaw.wa.us>
Sent: Monday, July 8, 2024 5:19 PM
To: Krueger, Morgan (DFW) <Morgan.Krueger@dfw.wa.gov>
Cc: Berejikian, Marian (DFW) <Marian.Berejikian@dfw.wa.gov>; Douglas, Julian K (DFW) <Julian.Douglas@dfw.wa.gov>; 'Shook, Erika' <Erika.Shook@jacobs.com>
Subject: RE: Discuss BAS Document

External Email

Soon. I would say by August 30. Thank you!

From: Krueger, Morgan (DFW) <Morgan.Krueger@dfw.wa.gov>
Sent: Monday, July 8, 2024 4:46 PM
To: Chris Pasinetti <CPasinetti@ci.enumclaw.wa.us>
Cc: Berejikian, Marian (DFW) <Marian.Berejikian@dfw.wa.gov>; Douglas, Julian K (DFW) <Julian.Douglas@dfw.wa.gov>; 'Shook, Erika' <Erika.Shook@jacobs.com>
Subject: RE: Discuss BAS Document

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Thanks Chris! When would be a good date to get comments back to you on these draft elements?

Thanks in advance,

Morgan Krueger (she/her)
Regional Land Use Lead, Habitat Division
Washington Dept. of Fish and Wildlife
Region 4

Morgan.Krueger@dfw.wa.gov
425-537-1354

From: Chris Pasinetti <CPasinetti@ci.enumclaw.wa.us>
Sent: Monday, July 8, 2024 4:03 PM
To: Krueger, Morgan (DFW) <Morgan.Krueger@dfw.wa.gov>
Cc: Berejikian, Marian (DFW) <Marian.Berejikian@dfw.wa.gov>; Douglas, Julian K (DFW) <Julian.Douglas@dfw.wa.gov>; 'Shook, Erika' <Erika.Shook@jacobs.com>
Subject: RE: Discuss BAS Document

External Email

Hi Morgan,

We do have DRAFT Elements on the city's website here:
https://cityofenumclaw.net/592/2024-Comprehensive-Plan-Periodic-Update

Natural Environment Element here:
https://cityofenumclaw.net/DocumentCenter/View/9072/20240412-Comp-Plan-REVIEW-DRAFT_outbound_NaturalEnvironment

We encourage applicants to apply for permits electronically. Instructions on how to apply online can be found here: https://tinyurl.com/478ez6a7. If you have questions about how to apply for permits electronically please email permits@ci.enumclaw.wa.us.

Chris Pasinetti, AICP
Community Development Director
City of Enumclaw | 1309 Myrtle Avenue | Enumclaw, WA 98022
Office 360-615-5726 | Email: cpasinetti@ci.enumclaw.wa.us
Hours: Mon – Fri 8:00am – 4:30pm

From: Krueger, Morgan (DFW) <Morgan.Krueger@dfw.wa.gov>
Sent: Monday, July 8, 2024 3:42 PM
To: Chris Pasinetti <CPasinetti@ci.enumclaw.wa.us>
Cc: Berejikian, Marian (DFW) <Marian.Berejikian@dfw.wa.gov>; Douglas, Julian K (DFW) <Julian.Douglas@dfw.wa.gov>; 'Shook, Erika' <Erika.Shook@jacobs.com>
Subject: RE: Discuss BAS Document

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Hi Chris,

I wanted to be sure to check in and ask how the periodic update is coming along. If there are any early draft elements, I would be more than happy to take a look at them.

Additionally, as the periodic update timeline speeds by, I wanted to highlight some key information that we touched on during our meeting this January regarding new best available science from WDFW. This BAS, released in 2020, is our Riparian Ecosystems, Volume 1: Science Synthesis and Management Implications. This synthesis and corresponding management recommendation document outline the need to update CAO's to reflect the most up-to-date science for protecting riparian critical areas. See the city of Anacortes' municipal code section 19.70.330 Specific standards for riparian management zones for how this science is being implemented as part of the current periodic update. Please also see our checklist as a helpful tool that outlines how this best available science can be implemented into code language. Please let us know if you'd like to discuss these items again in more detail, and I can set up a time to chat.

All the best,

Morgan Krueger (she/her)
Regional Land Use Lead, Habitat Division
Washington Dept. of Fish and Wildlife
Region 4

Morgan.Krueger@dfw.wa.gov
425-537-1354

From: Krueger, Morgan (DFW)
Sent: Thursday, February 1, 2024 1:57 PM
To: Chris Pasinetti <CPasinetti@ci.enumclaw.wa.us>; 'Shook, Erika' <Erika.Shook@jacobs.com>; Douglas, Julian K (DFW) <Julian.Douglas@dfw.wa.gov>
Cc: Berejikian, Marian (DFW) <Marian.Berejikian@dfw.wa.gov>
Subject: RE: Discuss BAS Document

Don't mention it, Chris! Please don't hesitate to reach out if you have any questions.

All the best,

Morgan Krueger (she/her)
Regional Land Use Planner, Habitat Division
Washington Dept. of Fish and Wildlife
Region 4

Morgan.Krueger@dfw.wa.gov
206-707-5434

From: Chris Pasinetti <CPasinetti@ci.enumclaw.wa.us>
Sent: Thursday, February 1, 2024 1:04 PM
To: Krueger, Morgan (DFW) <Morgan.Krueger@dfw.wa.gov>; 'Shook, Erika' <Erika.Shook@jacobs.com>; Douglas, Julian K (DFW) <Julian.Douglas@dfw.wa.gov>
Cc: Berejikian, Marian (DFW) <Marian.Berejikian@dfw.wa.gov>
Subject: RE: Discuss BAS Document

External Email

Thank you all. Appreciate it!

We encourage applicants to apply for permits electronically. Instructions on how to apply online can be found here: https://tinyurl.com/478ez6a7. If you have questions about how to apply for permits electronically please email permits@ci.enumclaw.wa.us.

Chris Pasinetti, AICP
Community Development Director
City of Enumclaw | 1309 Myrtle Avenue | Enumclaw, WA 98022
Office 360-615-5726 | Email: cpasinetti@ci.enumclaw.wa.us
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From: Krueger, Morgan (DFW) <Morgan.Krueger@dfw.wa.gov>
Sent: Thursday, February 1, 2024 10:57 AM
To: Chris Pasinetti <CPasinetti@ci.enumclaw.wa.us>; 'Shook, Erika' <Erika.Shook@jacobs.com>; Douglas, Julian K (DFW) <Julian.Douglas@dfw.wa.gov>
Cc: Berejikian, Marian (DFW) <Marian.Berejikian@dfw.wa.gov>
Subject: RE: Discuss BAS Document

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Hi Everyone,

I wanted to provide a follow-up email to our meeting this week and offer resources based on our conversation. The resource attached outlines what must be considered in regard to FWHCAs. You will find Habitats of Local Importance under the Minimum Protection Guidelines (WAC 360-190-130). The checklist attached is aimed at comparing your CAO against WDFW BAS. Additional resources are provided below:

Priority Habitats and Species (PHS) Info

-

- WDFW would recommend referring to the WDFW Priority Habitats and Species (PHS) list and mapping resources by name in your city's FWHCA section, as the Washington Administrative Code refers to PHS in sections dealing with Critical Area Ordinances (WAC 365-190-130), Shoreline Master Programs (WAC 173-26-221), and the Essential Facilities Siting Evaluation Council. The state supreme court has held that PHS is a valid source of best available science for the Growth Management Act. For example, see sections of city codes that meet this standard such as: the city of Anacortes', FWHCAs, 19.70.315 Designation

Webpage: https://wdfw.wa.gov/species-habitats/at-risk/phs
Online Map: https://geodataservices.wdfw.wa.gov/hp/phs/
Map Data for internal GIS department use: https://wdfw.wa.gov/sites/default/files/2019-02/orderinformationform.pdf
Site-Potential Tree Hight ($SPTH_{200}$) Map (Riparian Management Zone (RMZ) Map): https://wdfw.maps.arcgis.com/apps/MapJournal/index.html?appid=35b39e40a2af447b9556ef1314a5622d
$SPTH_{200}$/RMZ map data for internal use: **Upon request** (let us know if you'd like this data)

All the best,

Morgan Krueger (she/her)
Regional Land Use Planner, Habitat Division
Washington Dept. of Fish and Wildlife
Region 4

Morgan.Krueger@dfw.wa.gov
206-707-5434

From: Krueger, Morgan (DFW)
Sent: Monday, January 29, 2024 1:37 PM
To: Chris Pasinetti <CPasinetti@ci.enumclaw.wa.us>; Shook, Erika <Erika.Shook@jacobs.com>; Douglas, Julian K (DFW) <Julian.Douglas@dfw.wa.gov>
Cc: Berejikian, Marian (DFW) <Marian.Berejikian@dfw.wa.gov>; Whittaker, Kara A (DFW) <Kara.Whittaker@dfw.wa.gov>
Subject: RE: Discuss BAS Document

Hi Everyone,

Thanks for putting this together Julian and Chris! I wanted to provide a loose agenda for our meeting tomorrow, particularly to provide resources concerning the BAS brought up in the consultant's report. You'll find plenty of links and documents that are noted in the FWHCAs section of the consultant's report. Looking forward to our conversation tomorrow.

All the best,

Morgan Krueger (she/her)
Regional Land Use Planner, Habitat Division
Washington Dept. of Fish and Wildlife
Region 4

Morgan.Krueger@dfw.wa.gov
206-707-5434

-----Original Appointment-----
From: Chris Pasinetti <CPasinetti@ci.enumclaw.wa.us>
Sent: Monday, January 29, 2024 11:42 AM
To: Chris Pasinetti; Shook, Erika; Krueger, Morgan (DFW); Douglas, Julian K (DFW)
Subject: Discuss BAS Document
When: Tuesday, January 30, 2024 10:00 AM-11:00 AM (UTC-08:00) Pacific Time (US & Canada).
Where: Microsoft Teams Meeting

External Email

Meeting to get input on the BAS document.

Microsoft Teams meeting

Join on your computer, mobile app or room device
Click here to join the meeting

Meeting ID: 275 458 410 322
Passcode: 79TVqK
Download Teams | Join on the web

Or call in (audio only)
+1 253-666-8667,,928969063# United States, Tacoma
Phone Conference ID: 928 969 063#
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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

Updated July 2020

Riparian Ecosystems, Volume 1: Science Synthesis and Management Implications

Published May 2018, updated July 2020

Technical Editors
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George F. Wilhere
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Production Manager
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Accessibility:
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.

Acknowledgements

Many people were involved with the creation of this document. WDFW would like to acknowledge the Washington Department of Ecology and US Environmental Protection Agency for the funds that made this document possible. Contract planning and budgeting for this work was led by Keith Folkerts. We appreciatively acknowledge the participation of our Technical Advisory Group:

Nichole Embertson, PhD	Whatcom Conservation District
Martin Fox, PhD	Muckleshoot Tribe
Aimee Fullerton, PhD	NOAA Fisheries
Marc Hayes, PhD	WA Department of Fish and Wildlife
Tim Hyatt	Skagit River System Cooperative
Jack Janisch	WA Department of Ecology
Peter Leinenbach	US Environmental Protection Agency
Chris May, PhD	Kitsap County
Michael Pollock, PhD	NOAA Fisheries
Jeremy Sikes	WA Department of Ecology
Carol Smith, PhD	WA State Conservation Commission
Steve Wondzell, PhD	US Forest Service

The scientific rigor of this document was improved through the peer review provided by the Washington State Academy of Sciences, with coordination provided by Dr. Robert Bates. Draft versions of this document were reviewed by numerous staff in state agencies, including the Department of Ecology, Department of Natural Resources, Department of Commerce, Recreation and Conservation Office, State Conservation Commission, and Puget Sound Partnership. These reviews improved the document and we appreciate the helpful feedback. We also appreciate the reviews by federal and tribal entities including EPA, NOAA Fisheries, Northwest Indian Fisheries Commission, Columbia River Inter-Tribal Fish Commission, Upper Columbia United Tribes, and individual tribes. We express our appreciation for all local governments and individuals who provided feedback during our public comment period. Finally, thank you to Peggy Ushakoff for creating graphics that help us better portray the science.

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).

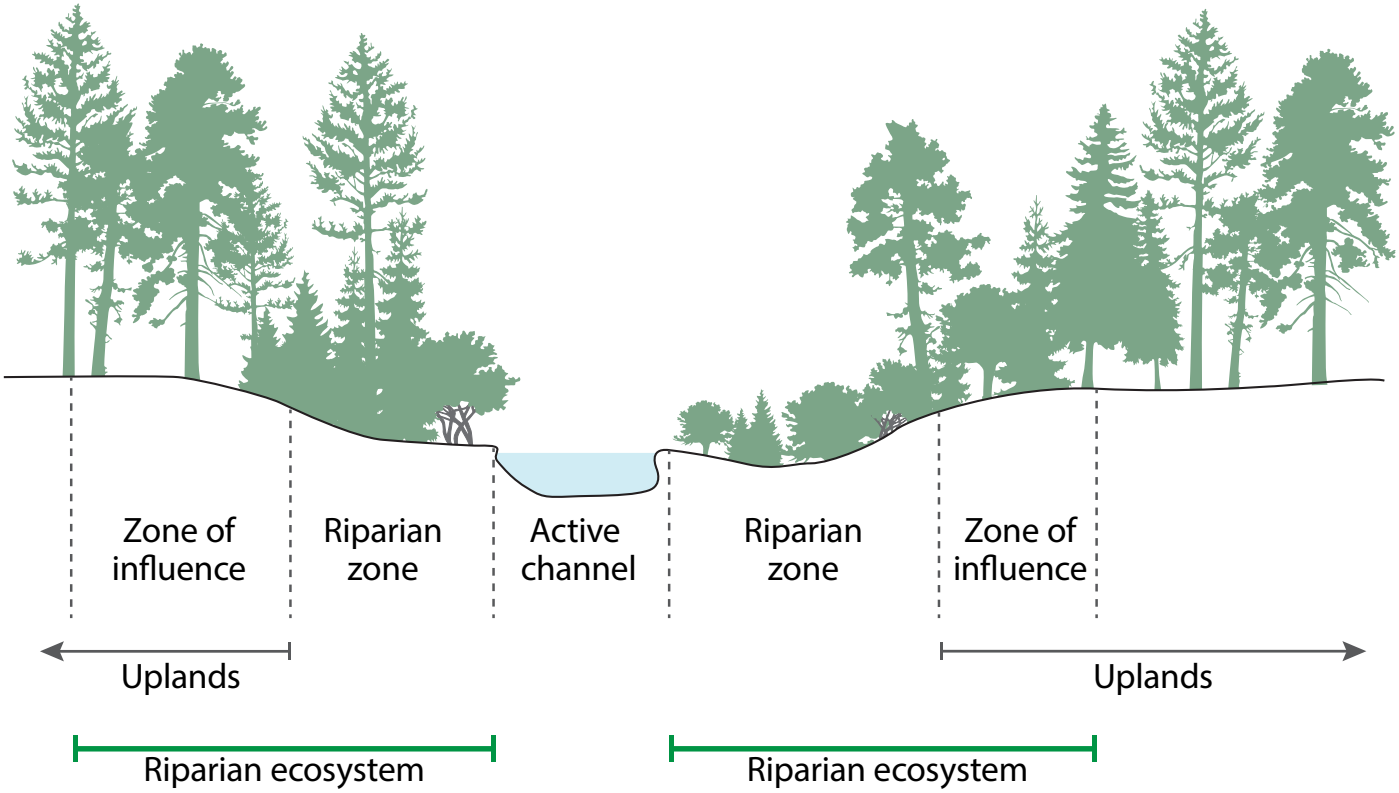
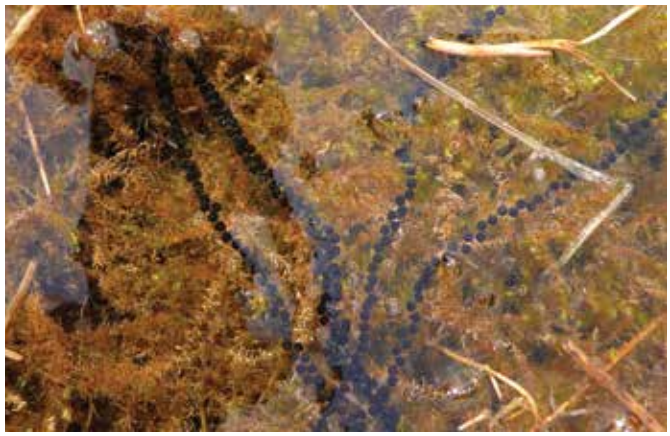


Figure 1.1. A generalized diagram of the riparian ecosystem. The NRC (2002) states that, "Riparian areas are transitional between terrestrial and aquatic ecosystems and are distinguished by gradients in biophysical conditions, ecological processes, and biota. They are areas through which surface and 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

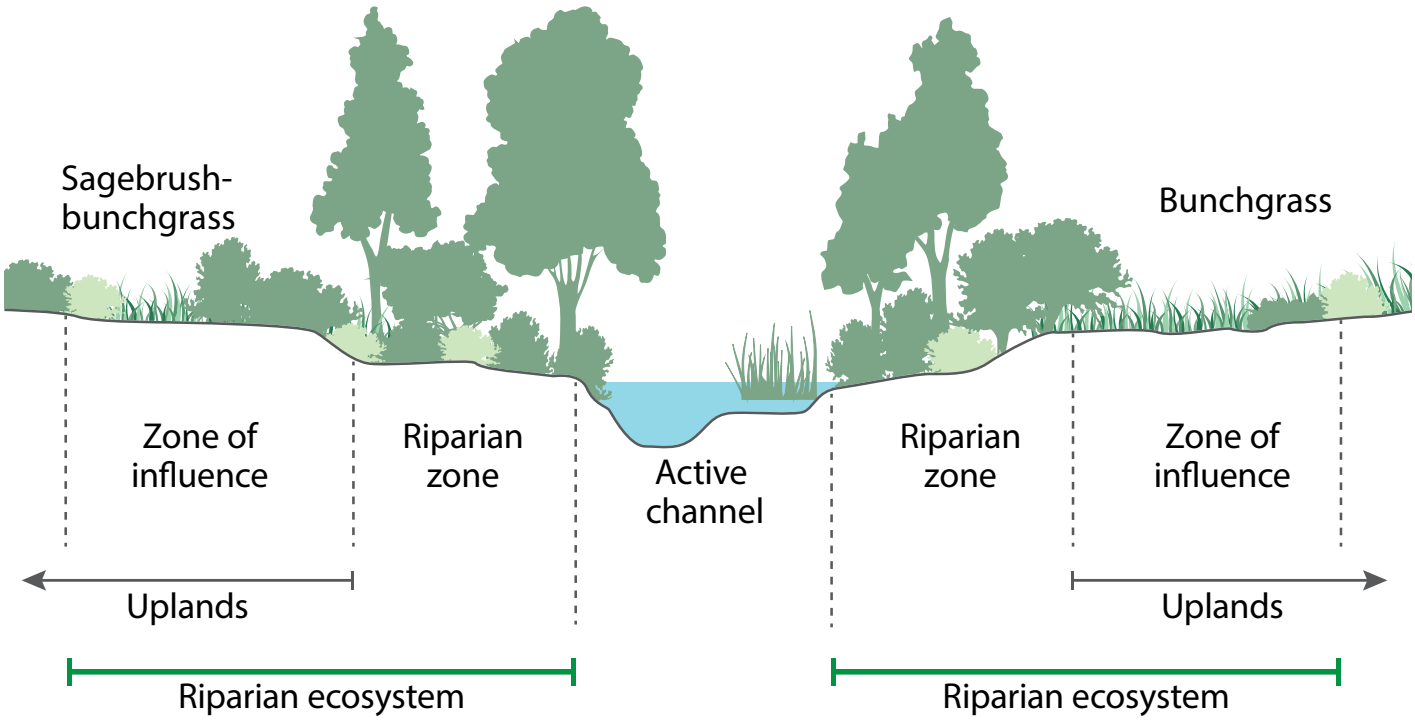


Figure 1.2. Dryland Riparian Ecosystem. The riparian ecosystem consists of two zones: riparian and zone of influence. The riparian zone extends from the edge of the active channel towards the uplands. This zone includes areas where terrestrial biota and soils are influenced, at least periodically, by 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.

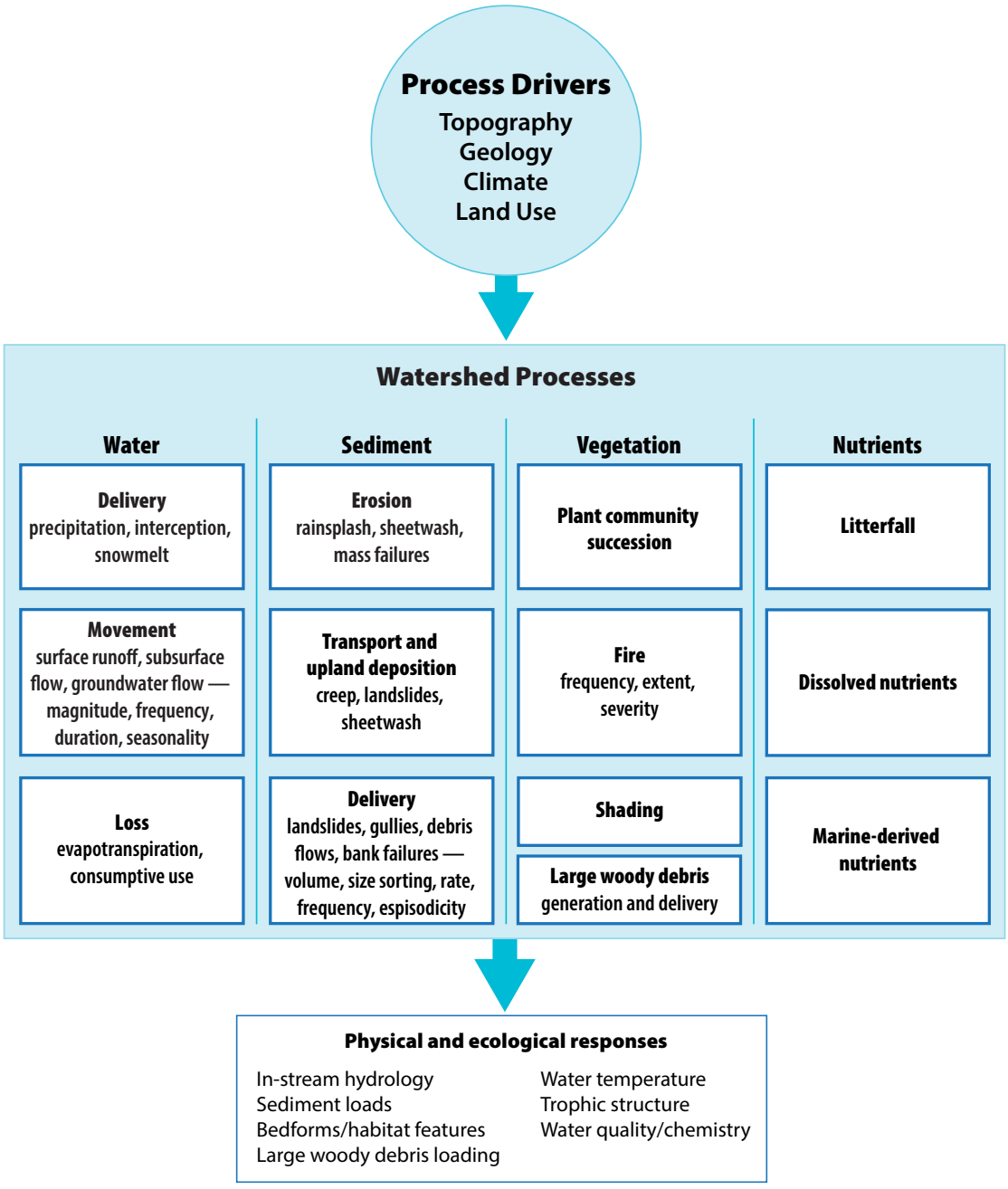


Figure 1.3. Conceptual framework for the hierarchical relationship of invariant, large-scale "process drivers," the suite of watershed processes that are determined by these drivers, and the instream physical and biological responses to those processes. Multiple additional interactions between elements 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.

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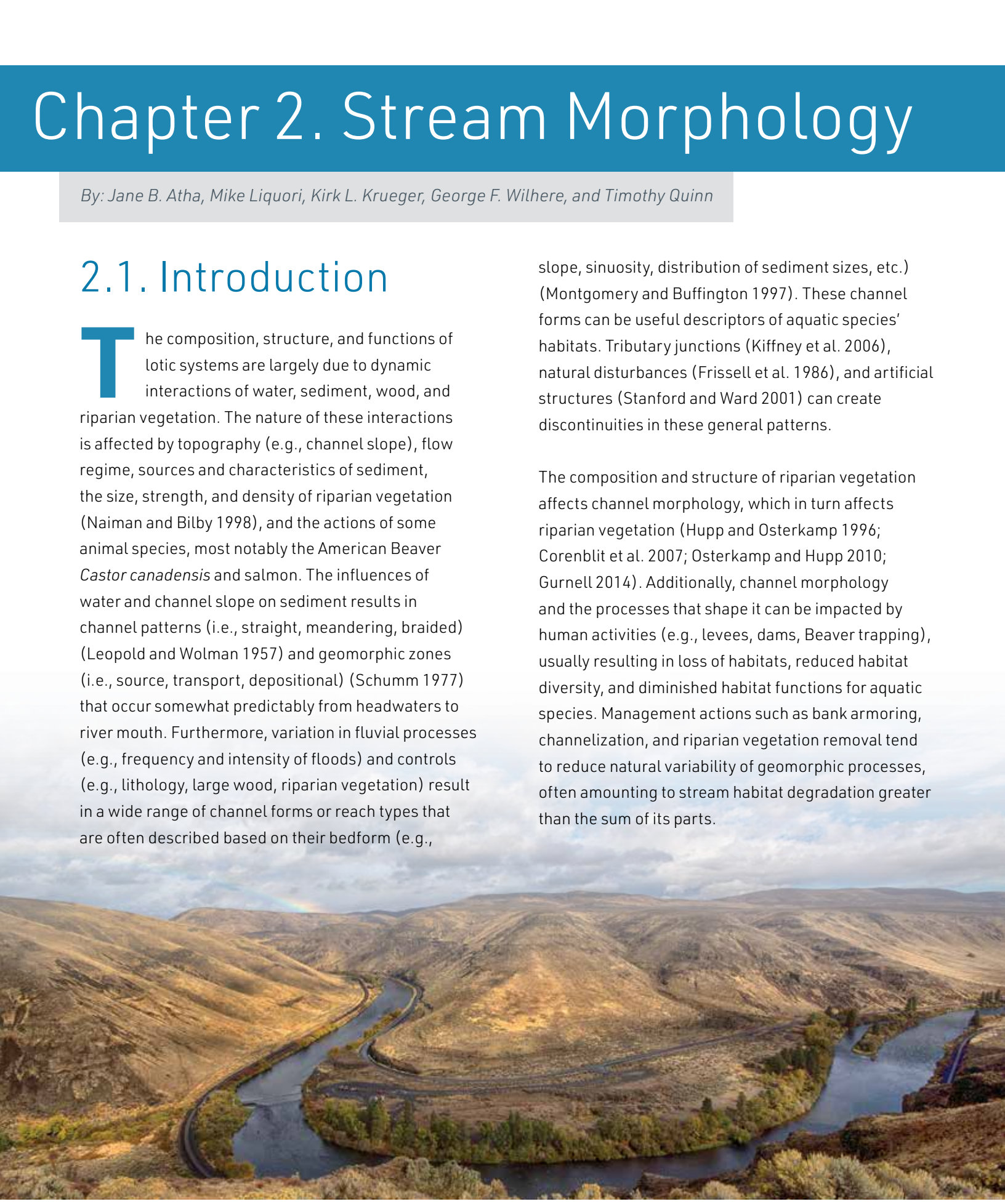
Chapter 2. Stream Morphology

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).

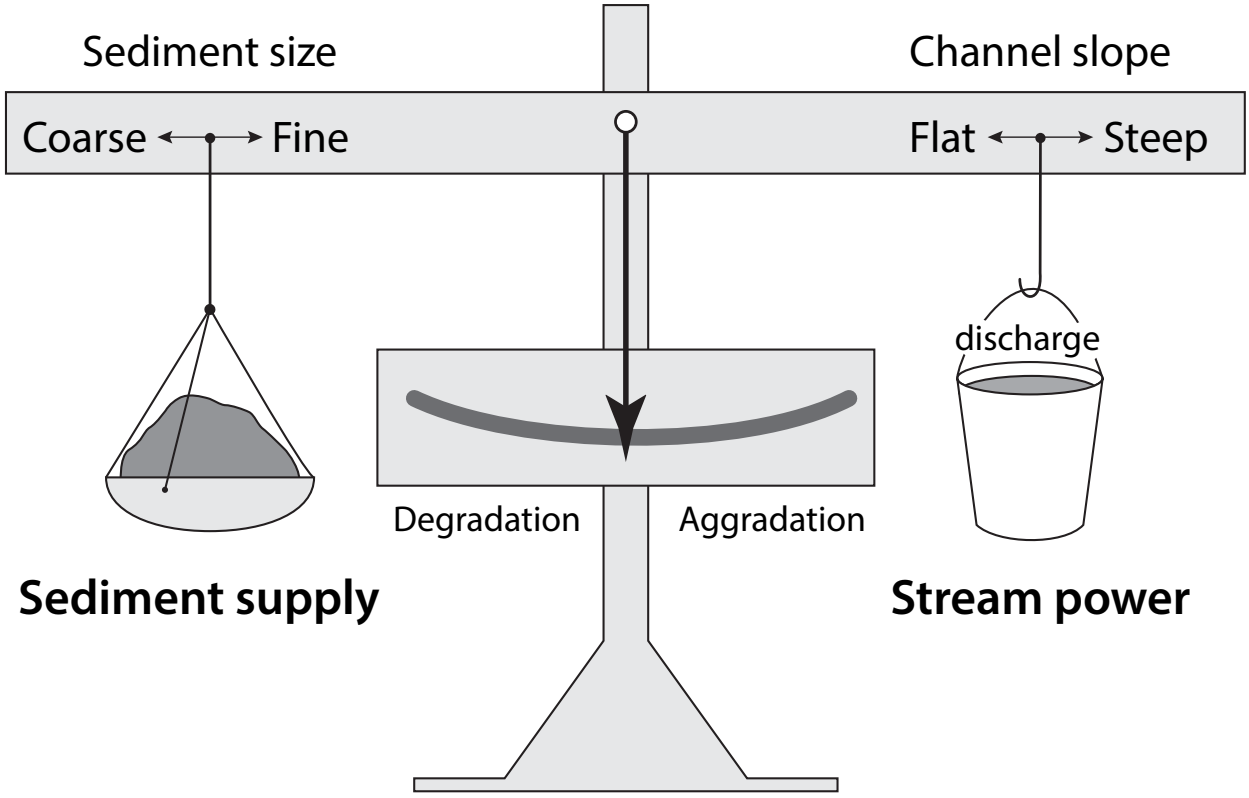


Figure 2.1. Lane's Balance illustrating the concept of channel adjustment (i.e., vertical aggradation or degradation of the streambed) in response to changes in water or sediment yield (from Dust and Wohl 2012).

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.

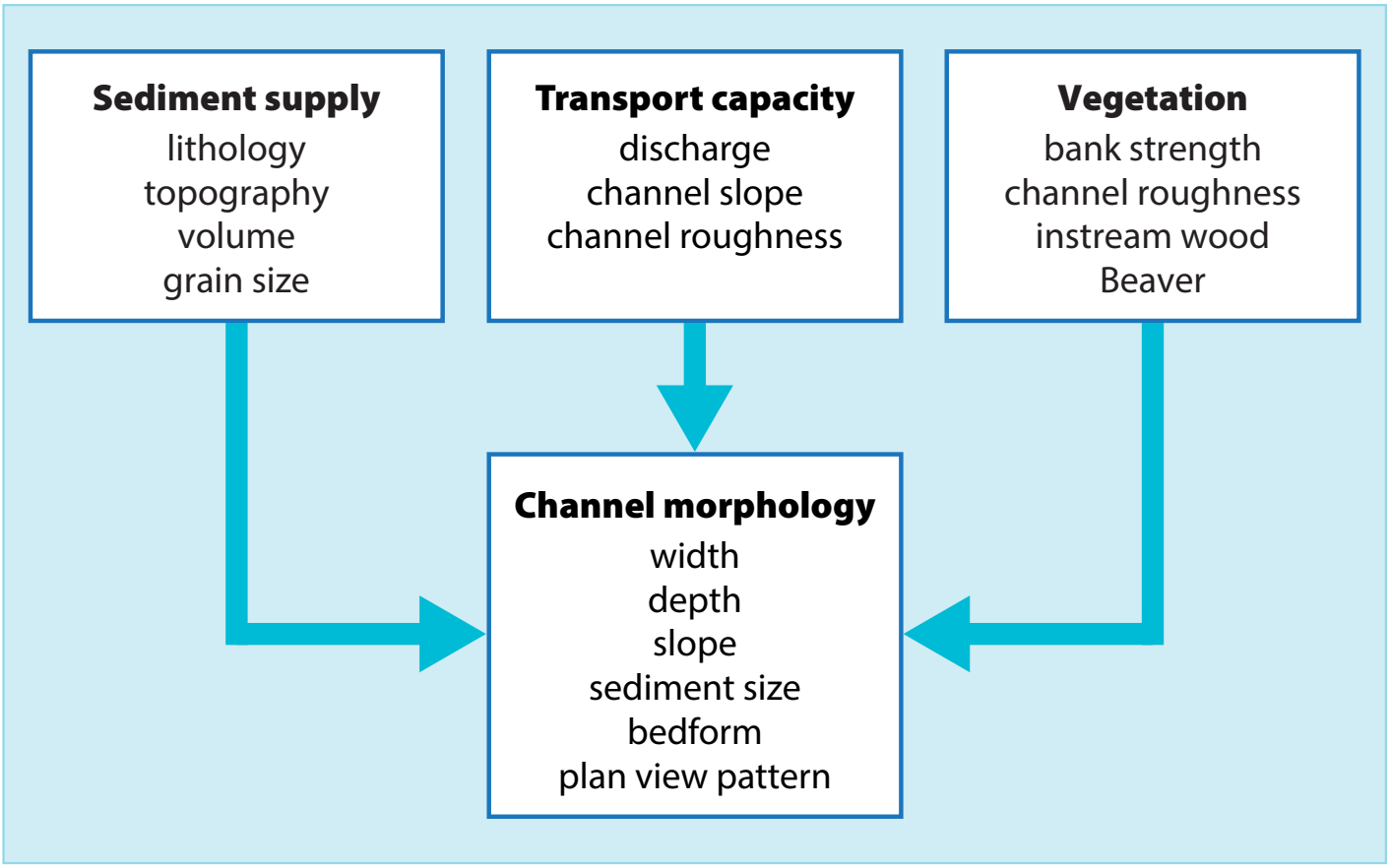


Figure 2.2. Influences on channel morphology (modified from Naiman and Bilby 1998).

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).

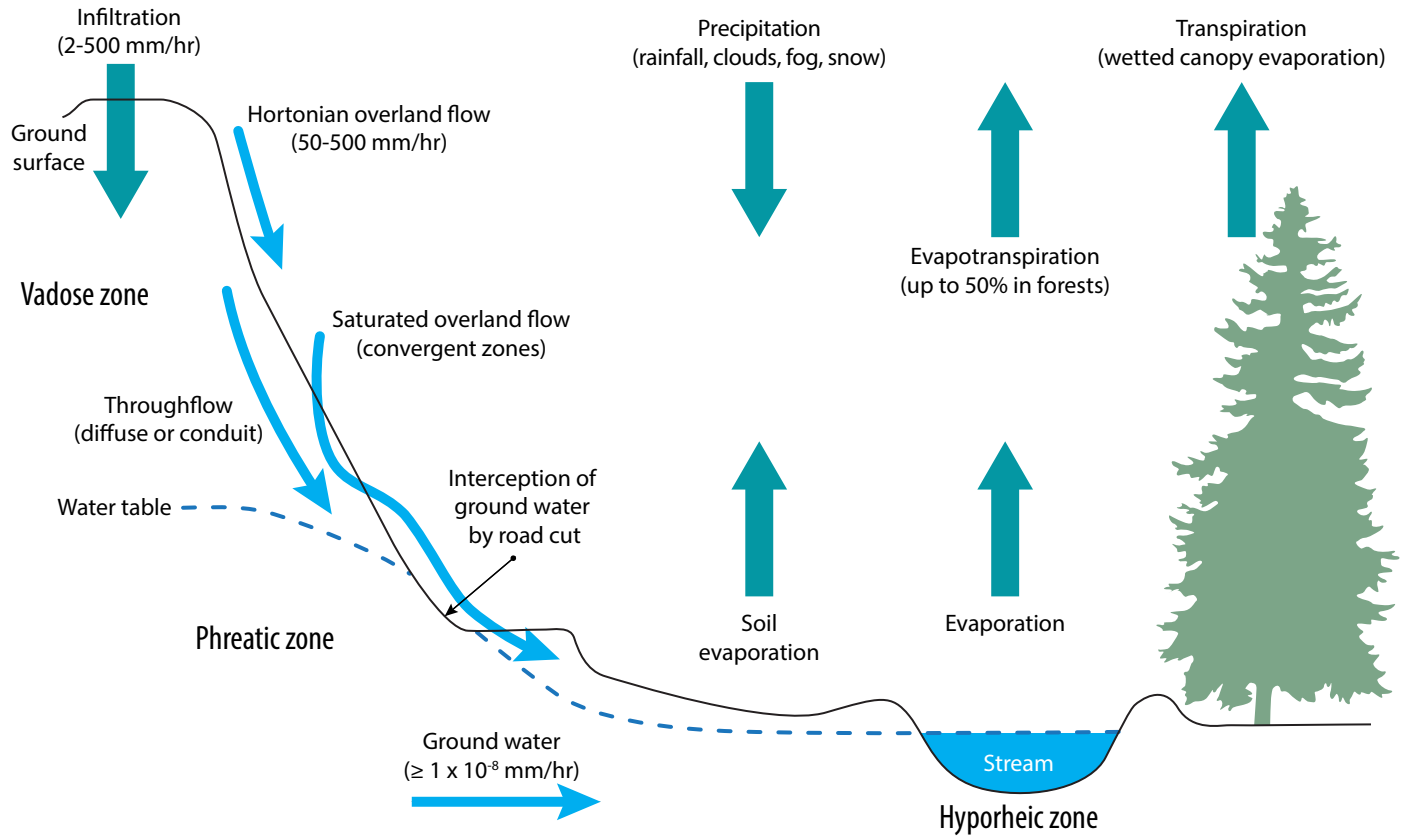


Figure 2.3. Illustration of different types and rates of downslope movement of water on a hillslope (modified from Ziemer and Lisle 1998, and Wohl 2014).

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

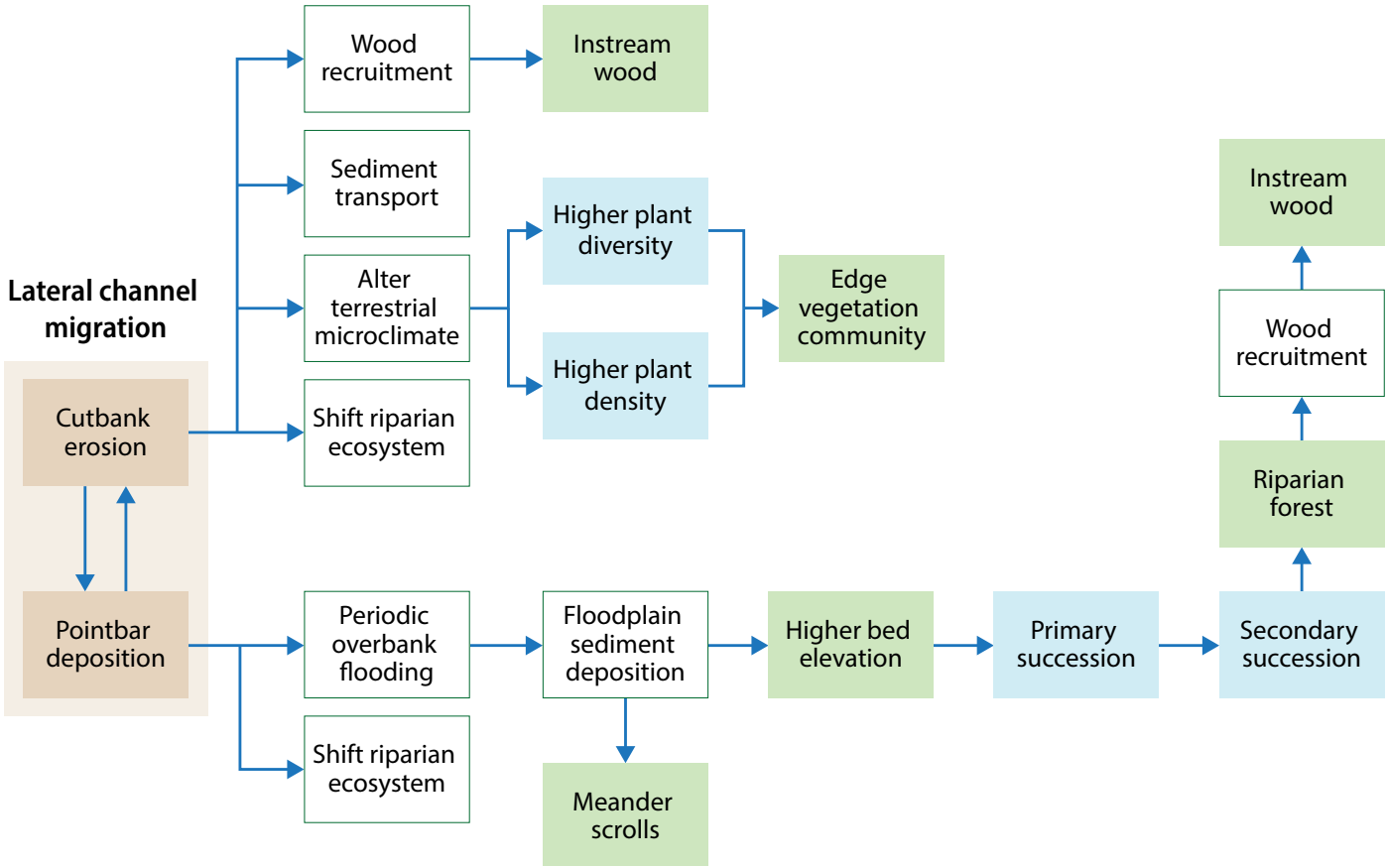
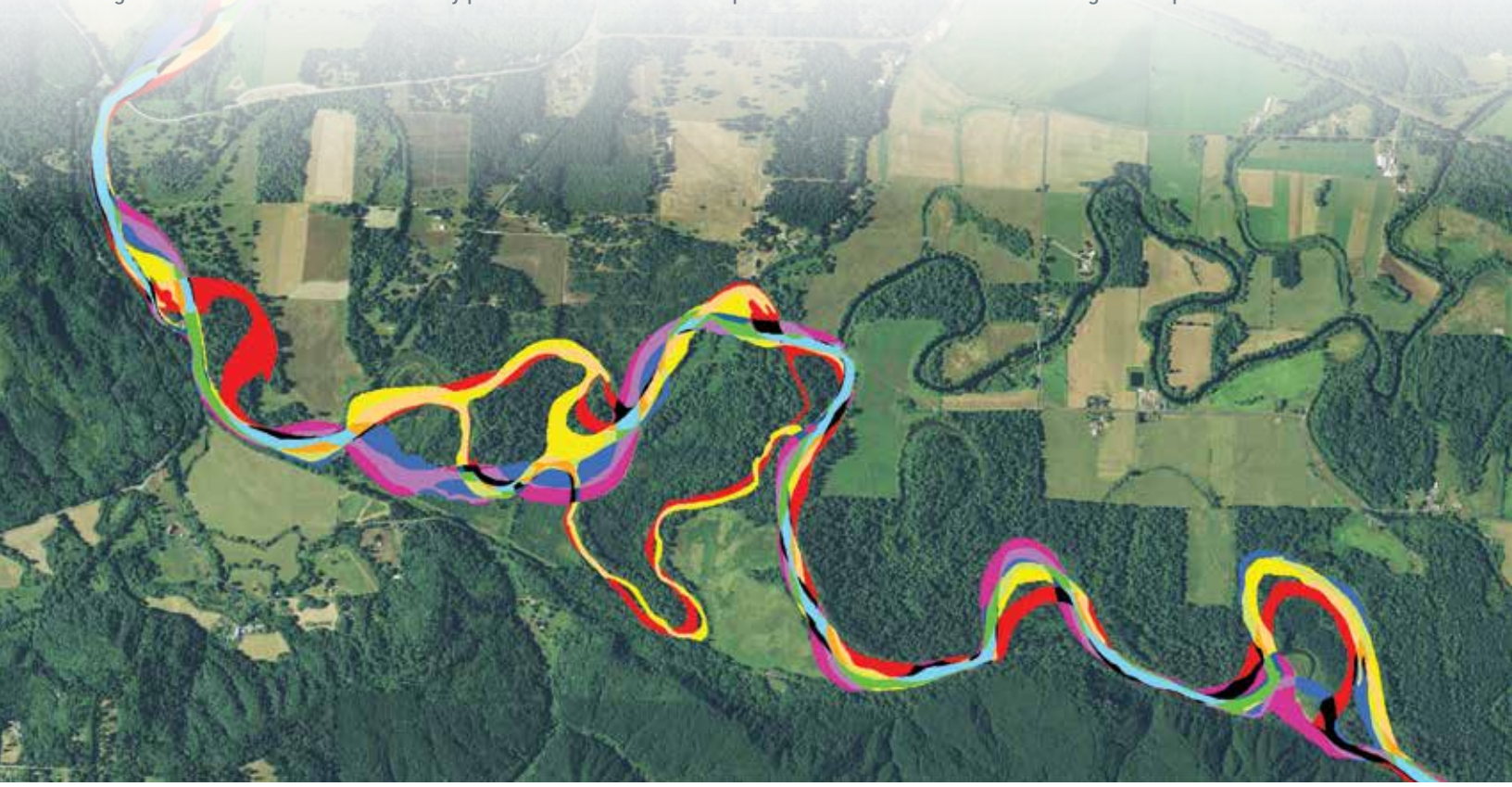


Figure 2.4. A conceptual model of lateral channel migration processes and riparian forest responses (modified from Meitzen 2009). Arrows indicate the hypothesized directions of causal relationships. Brown boxes represent proximal processes leading to channel migration. White boxes are secondary processes. Green boxes depict structures. Blue boxes are biological responses.



Chehalis River meander paths between 1938 and 2013/Ken Pierce, WDFW

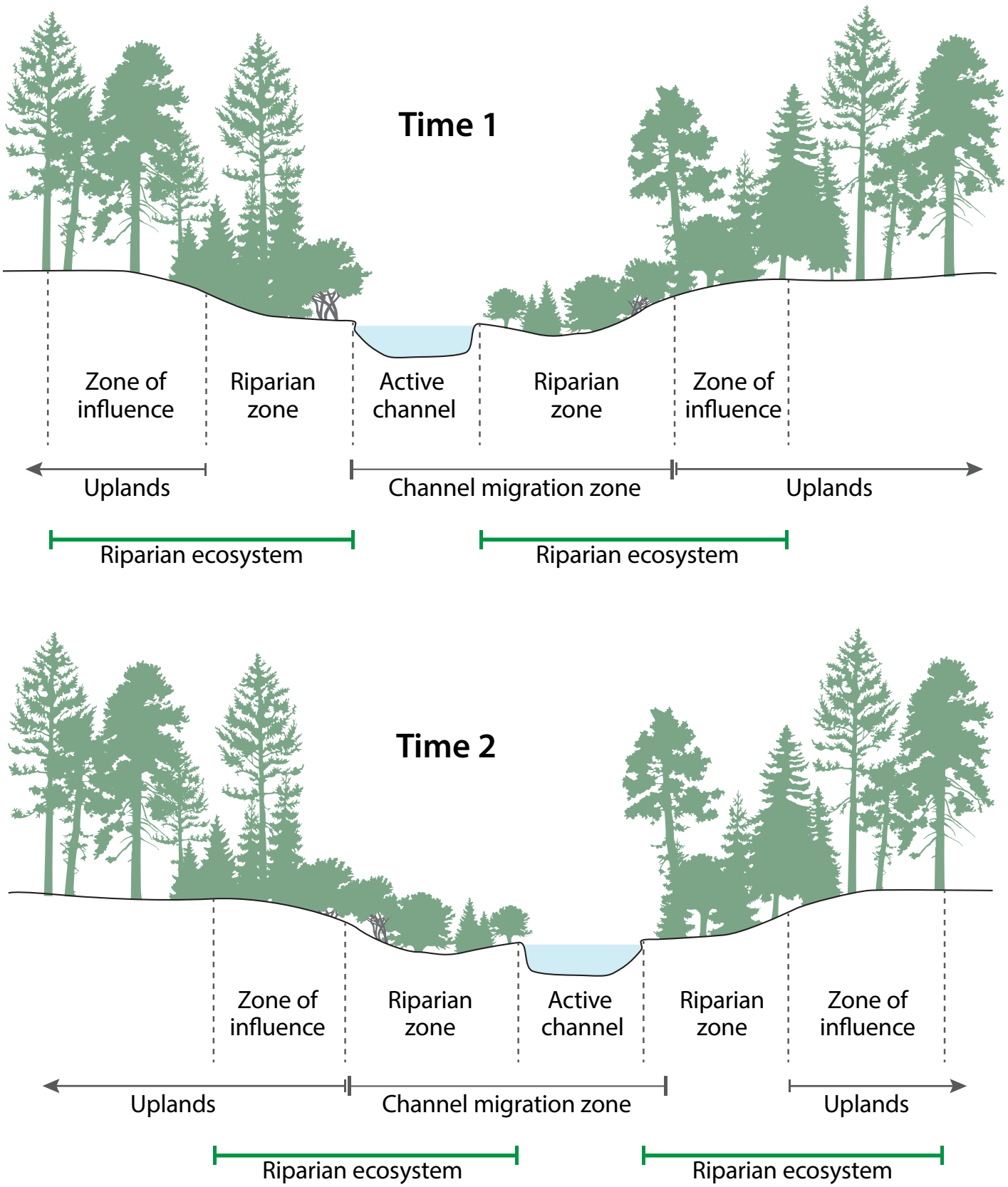


Figure 2.5. Spatial relationships between the riparian ecosystem and channel migration zone (CMZ) over time. As the active channel moves laterally within the CMZ the riparian ecosystem moves with it. Time 1 and time 2 could be separated by days or centuries.

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

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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

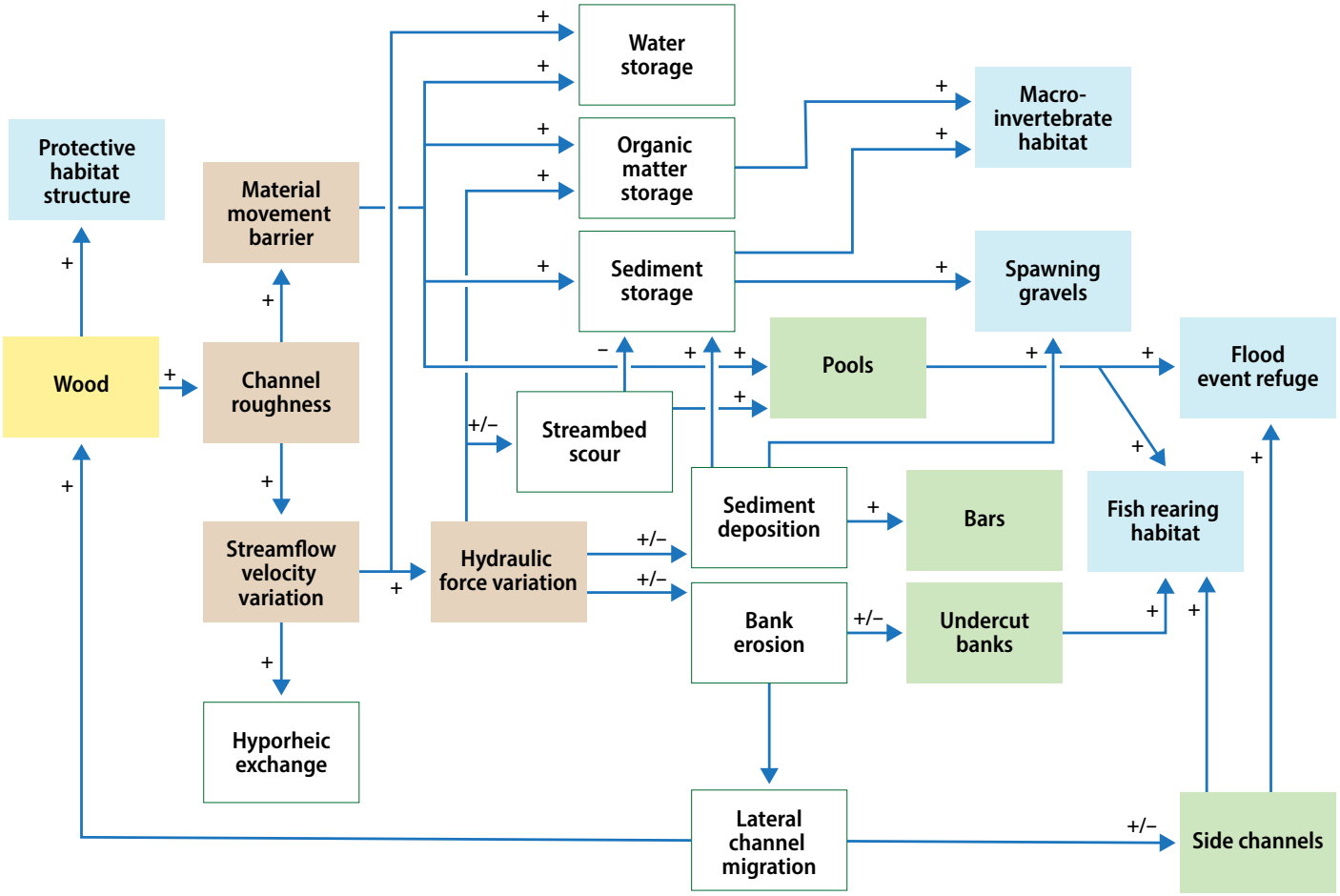

Figure 3.1. Conceptual model depicting the effects of wood on fluvial systems and fish habitats. Arrows indicate the hypothesized directions of causal relationships; pluses and minuses indicate the hypothesized slope of each relationship. Brown boxes represent direct effects of wood on fluvial processes. 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

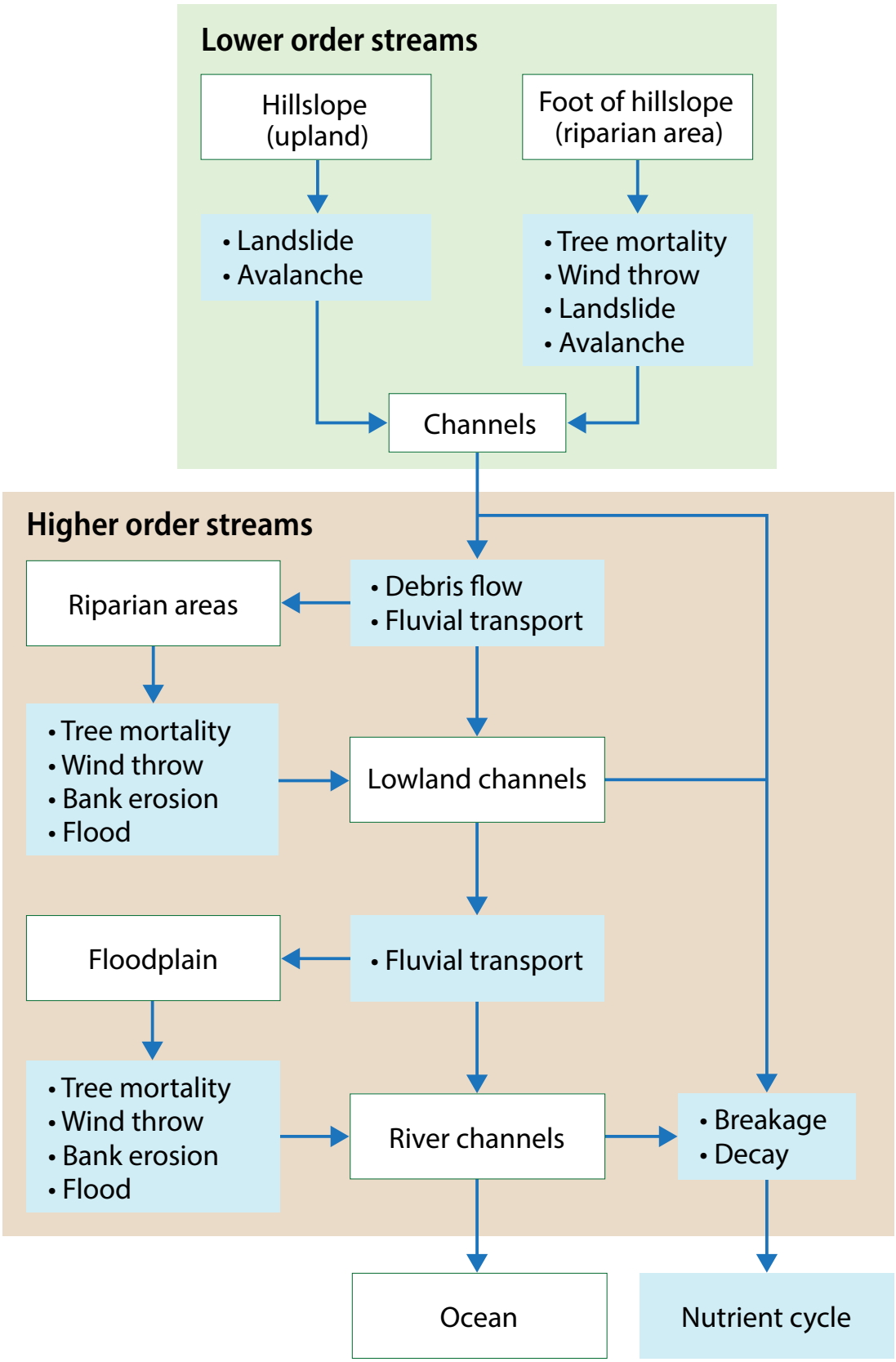

Figure 3.4. Wood recruitment mechanisms and wood transport pathways (adapted from Hassan et al. 2005). Lower order streams are first and second order headwaters. White and blue boxes are ecosystem structures and processes, respectively.

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

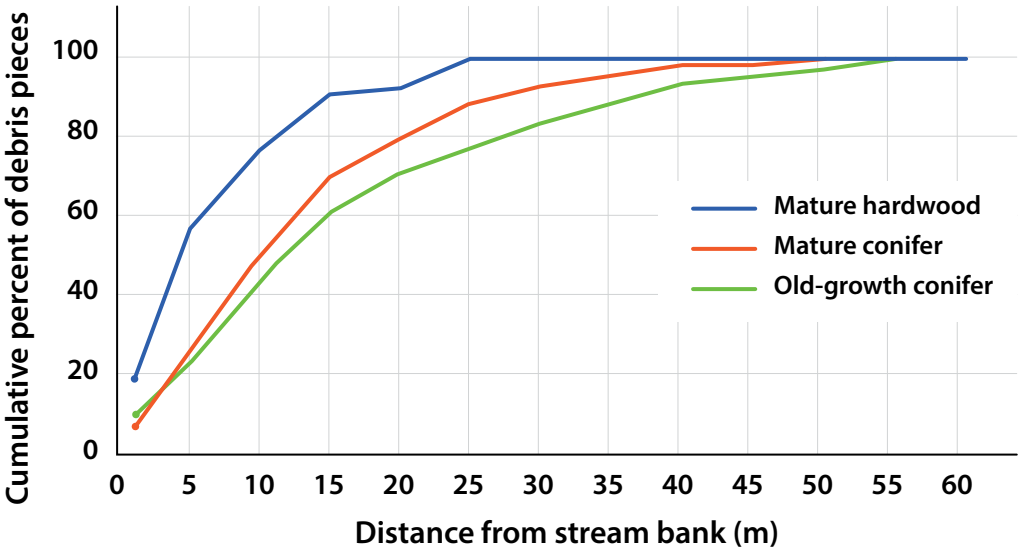

Figure 3.5. Distribution of source distances from tree origin to streambank. Empirically derived curves for old-growth conifer, mature conifer, and mature hardwood stands in western Oregon and Washington (from McDade et al. 1990). Empirically derived curves based on large wood with an identified source. 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).

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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.

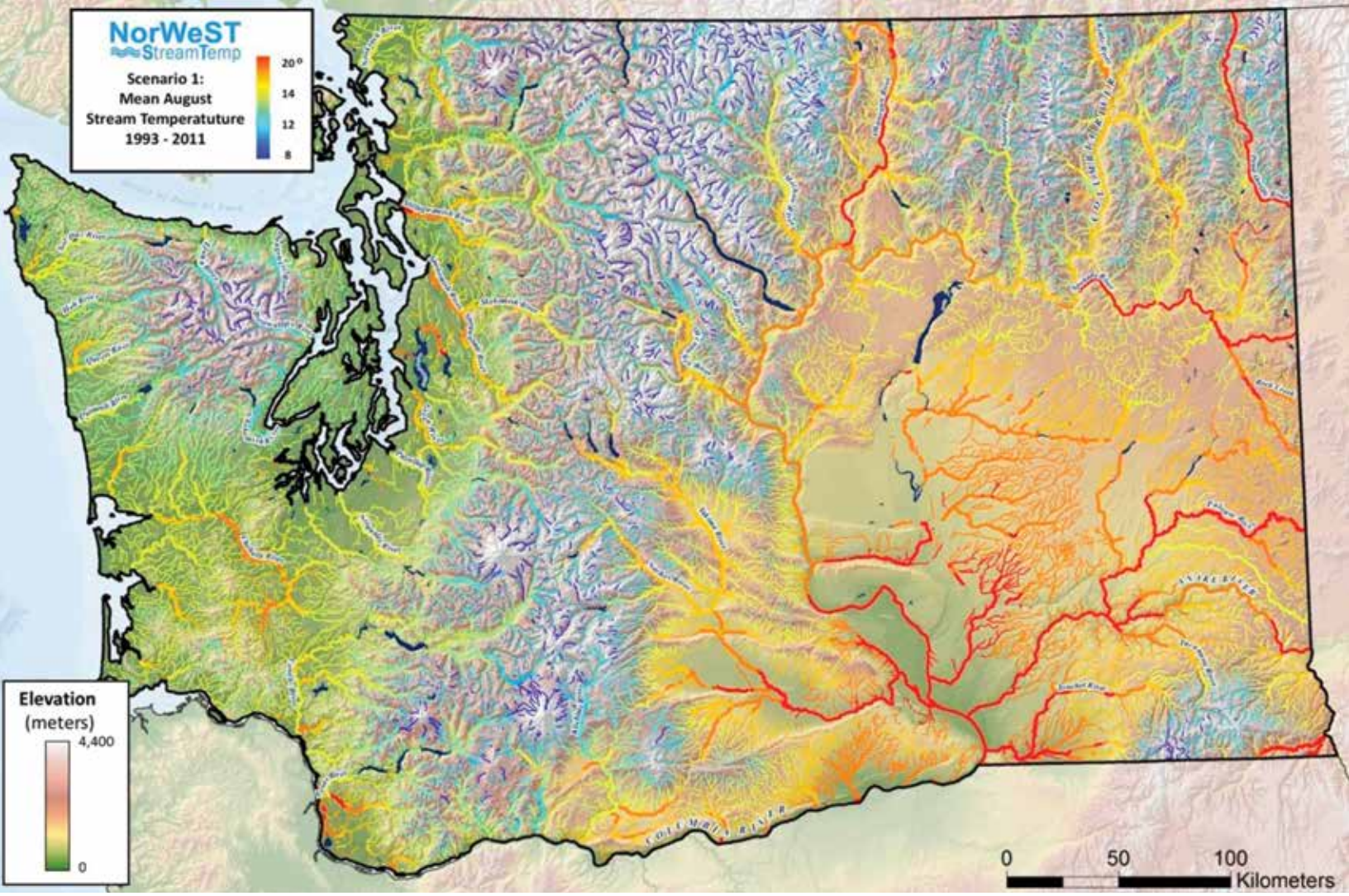

Figure 4.1. Stream thermalscape showing mean August temperatures for 66,236 kilometers (41,157 miles) of streams across Washington that was developed in the NorWeST project (poster available here: http://www.fs.fed .us/rm/boise/AWAE/projects/stream_temp/downloads/14NorWeST_WashingtonStreamTemperatureMap.pdf). 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

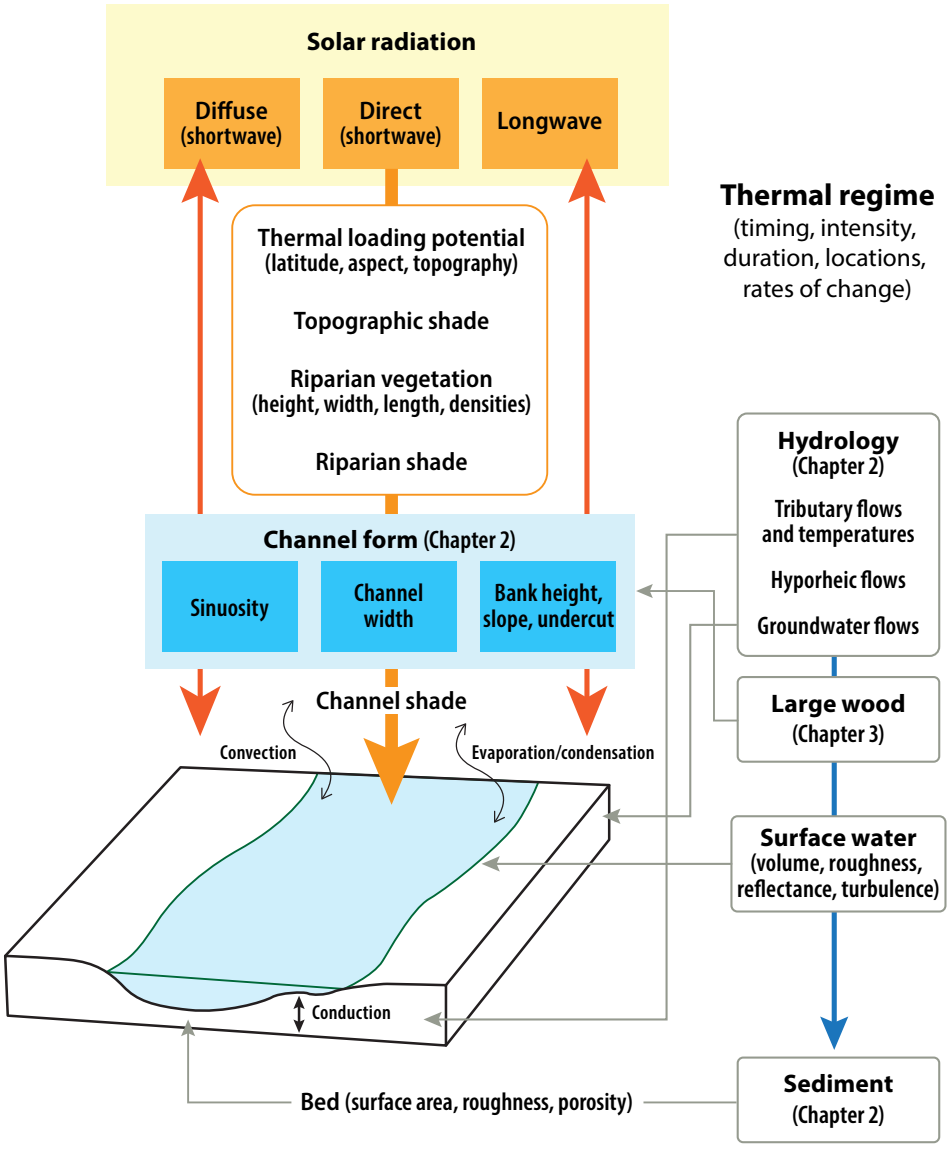

Figure 4.2. Conceptual model that identifies some factors that affect the thermal regime of stream networks. Relative importance is noted by line weight and arrows indicate directions of flows. Note that most of the elements in the model are influenced by human activities and that many components and 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

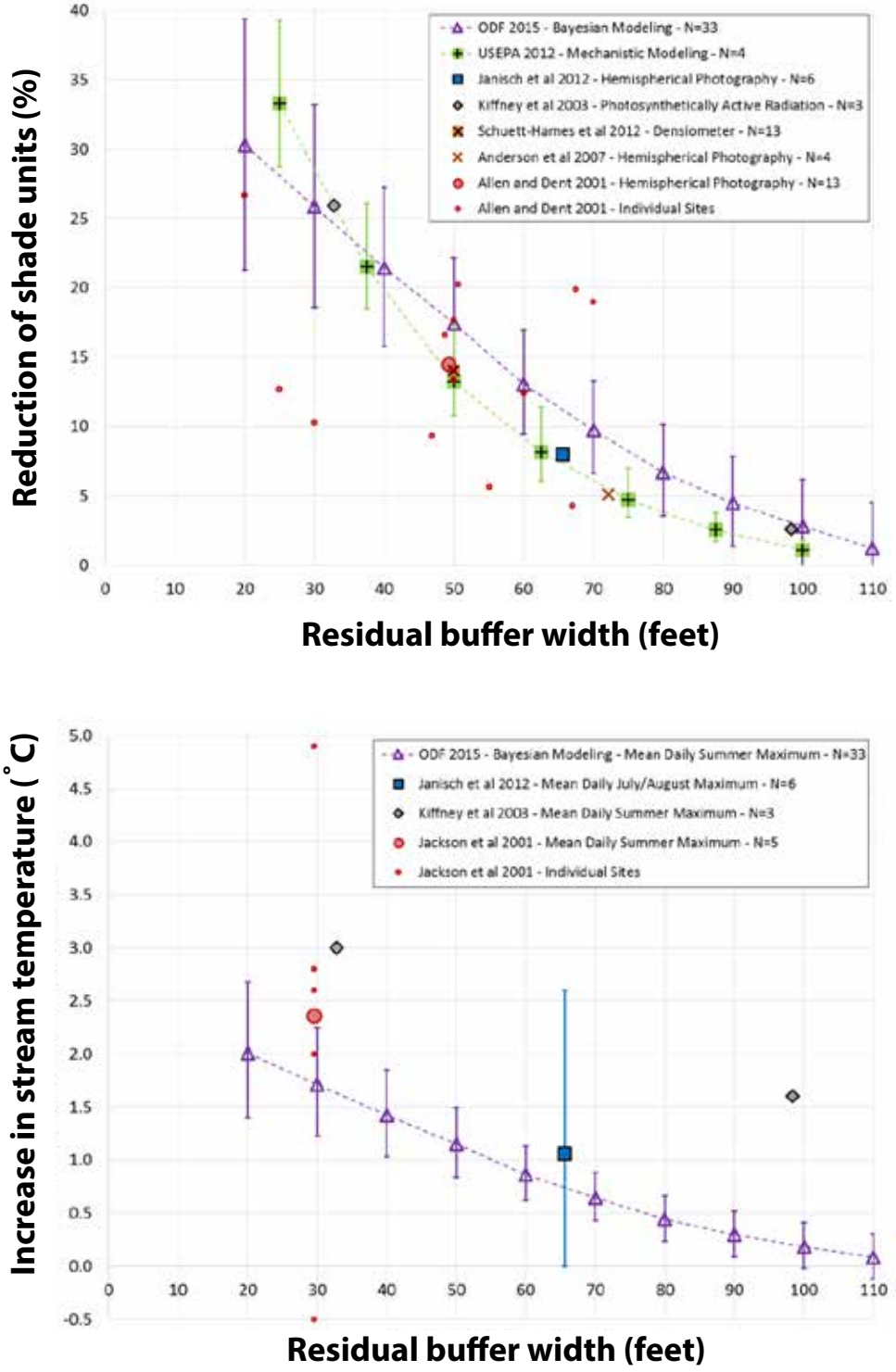

Figure 4.3. Observed shade (a: top panel) and temperature response (b: bottom panel) associated with "no-cut" riparian buffers with adjacent clearcut harvest. Only studies that employed a Before-After-Control-Impact design and conducted in Pacific Northwest forests are included. Shade unit is percent 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.

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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).

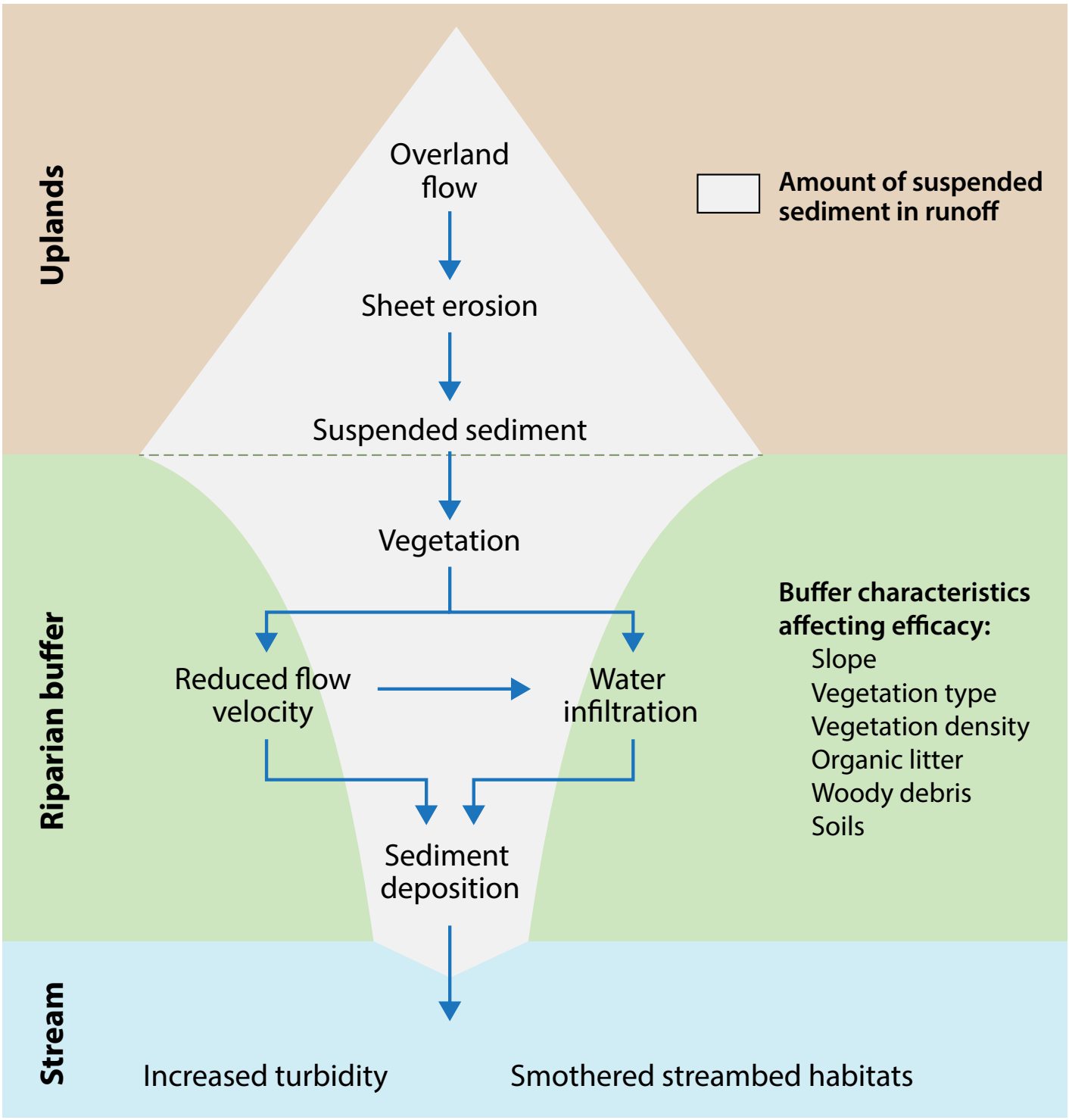


Figure 5.1 Efficacy of riparian buffer in removal of sediment from runoff. The amount of suspended sediment in runoff increases through sheet erosion of upland soils. Vegetation, woody debris, and organic litter in riparian buffer reduce flow velocity. Reduced flow velocity and increased water infiltration 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

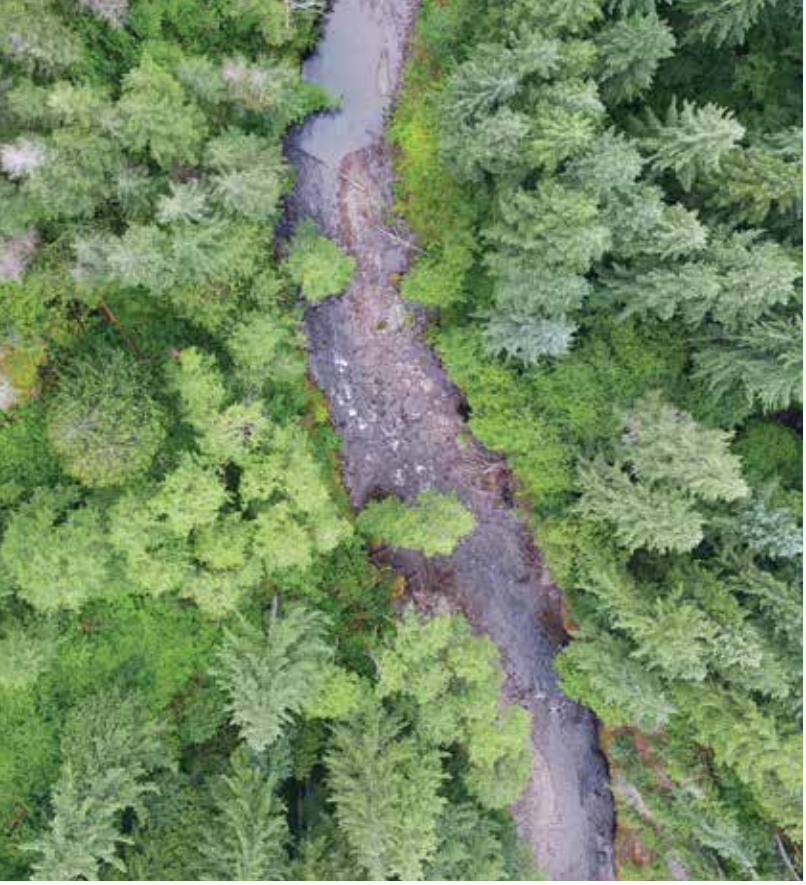
salinity. Carbonates in riparian soils promote metal retention by buffering acidity (i.e., preventing increased acidity), limiting metal solubility, and forming insoluble precipitates with metals.

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.

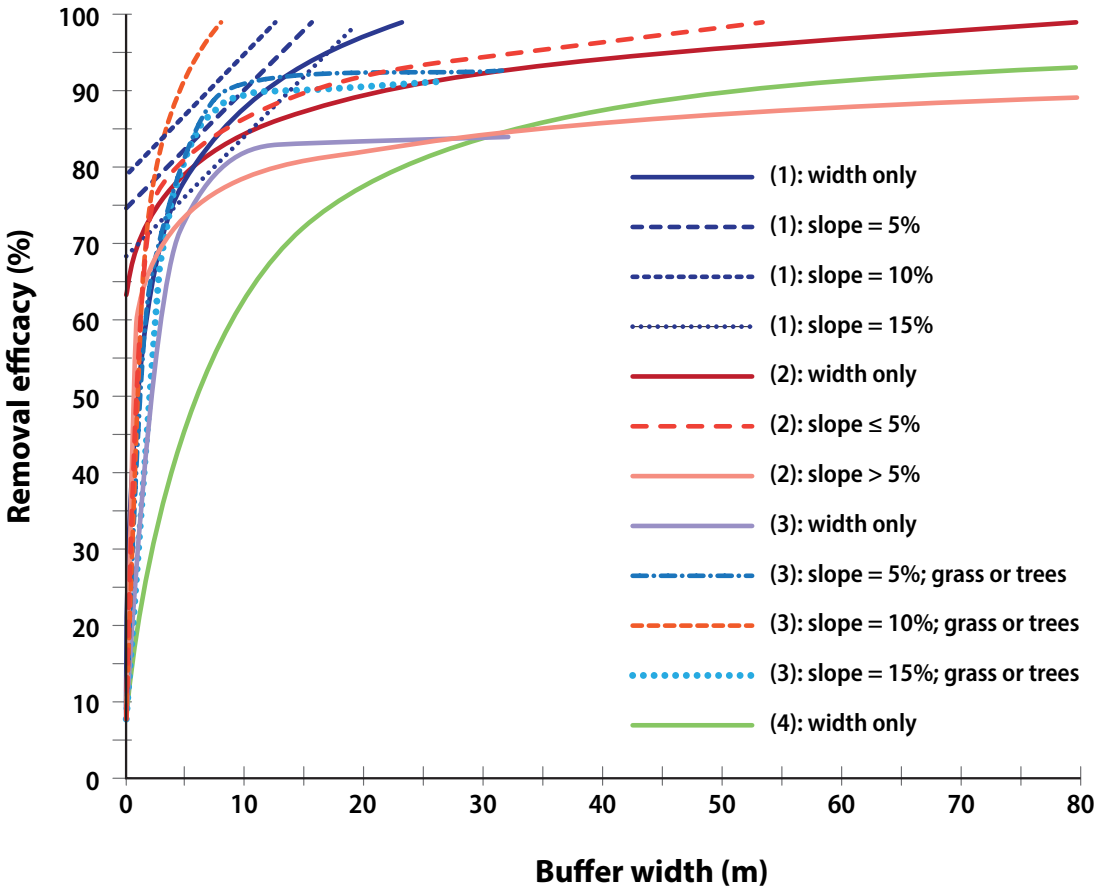


Figure 5.2. Relationships between sediment removal efficacy and riparian buffer width developed by four separate meta-analyses. Numbers in parentheses refer to different meta-analyses. See descriptive information in Table 5.1.

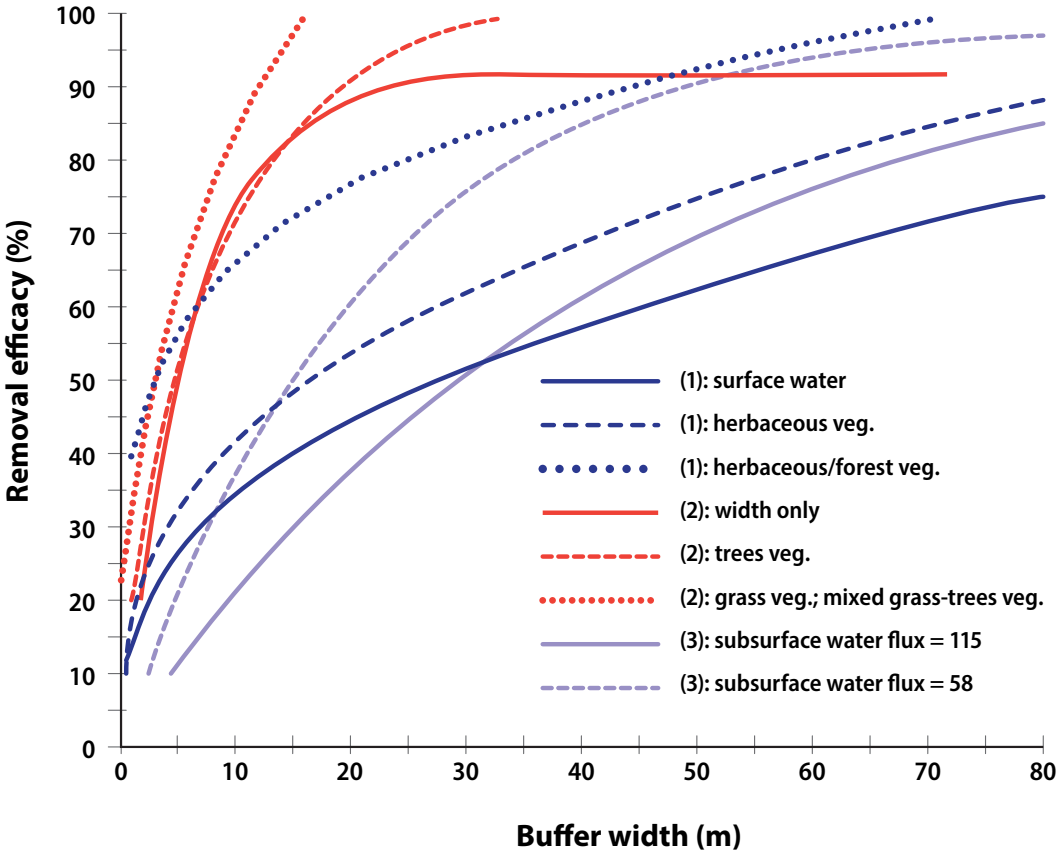


Figure 5.3. Relationships between nitrogen removal efficacy and riparian buffer width developed by three separate meta-analyses. Numbers in parentheses refer to different meta-analyses. See descriptive information in Table 5.1.

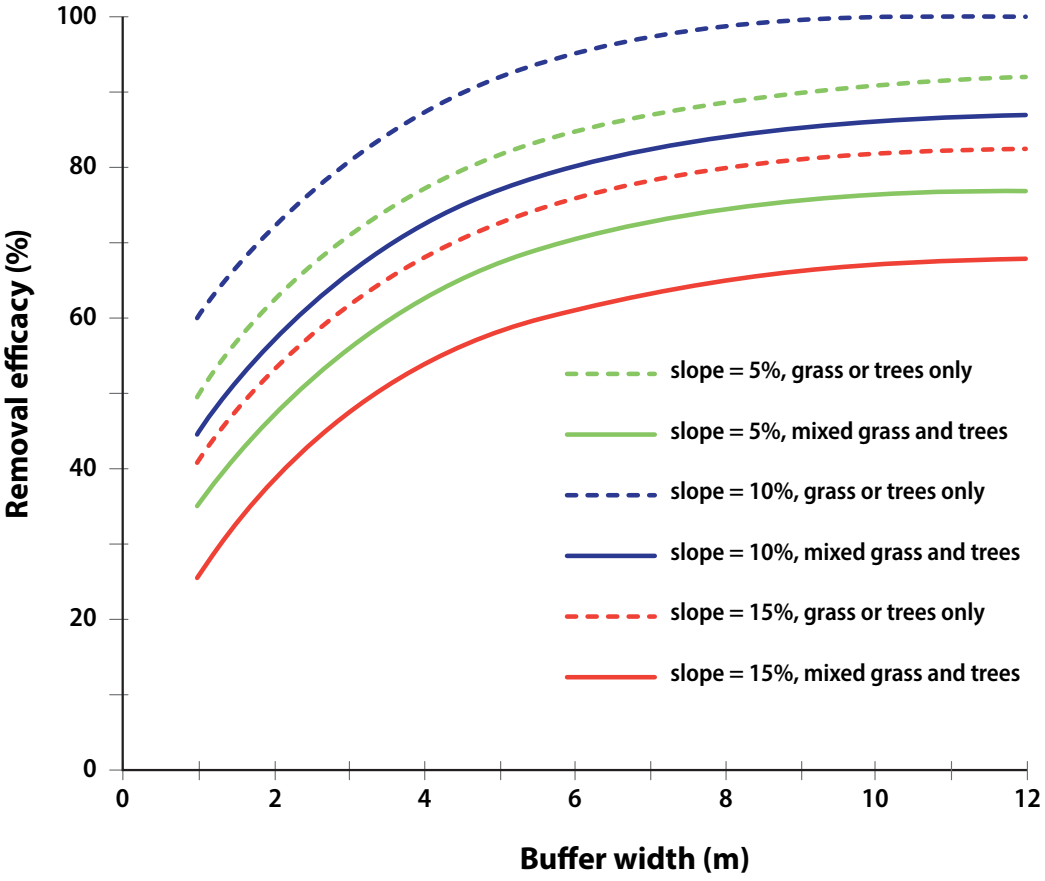


Figure 5.4. A result from meta-analysis of Zhang et al. (2010). Sediment removal efficacy as a function of buffer width, site slope, and buffer vegetation ($N = 81$, $R^2 = 0.65$, $P < 0.001$).

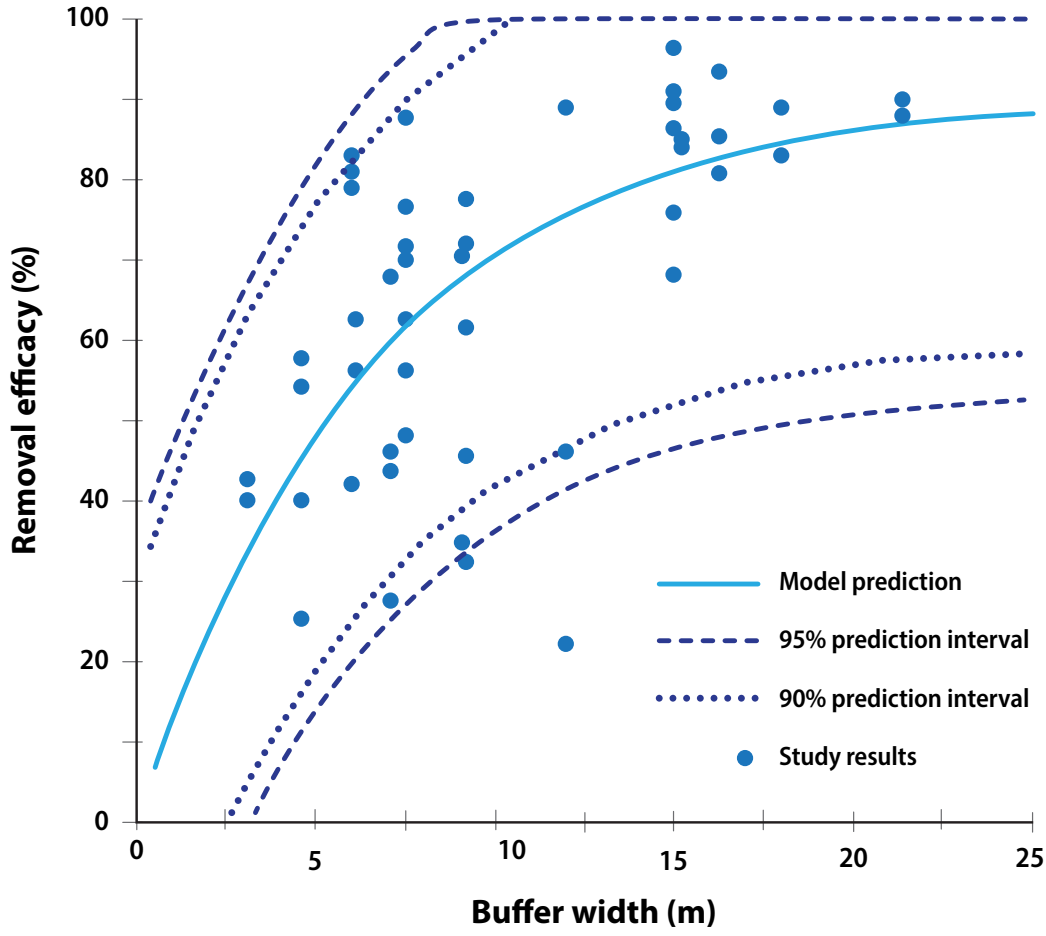


Figure 5.5. Meta-analysis of Zhang et al. (2010). Results of nonlinear regression for phosphorus removal efficacy as a function of buffer width ($N = 52$, $R^2 = 0.35$, $P < 0.0001$) with 90% and 95% prediction intervals.

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).

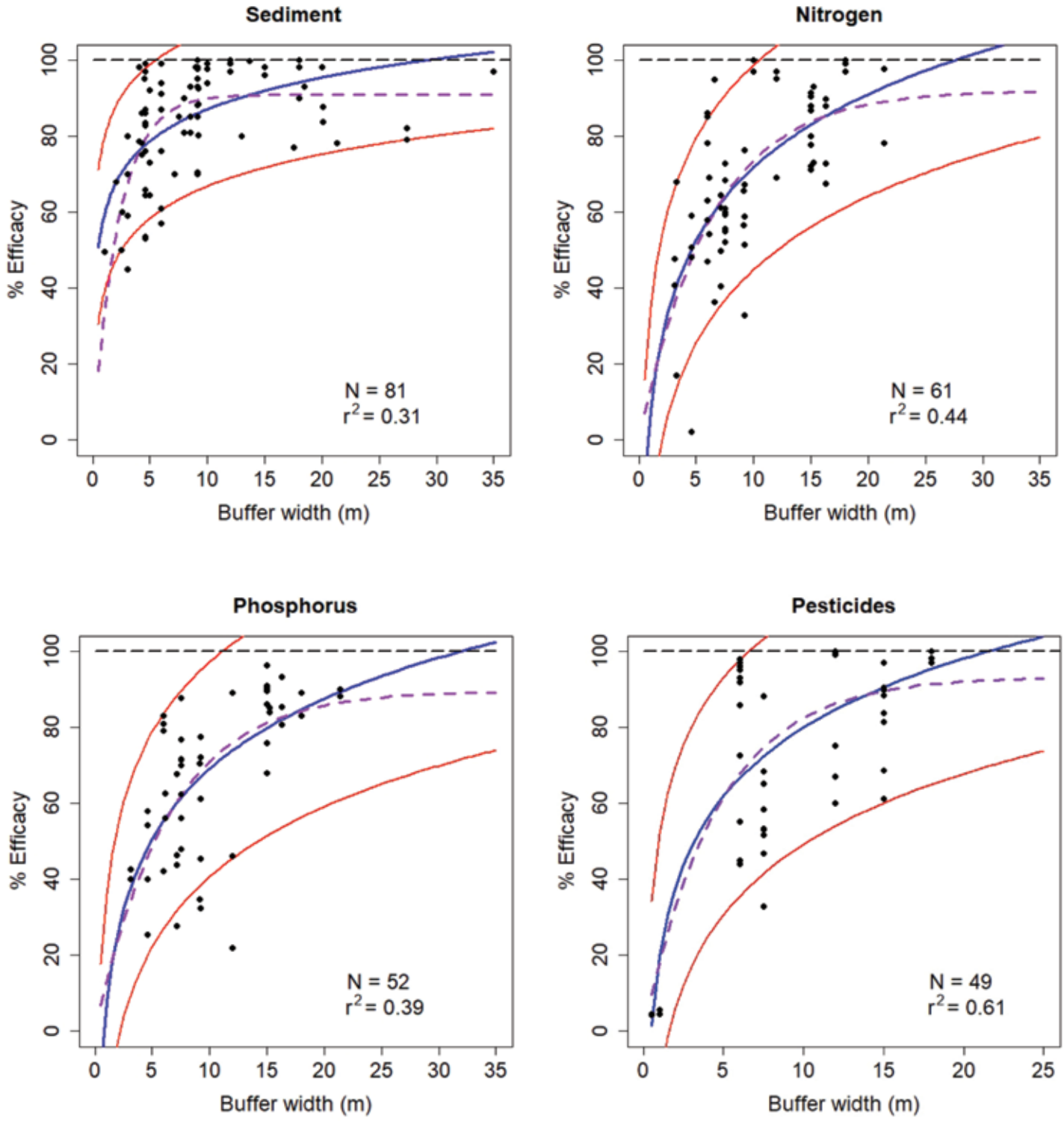


Figure 5.6. Relationship between removal efficacy and buffer width. Data from meta-analysis of Zhang et al. (2010) but reanalyzed using different form of nonlinear model. Line colors: blue: best fit model, red: 90% prediction interval, purple dashed: original model of Zhang et al. (2010), black dashed: 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.

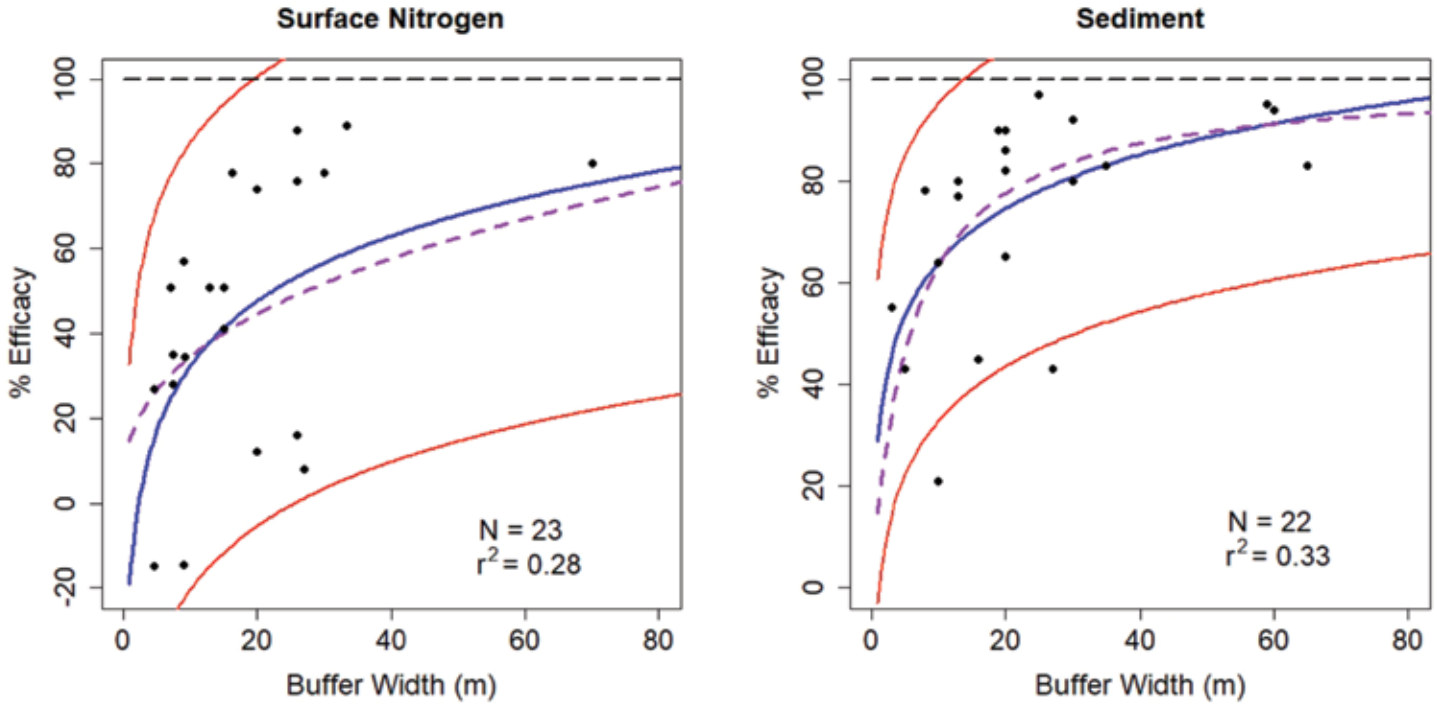


Figure 5.7. Relationship between removal efficacy and buffer width. Study results from meta-analyses reanalyzed using different form of equation in a linear regression. Left: nitrogen study results from Mayer et al. (2007). Right: sediment study results from Sweeney and Newbold (2014). Line colors: blue: 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).

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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).

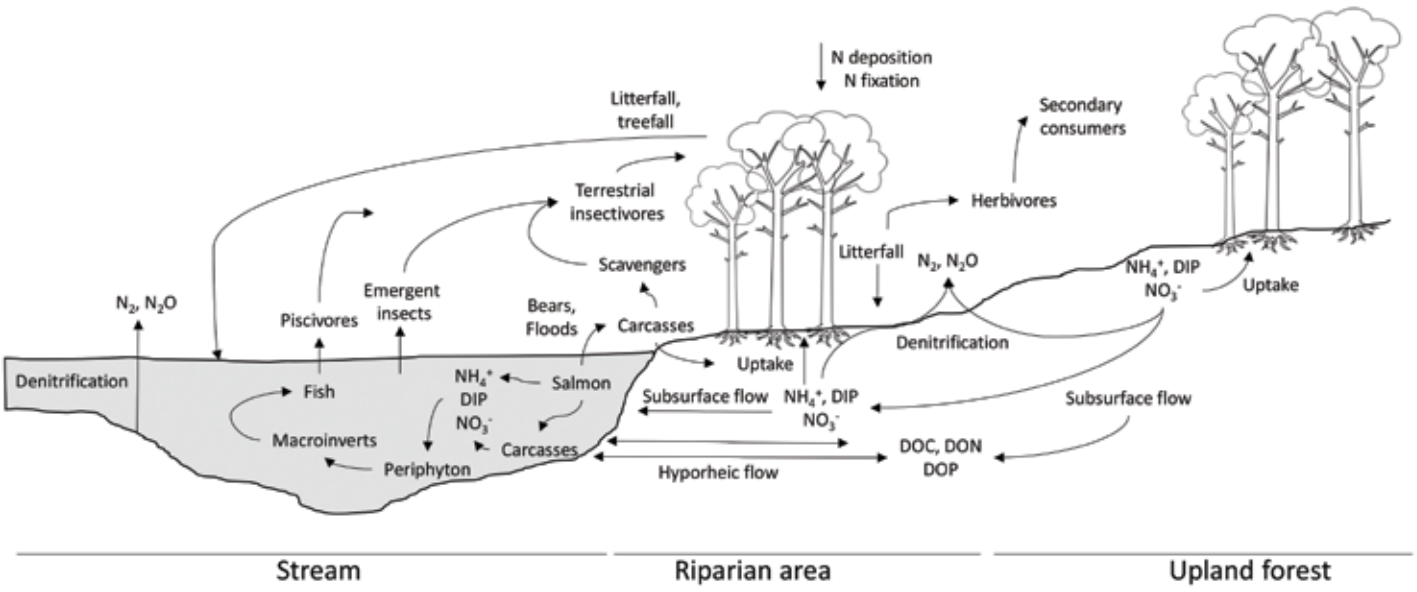


Figure 6.1. Nutrient cycle of an undisturbed PNW forested riparian ecosystem and connected stream and upland forest. Modified from Moyle et al. (2009). DIP = dissolved inorganic phosphorus; DOC, DON, DOP = dissolved organic carbon, nitrogen and phosphorus, respectively.

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 (NO_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).

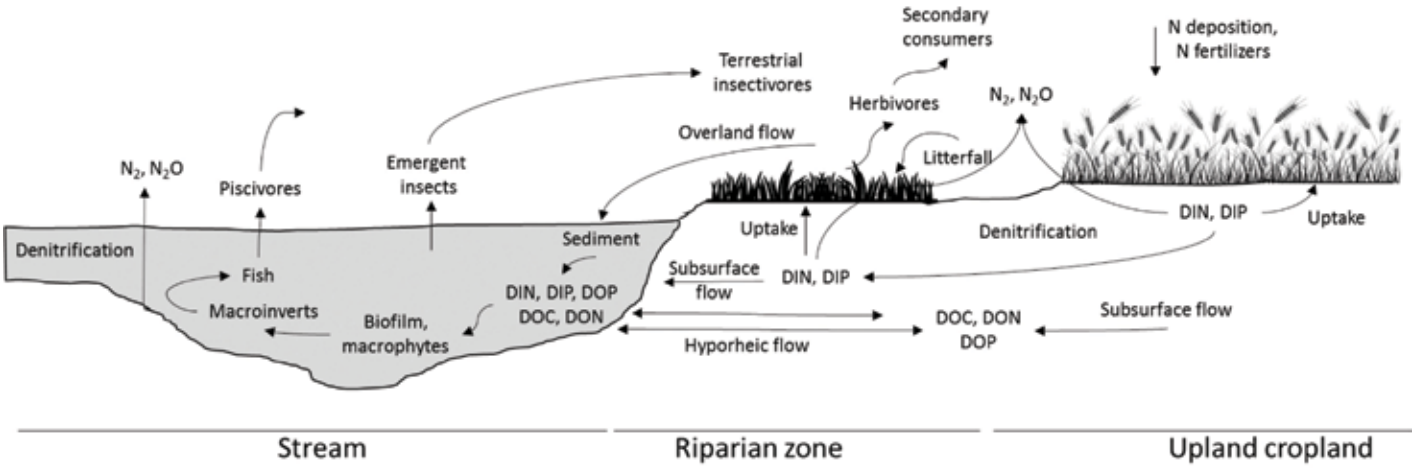


Figure 6.2. Nutrient cycle of a disturbed PNW riparian ecosystem and connected stream and upland cropland. Much of the cycling of marine-derived nutrients is facilitated by predators and scavengers that move nutrients into the terrestrial environment either as salmon carcasses or as urine and feces. 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.

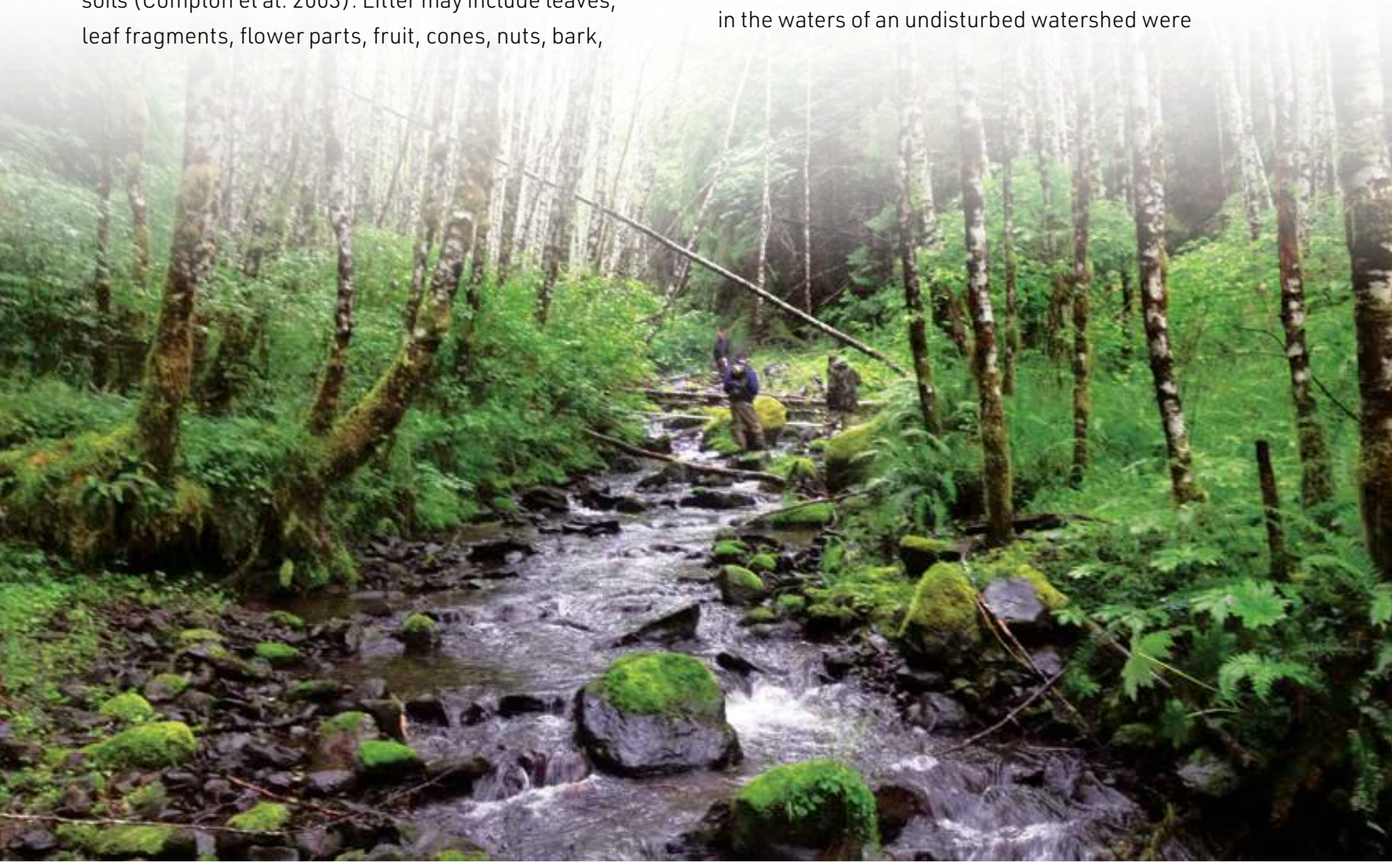
Large wood in stream channels can affect nutrient cycling by slowing the downstream transport of water, sediment, organic matter, and other materials (Chapter 3). Large wood in riparian areas ultimately decomposes, providing nutrients to the forest floor thereby increasing moisture holding capacity (Harmon 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

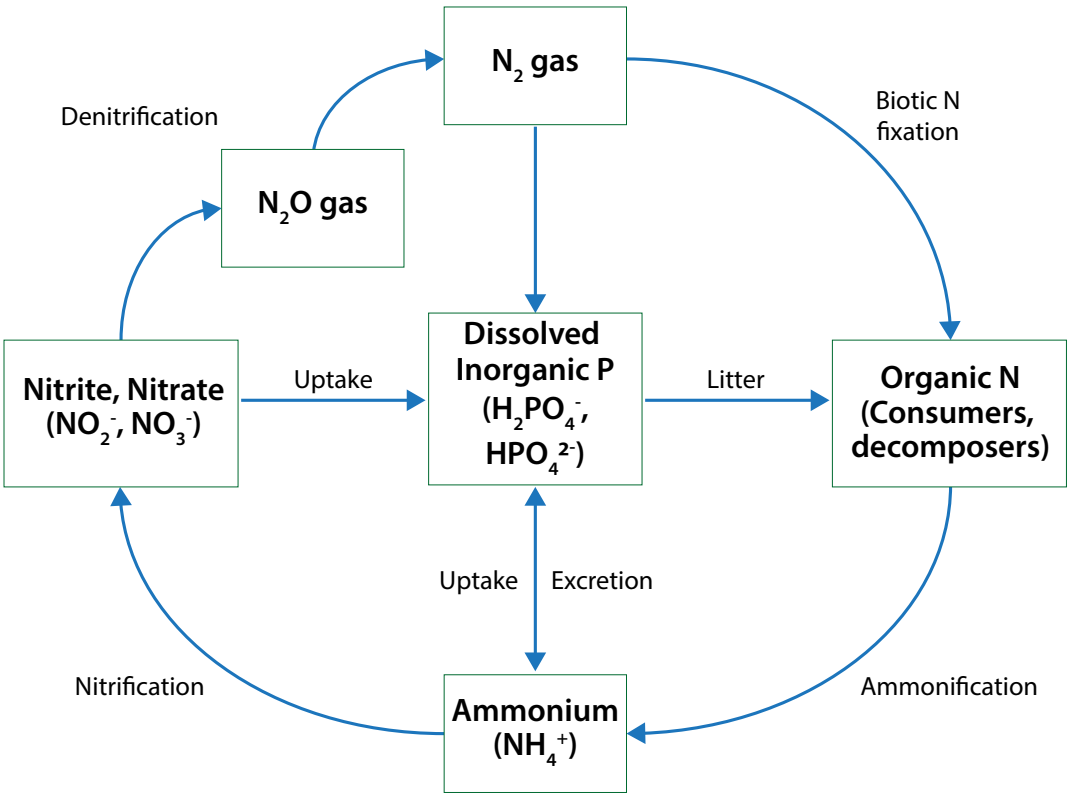


Figure 6.3. Nitrogen cycle pools and processes in ecosystems.

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

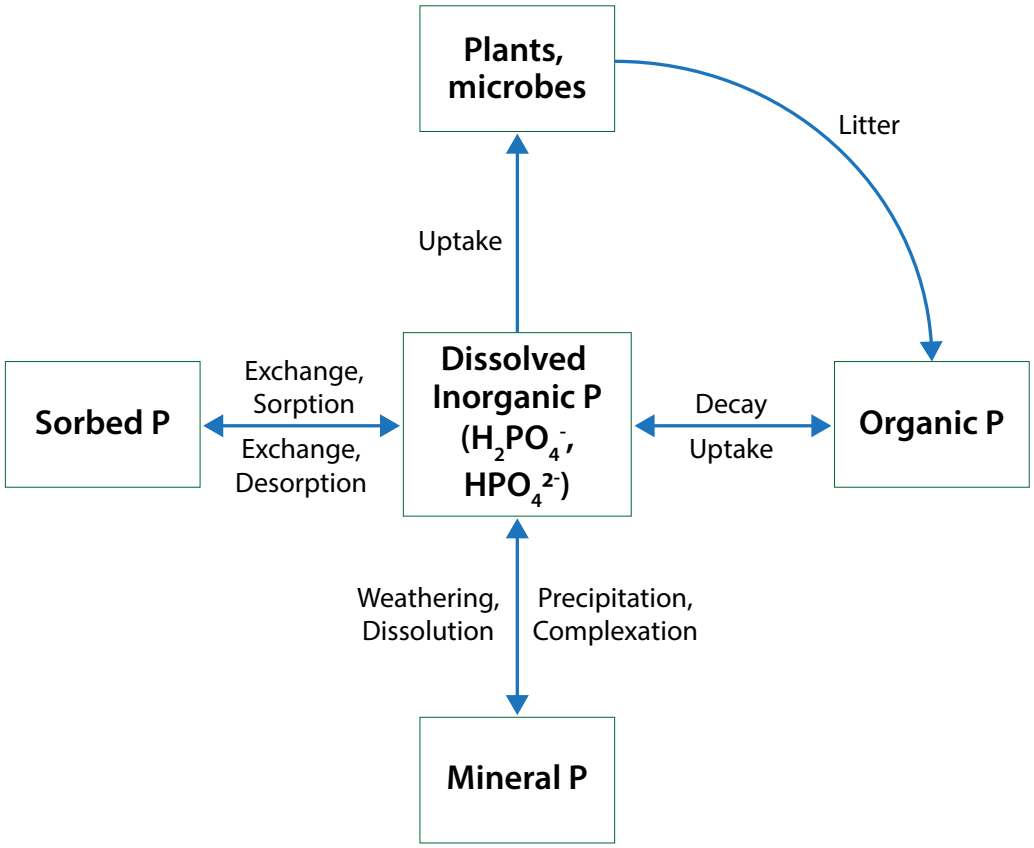


Figure 6.4. Phosphorus cycle pools and processes in ecosystems.

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

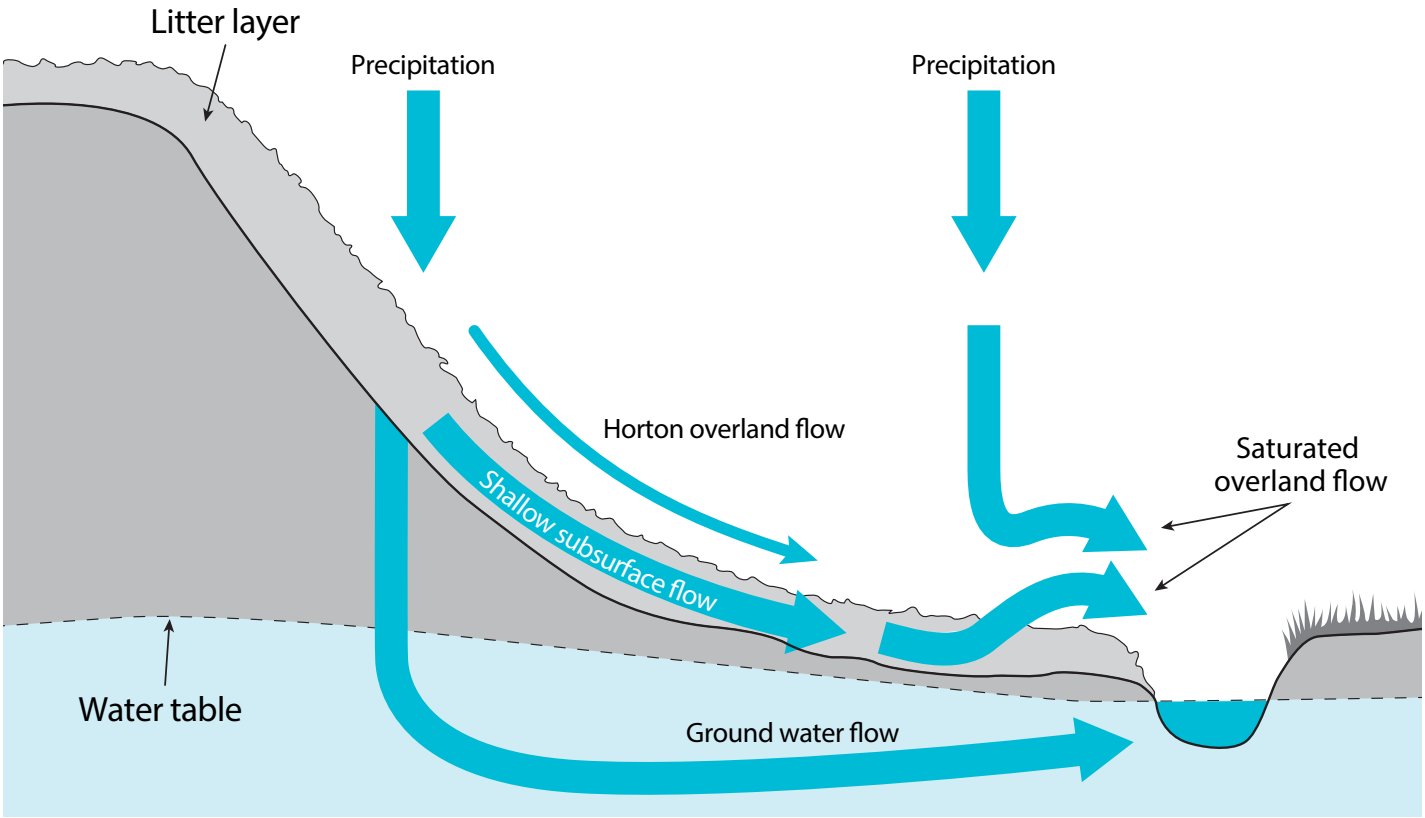


Figure 6.5. Water flow paths. Precipitation reaches a stream as surface runoff and by infiltration into the ground where it contributes to groundwater flow. The amount of water following each flow path depends on the capacity of the soil to absorb water, the amount of storage in surface depressions, 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

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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

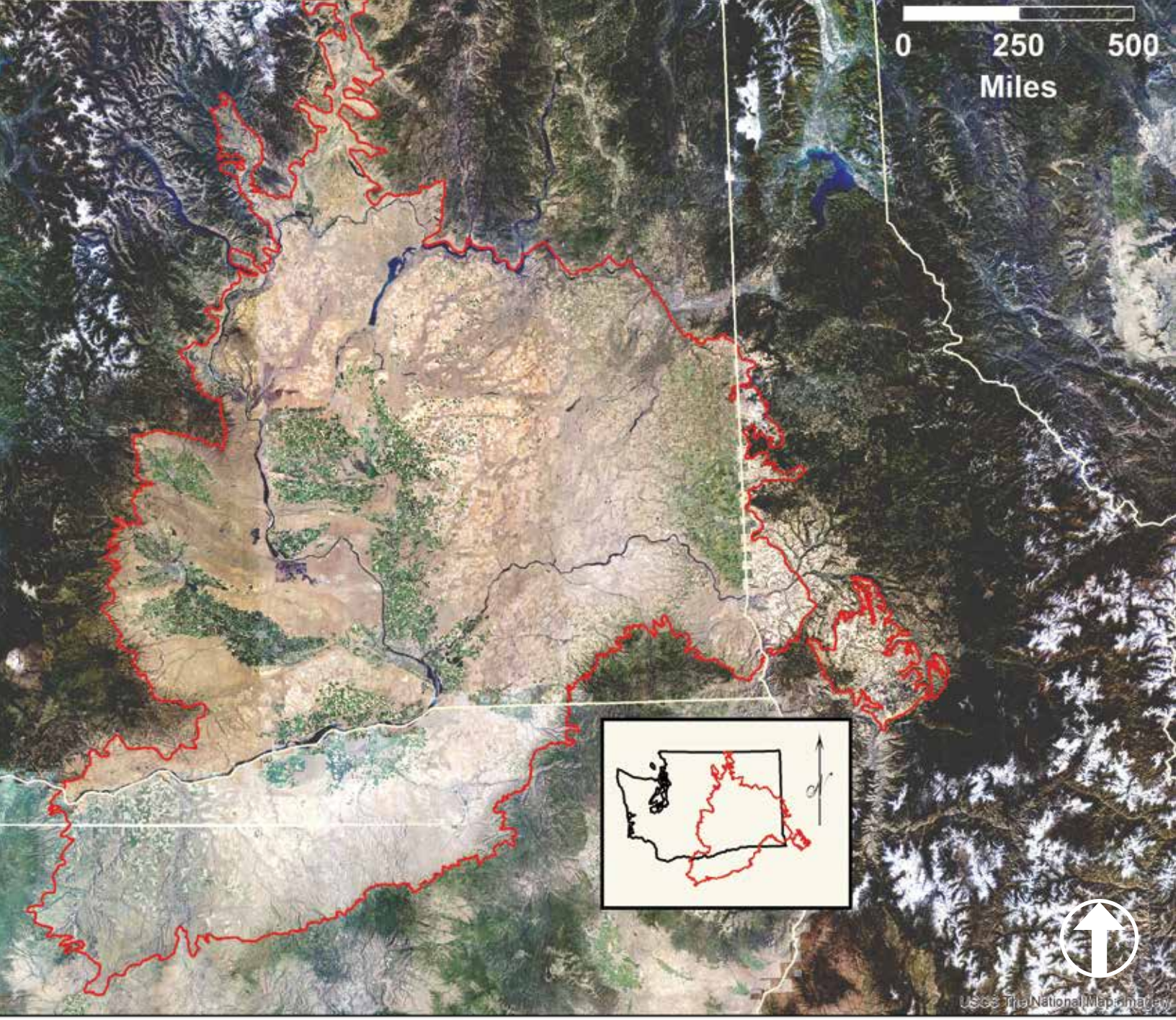


Figure 7.1. Boundary (in red) of the Columbia Plateau Ecoregion. State boundaries are white. Aerial photography for Washington State done in 2015 by the National Agriculture Imagery Program.

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.

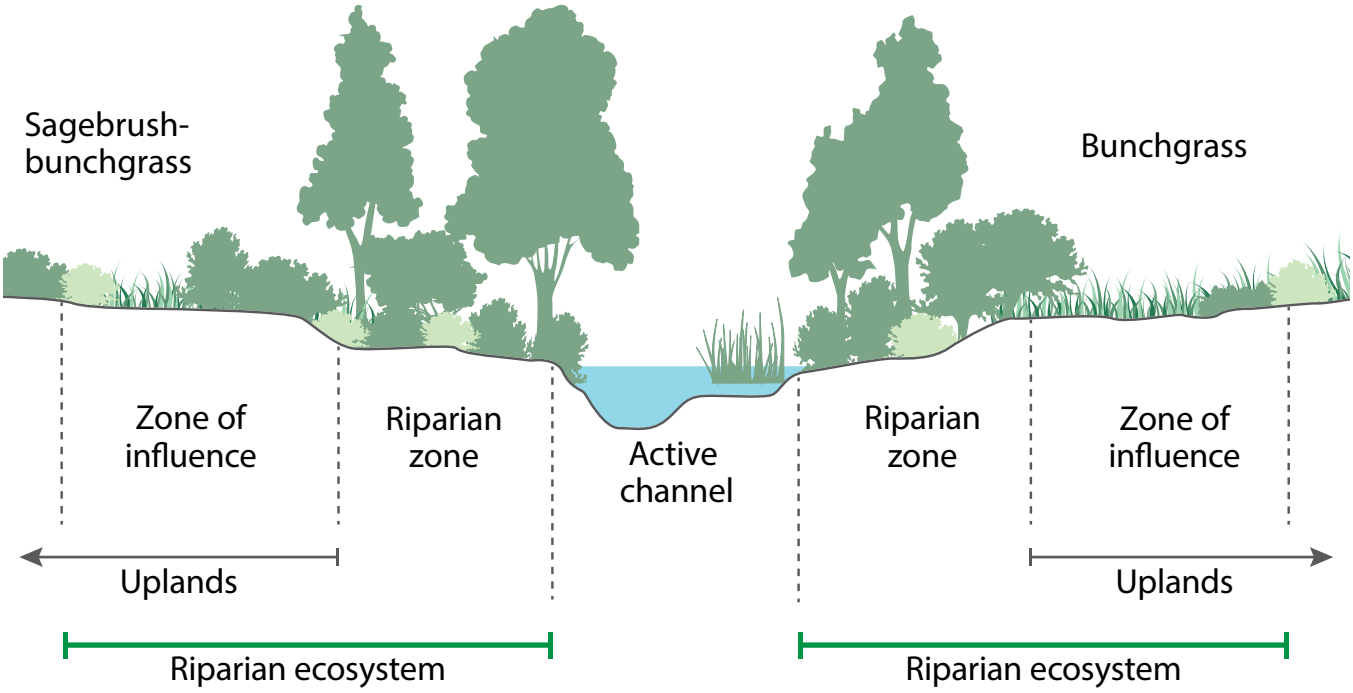


Figure 7.2. Dryland Riparian Ecosystem. The riparian ecosystem consists of two zones: riparian and zone of influence. The riparian zone extends from the edge of the active channel towards the uplands. This zone includes areas where terrestrial biota are influenced, at least periodically, by surface or 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.

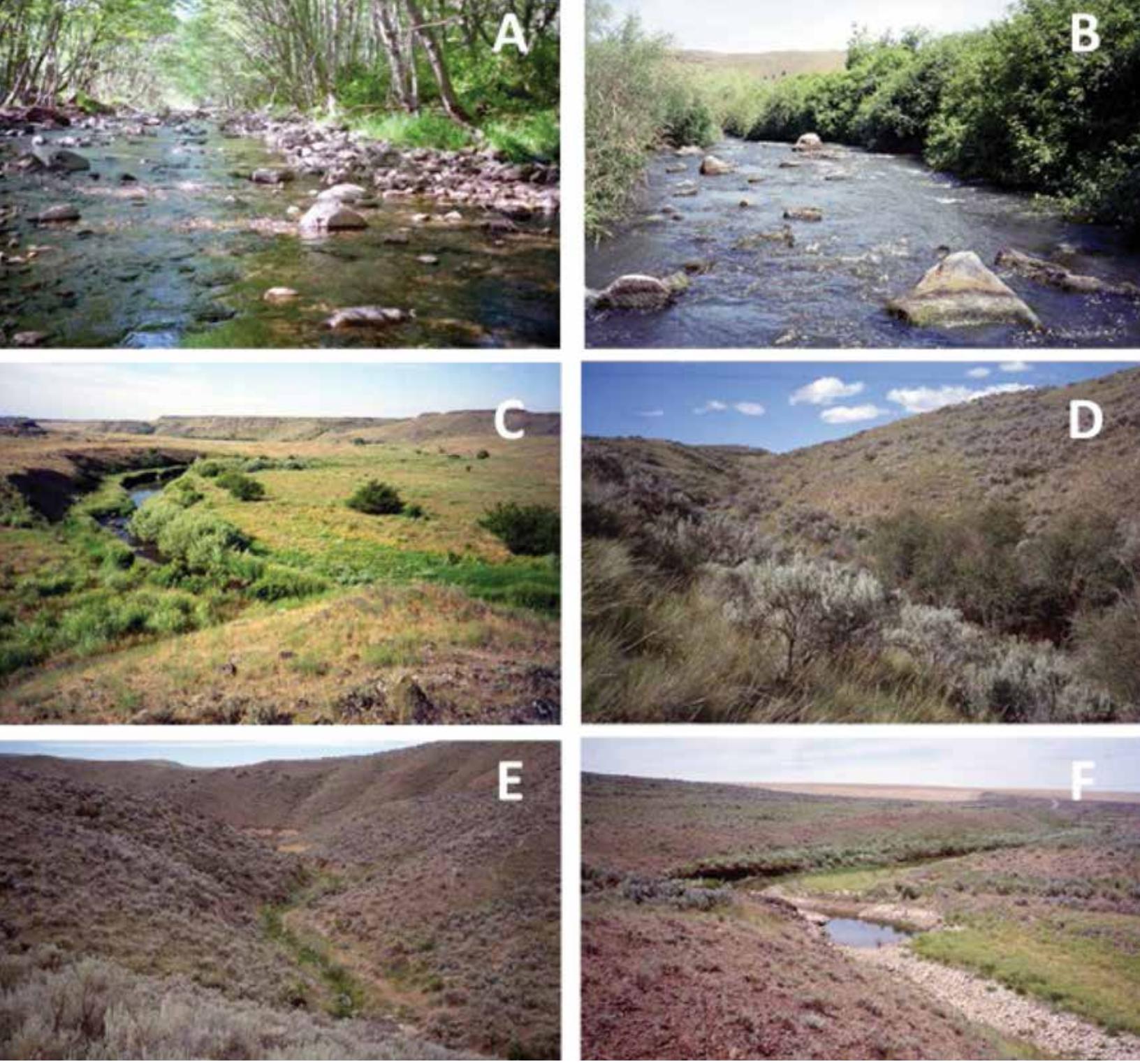


Figure 7.3. Different riparian vegetation structure types: A) tall tree, B) short tree, C) tall shrub, D) shrub on an intermittent stream, E) grass-like, F) forb/Rex Crawford, WNHP

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

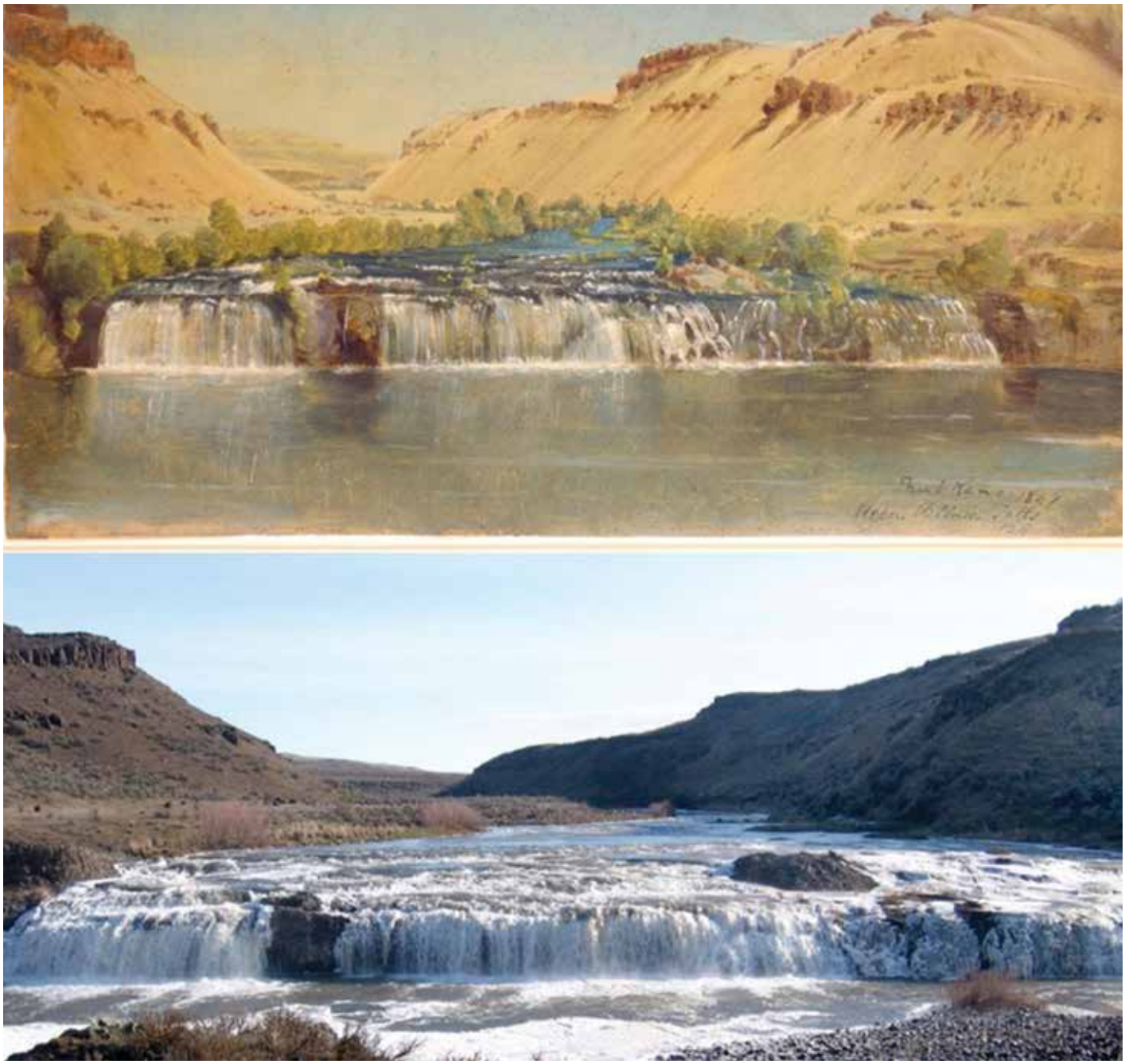


Figure 7.4. Historical drawings and paintings can provide invaluable information for riparian area restoration. A 1847 painting by Paul Kane of Upper Palouse Falls (top) shows extensive, uninterrupted small tree or tall shrub vegetation along the river banks. A recent photo by Jack Nisbet (bottom) although 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.

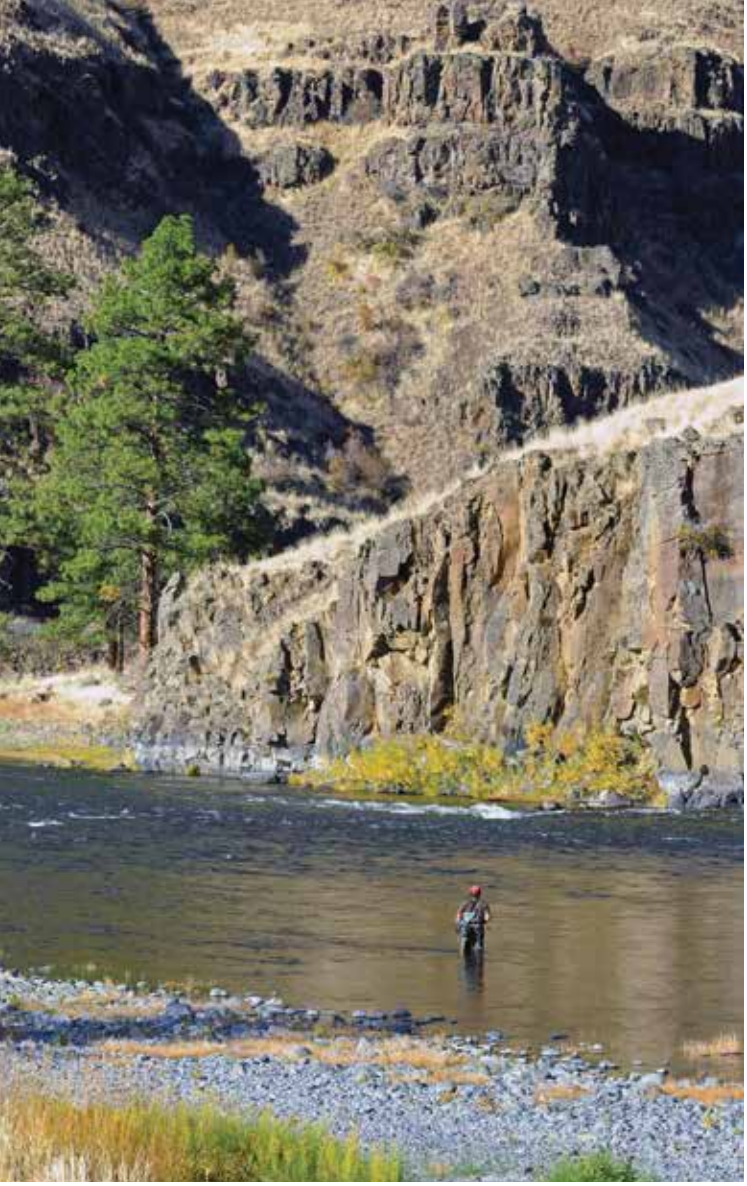
The only study I could find on litter source distances was conducted in mature conifer forest in western Washington. Bilby and Heffner (2016) found that about 95% of litter delivered to streams comes from distances between 39 and 54% of mean tree height, depending upon forest type, topography, and wind. 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.

7.6. Acknowledgements

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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.

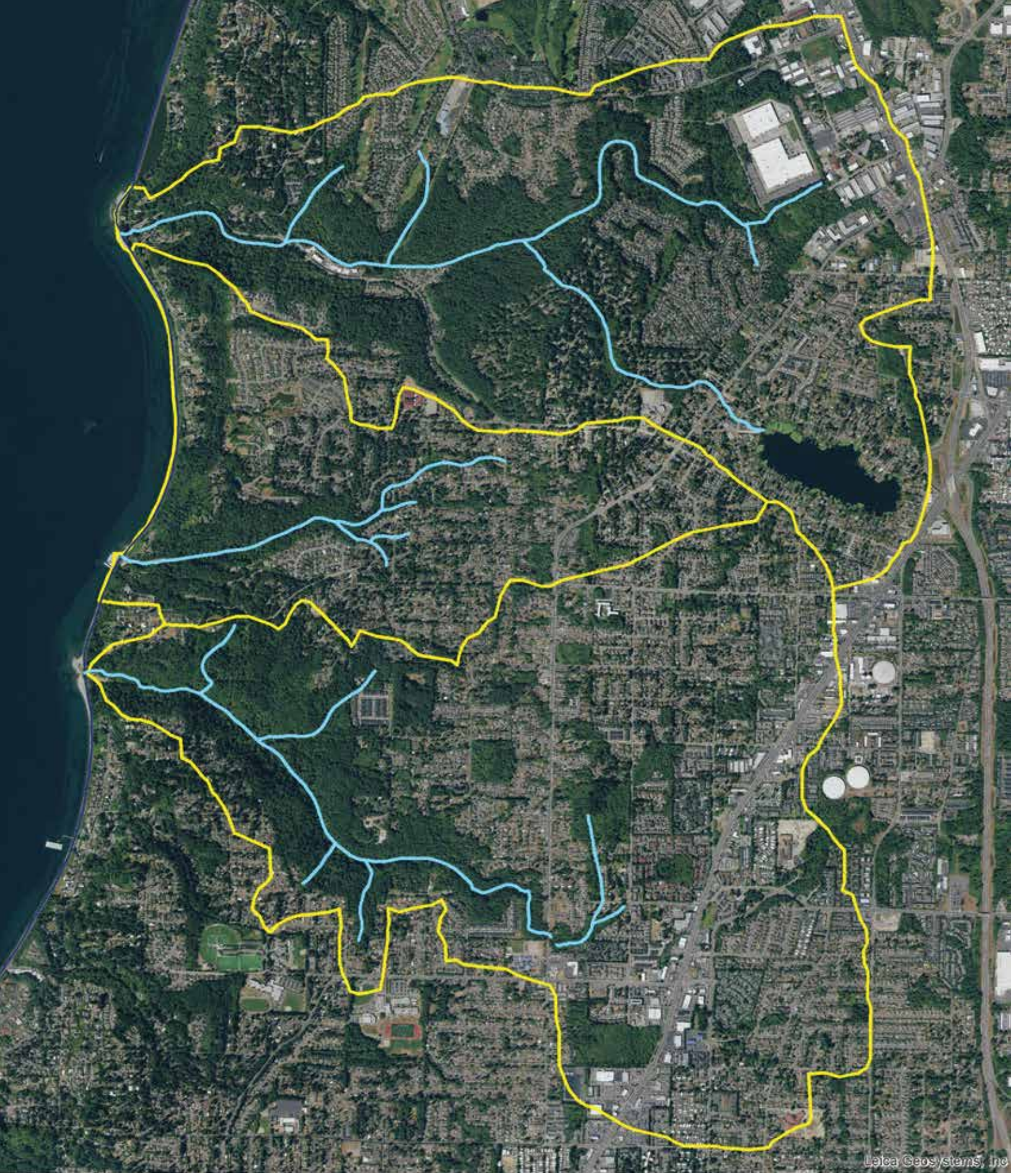
The chapter is divided into four primary sections:

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).

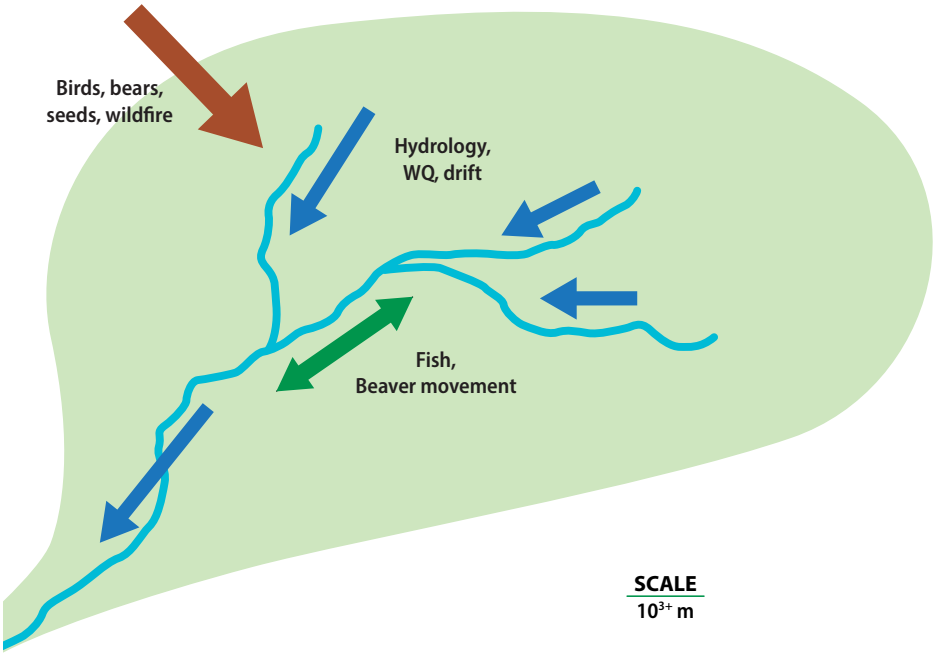


Figure 8.1. Movement of water and biota at the whole-watershed scale. WQ refers to water quality, and drift refers to the downstream transport of bottom-dwelling invertebrates by flowing water.

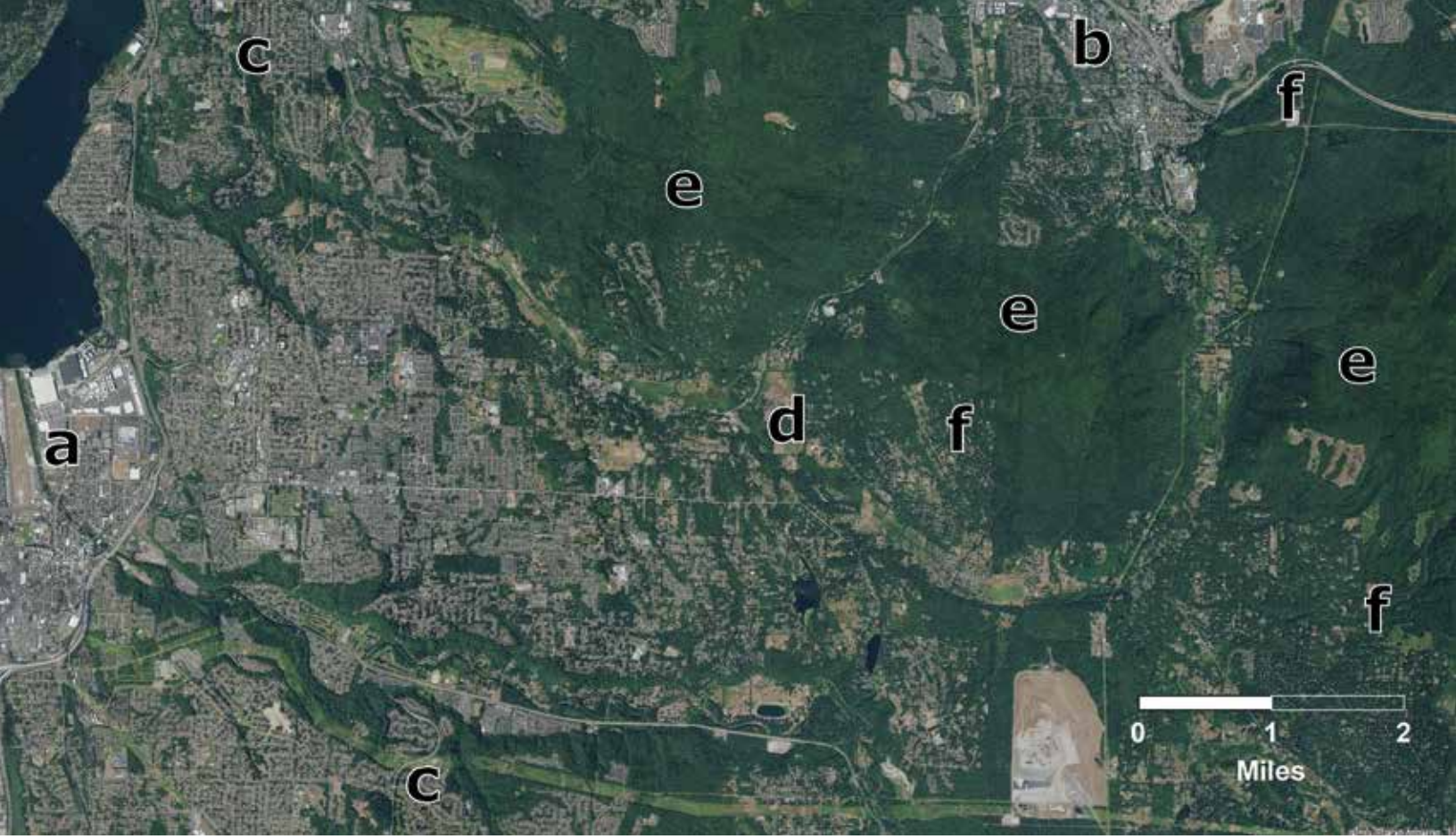


Figure 8.2. An example of landscape heterogeneity at multiple scales in an aerial view that includes the urban centers of Renton (west edge, labeled a) and Issaquah (northeast corner, b); suburban development throughout the south-central and northwest parts of the image (c); agriculture and rural-residential 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].*

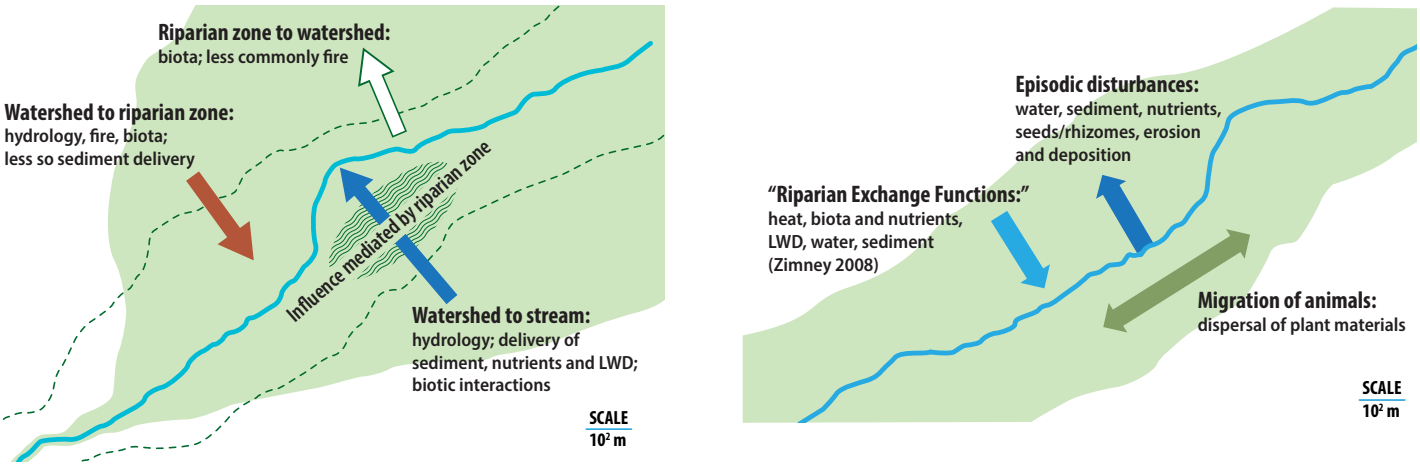


Figure 8.3. Movement of water, biota, and other elements of the aquatic system from the watershed into and through riparian areas (left) and between riparian areas and the stream (right).

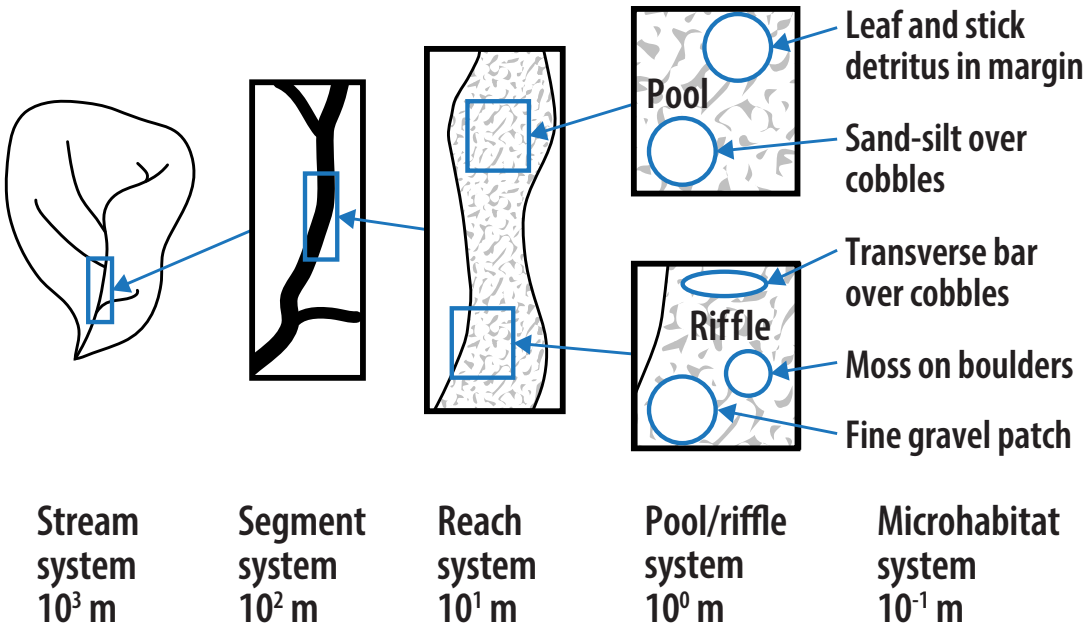


Figure 8.4. Hierarchical spatial organization of a watershed and its aquatic habitats. Approximate spatial scale, appropriate to second or third-order mountain stream (modified from Frissell et al. 1986).

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

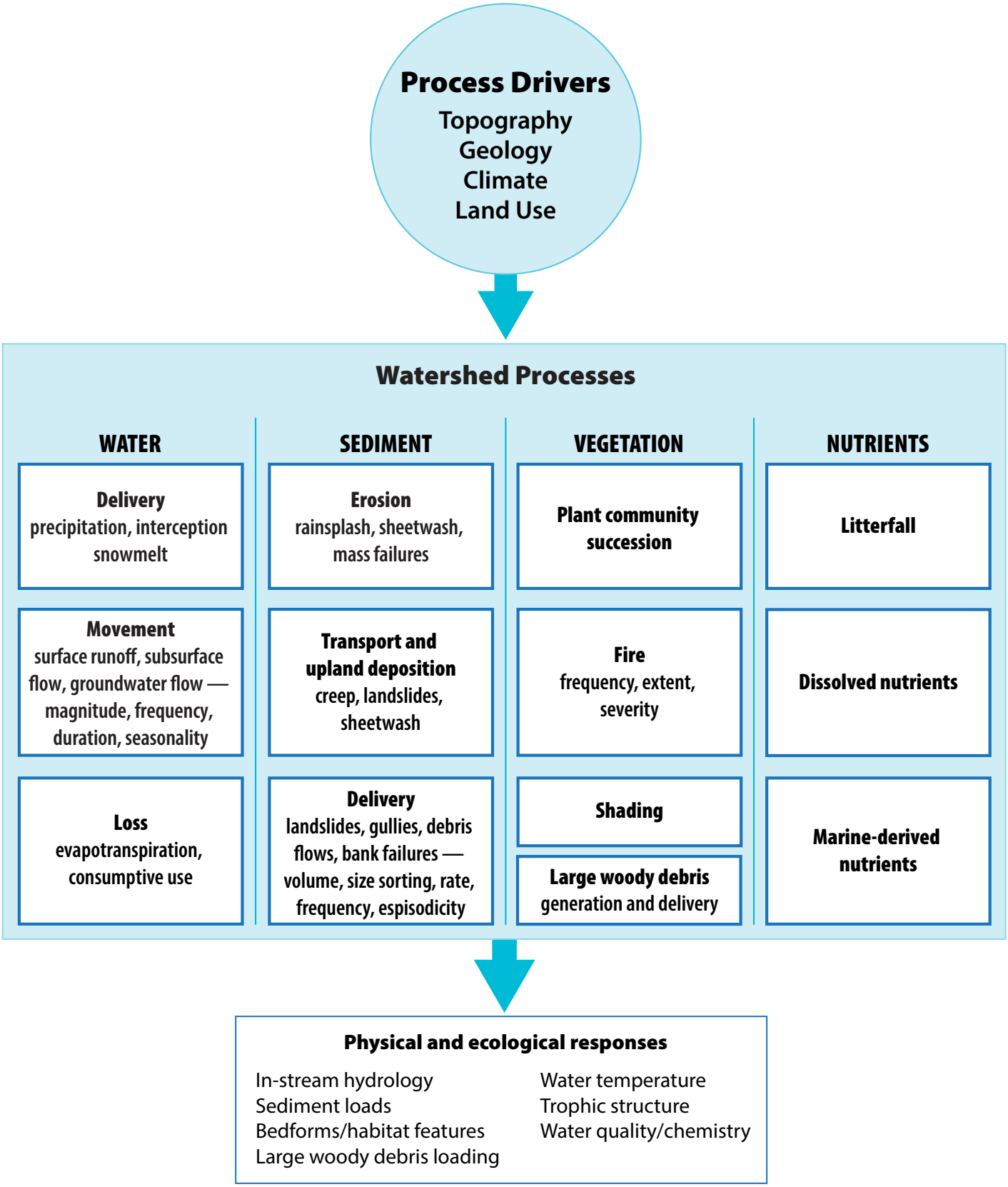


Figure 8.5. Conceptual framework for the hierarchical relationship of invariant, large-scale process drivers, the suite of watershed processes that are determined by these drivers, and the instream physical and biological responses to those processes. Multiple additional interactions between elements 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.]***

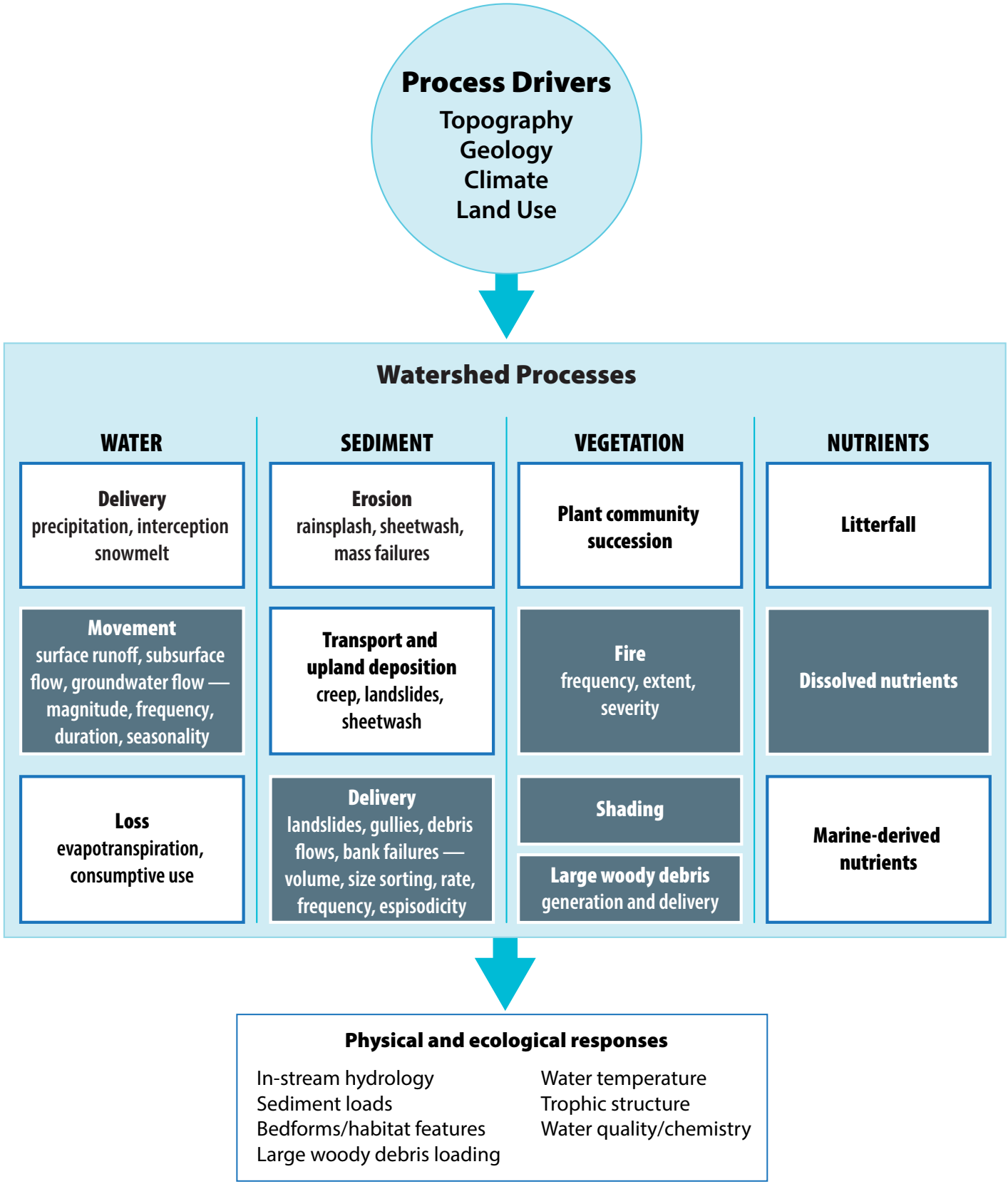


Figure 8.6. The conceptual framework of Figure 8.4, highlighting the subset of watershed processes (dark shaded boxes) that most directly affect instream conditions.

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.

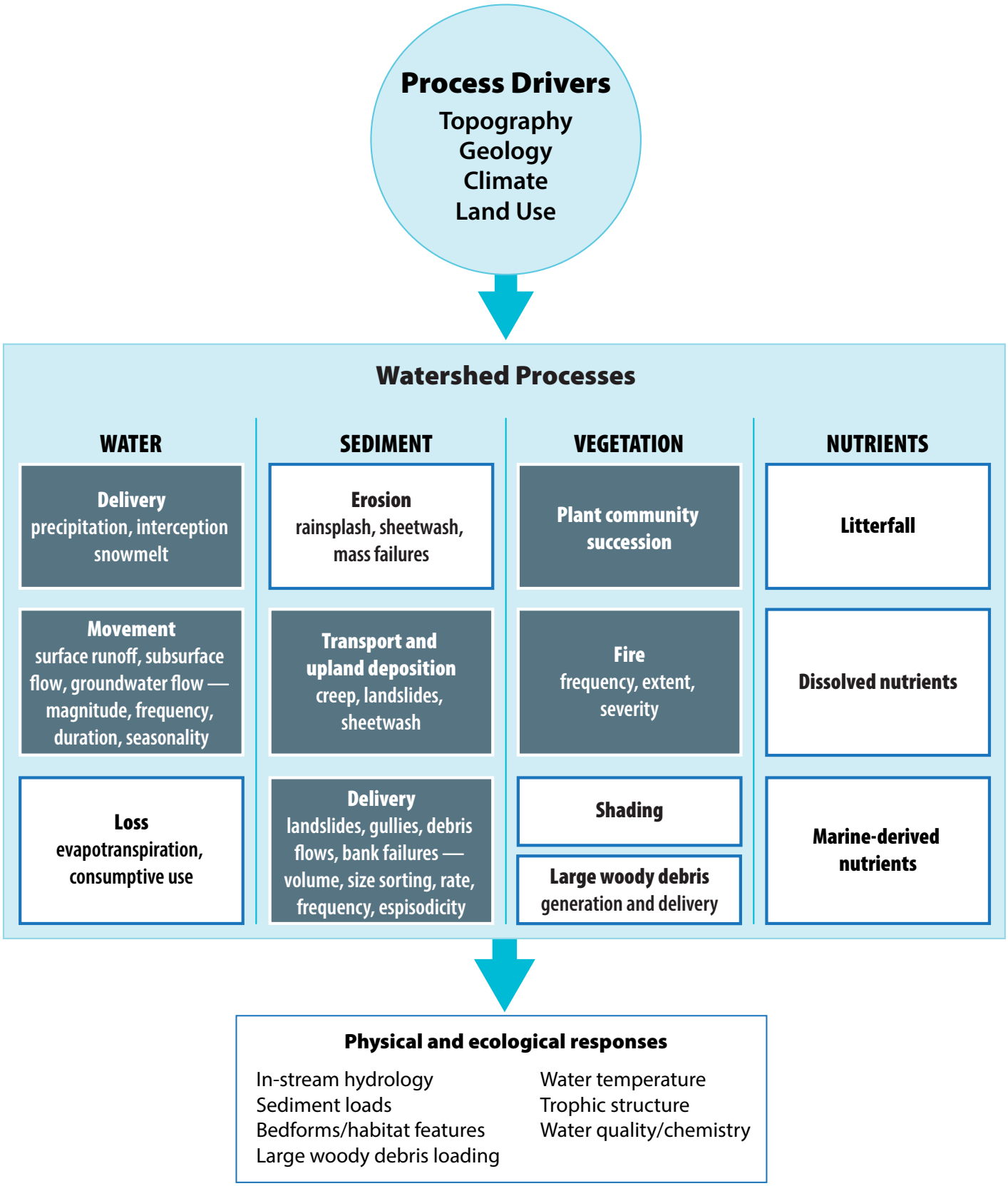


Figure 8.7. The conceptual framework of Figure 8.4, highlighting the subset of watershed processes (dark shaded boxes) that most directly affect conditions in riparian areas.

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

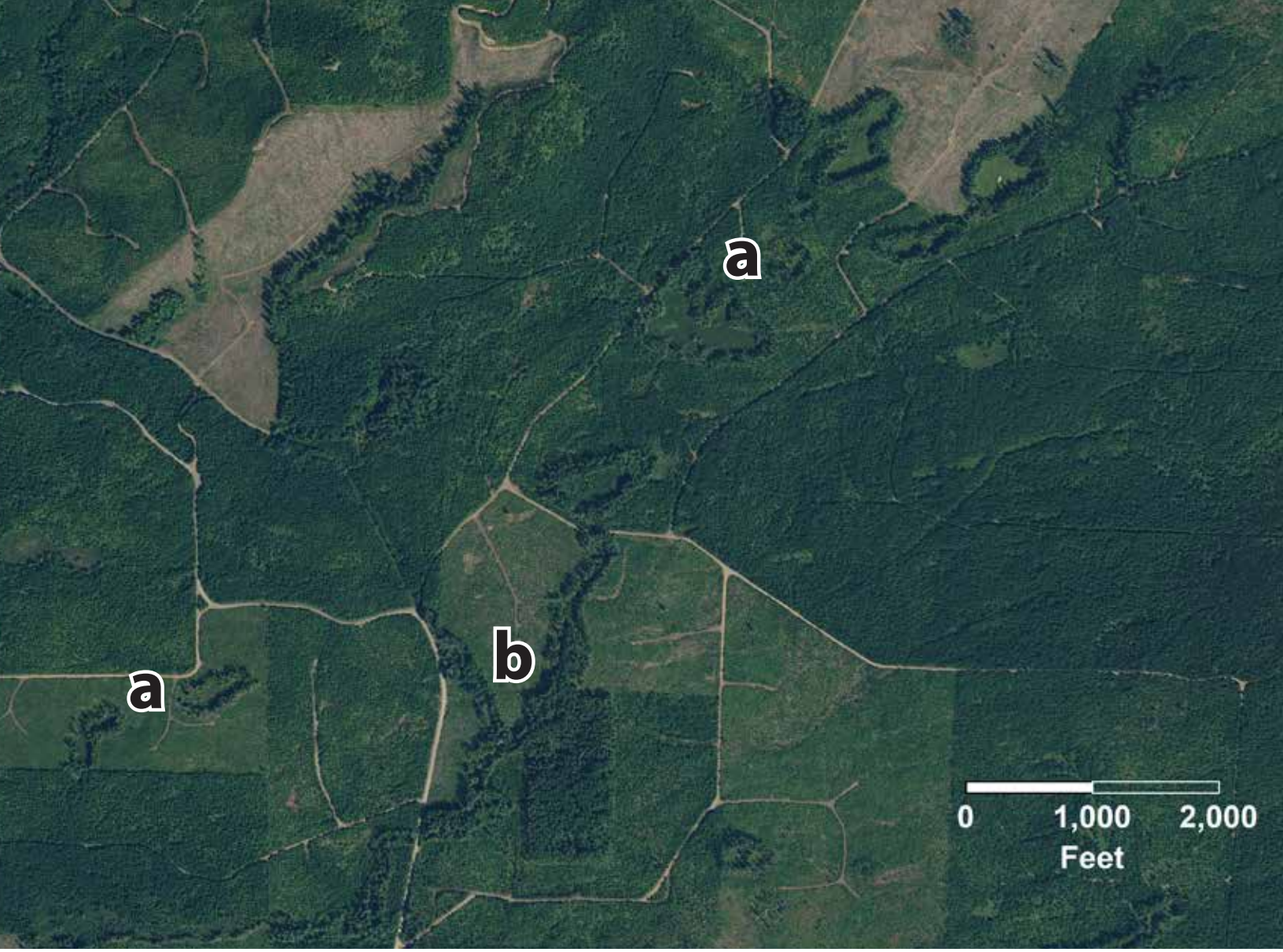


Figure 8.8. View of isolated wetlands (a) and riparian management zones (b) in a commercially logged portion of southwest Washington, providing some degree of local, structural connectivity within each buffer but no functional connectivity between them. Forested buffers in this image are approximately 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.

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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:

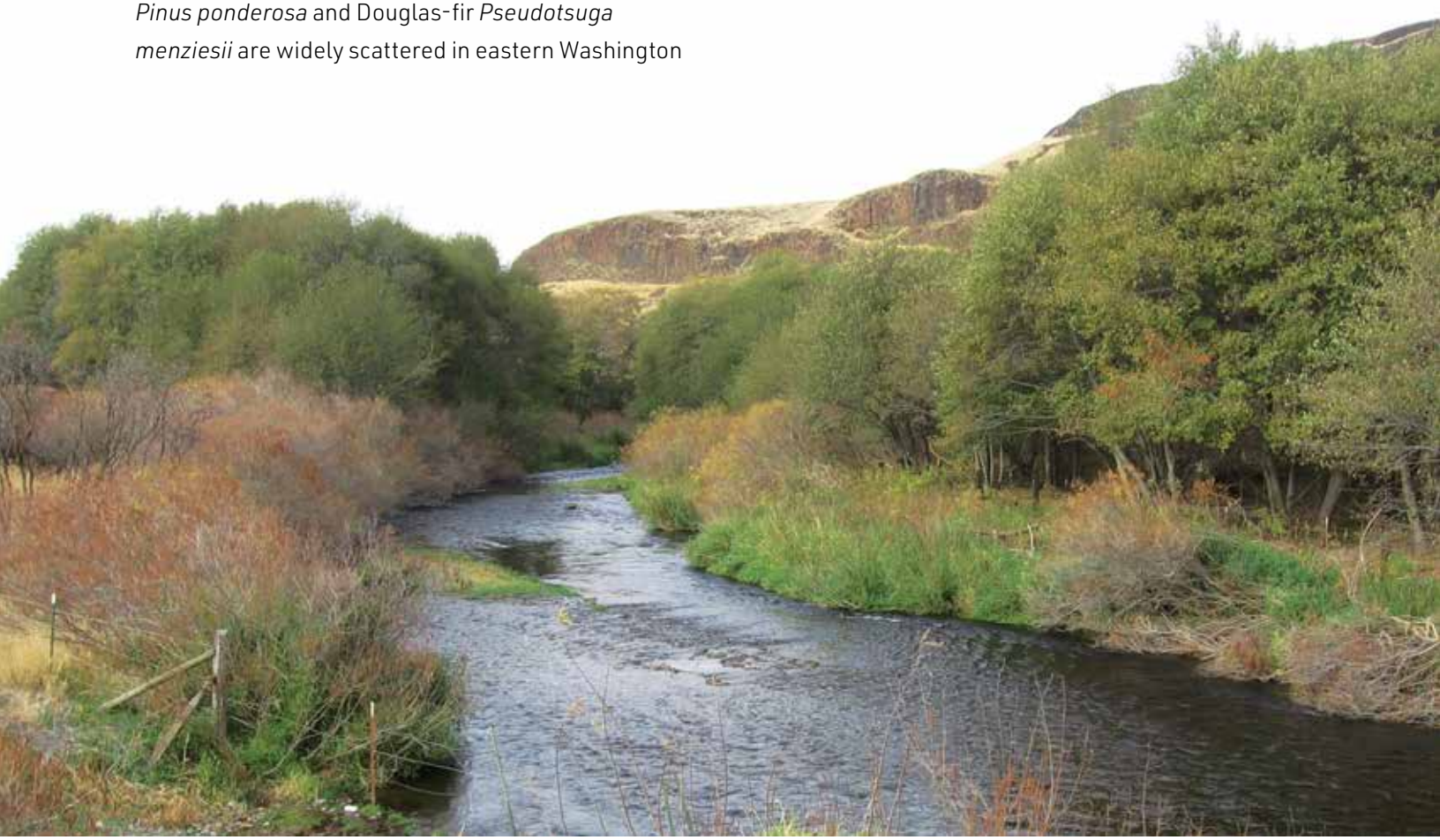
- Vegetation within riparian ecosystems of the Columbia Plateau often exhibits an abrupt demarcation between the riparian zone and the zone of influence. Phreatophytic trees and shrubs and hydrophytic herbaceous plants are confined to moist streamside areas, but the upland zone of influence may consist 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

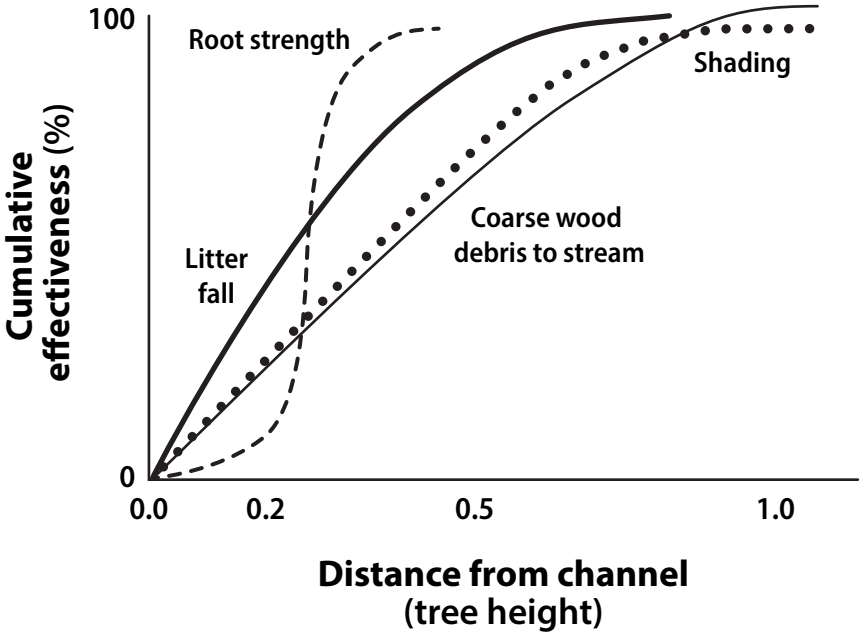


Figure 9.1. The "FEMAT Curves" (FEMAT 1993) are generalized conceptual models describing some riparian ecosystem functions and processes as the distance from a stream channel increases. "Tree height" in this figure is based on the average maximum height of the tallest dominant trees (200 years old or 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.

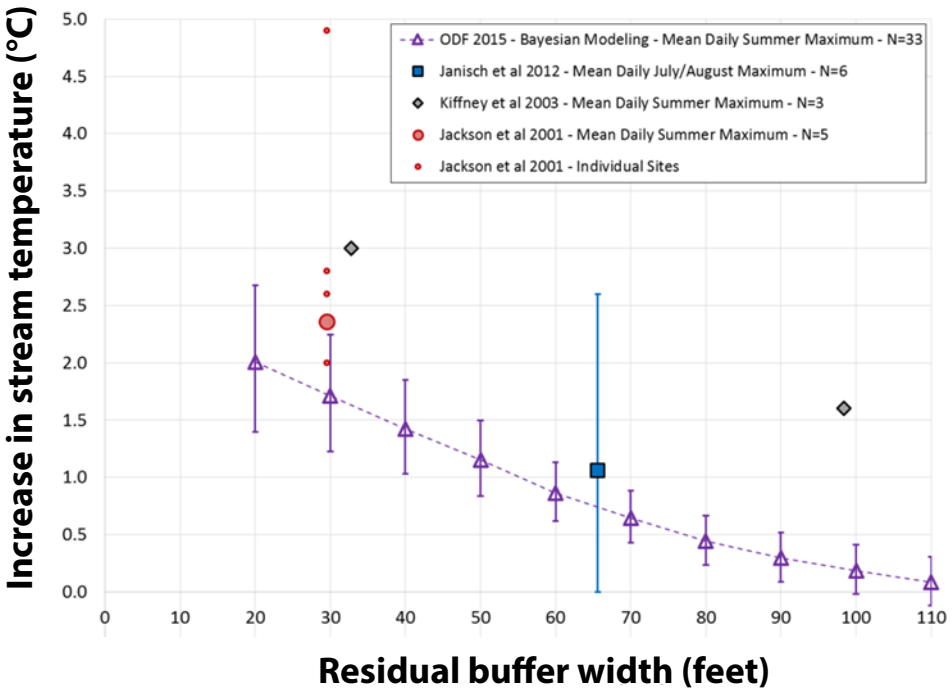


Figure 9.2. Observed temperature response associated with "no-cut" riparian buffers with adjacent clearcut harvest. Only studies that employed a Before-After-Control-Impact design and conducted in Pacific Northwest forests are included. Bayesian modeling results (and 90% credible intervals) were derived 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).

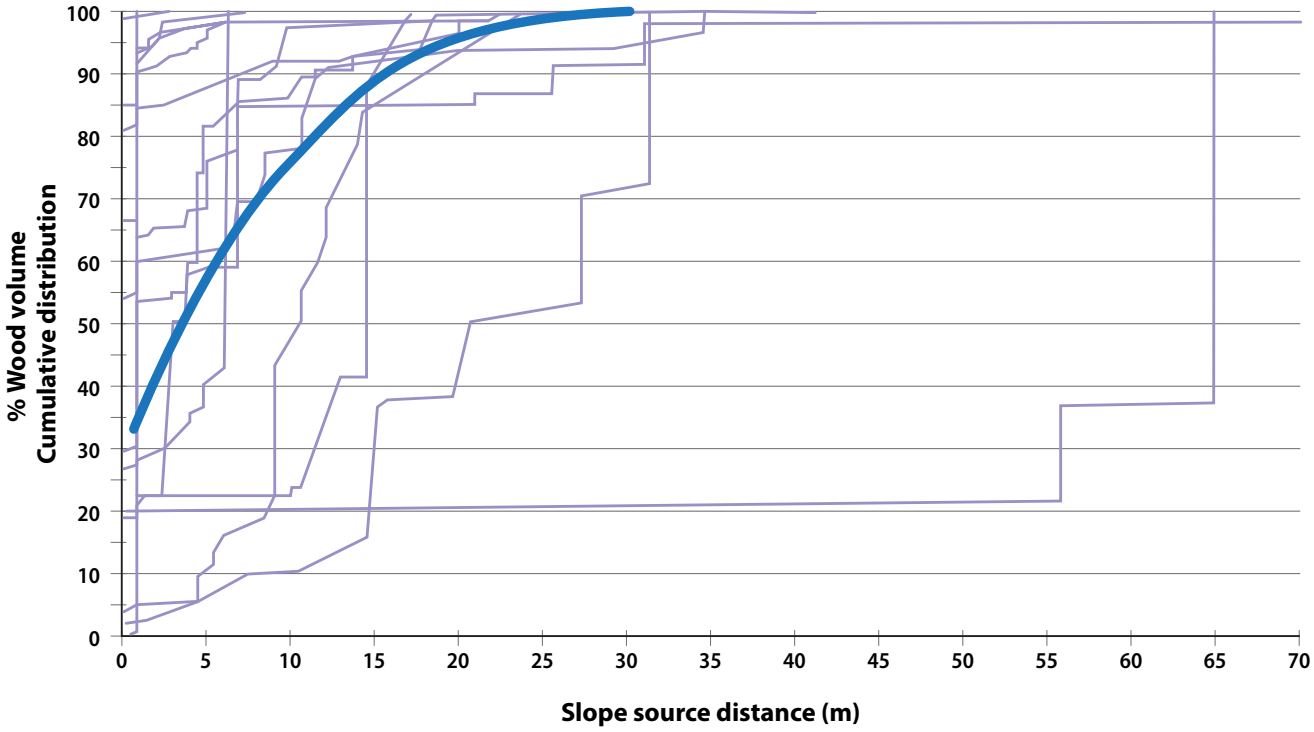


Figure 9.3. Sixteen large wood recruitment curves for second-growth redwood forest on 16 sites in northern California (from Benda et al. 2002). The theoretical prediction curve (thick line) is based on mortality recruitment only using random 360° fall trajectories. Curves to the left of the theoretical 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.

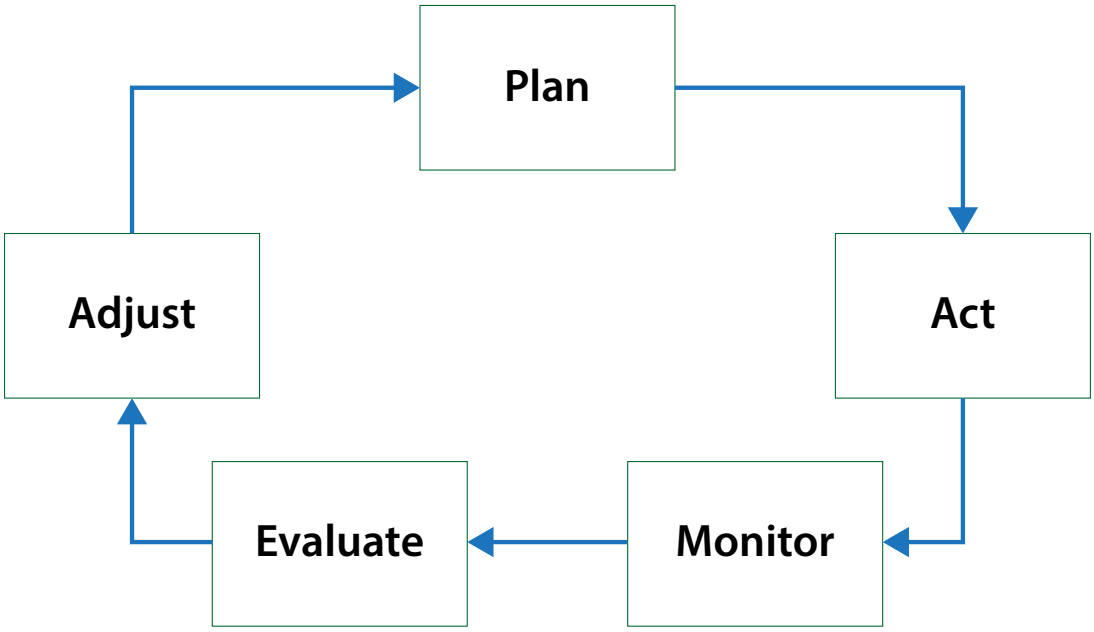


Figure 9.4. The adaptive management cycle (modified from Bormann et al. 1994).

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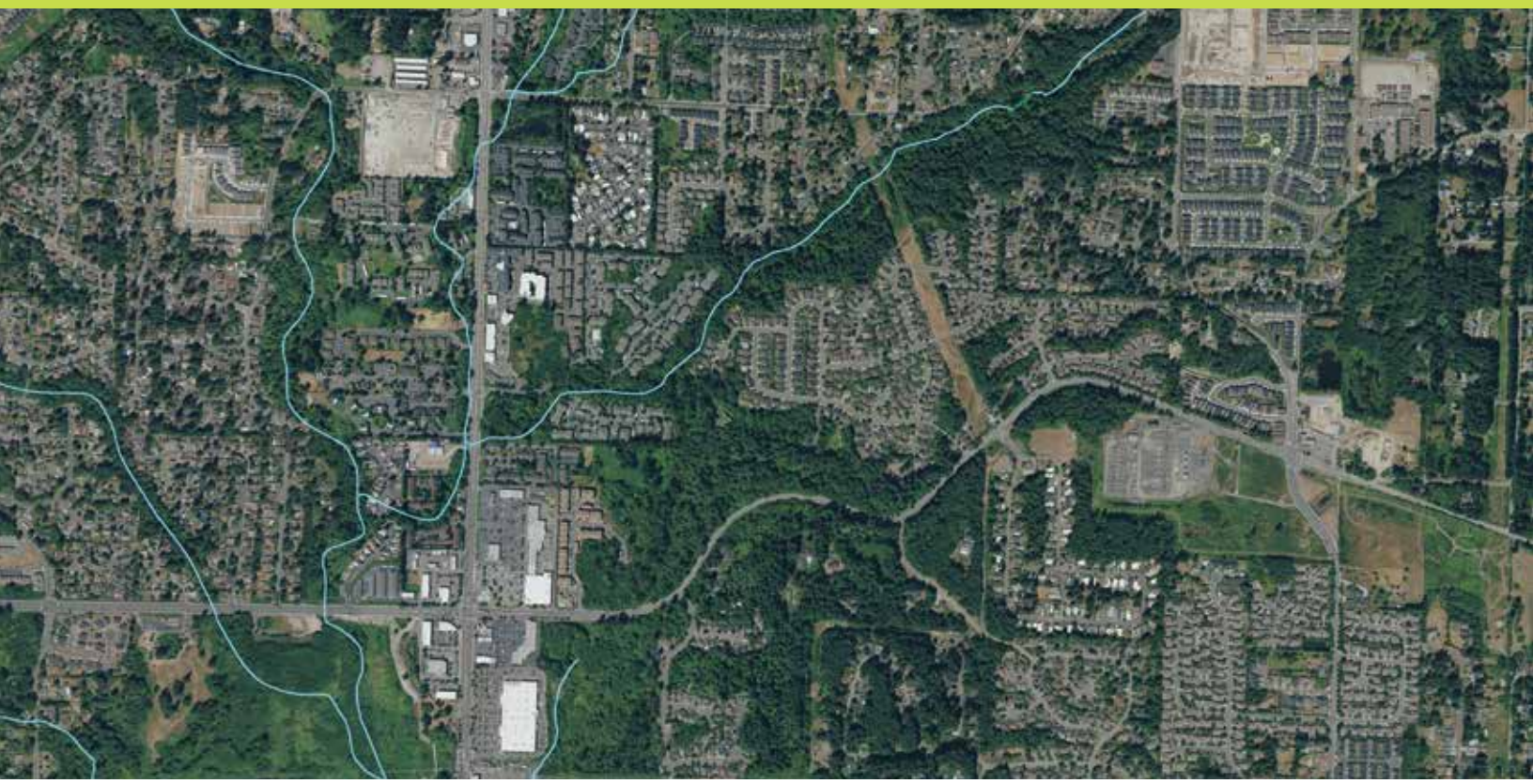
Grande Ronde River/Alan Bauer

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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Riparian Ecosystems, Volume 2: Management Recommendations

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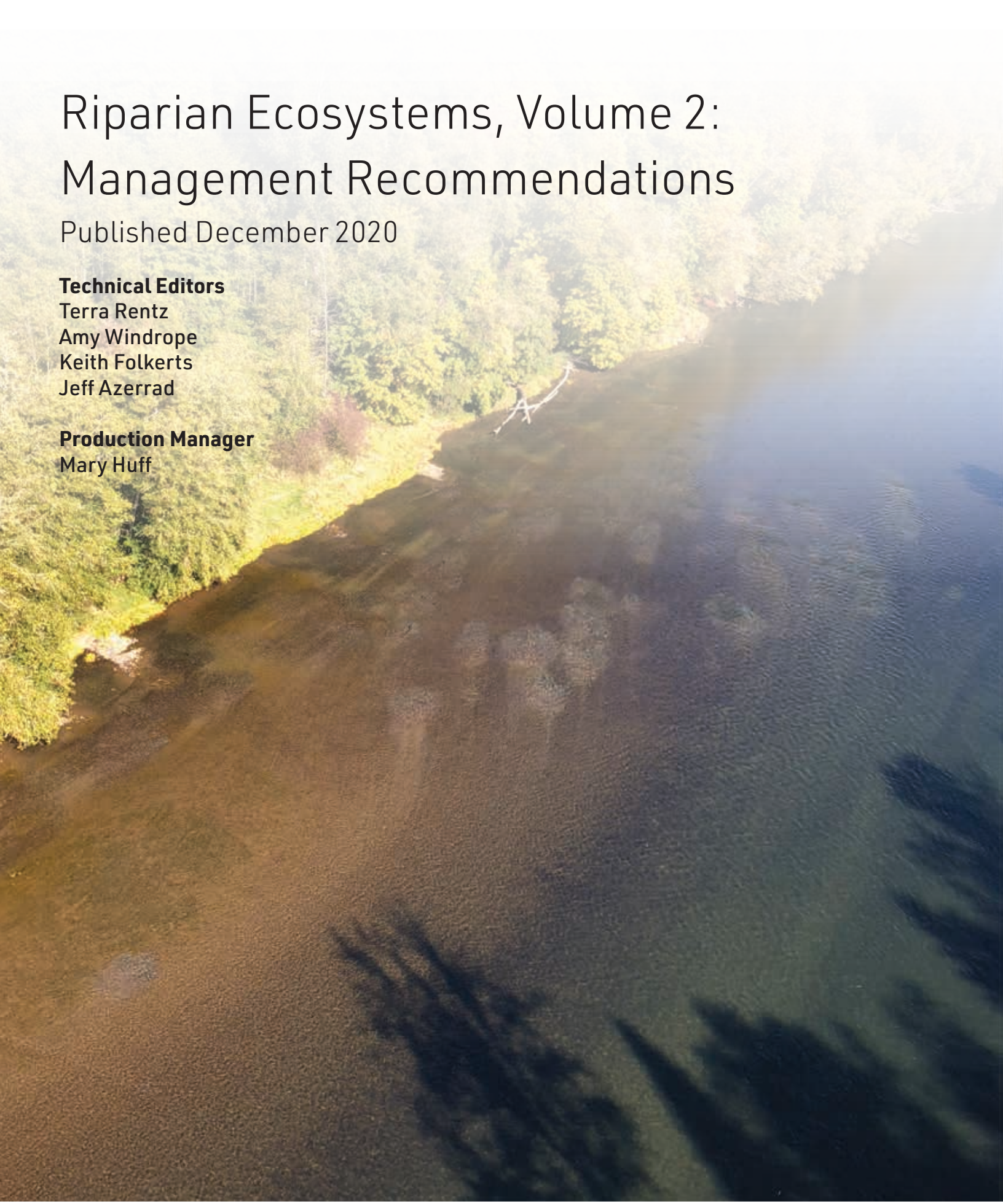

Salmon redds along the Cowlitz River, Lewis County/George Fornes, WDFW

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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.

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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.

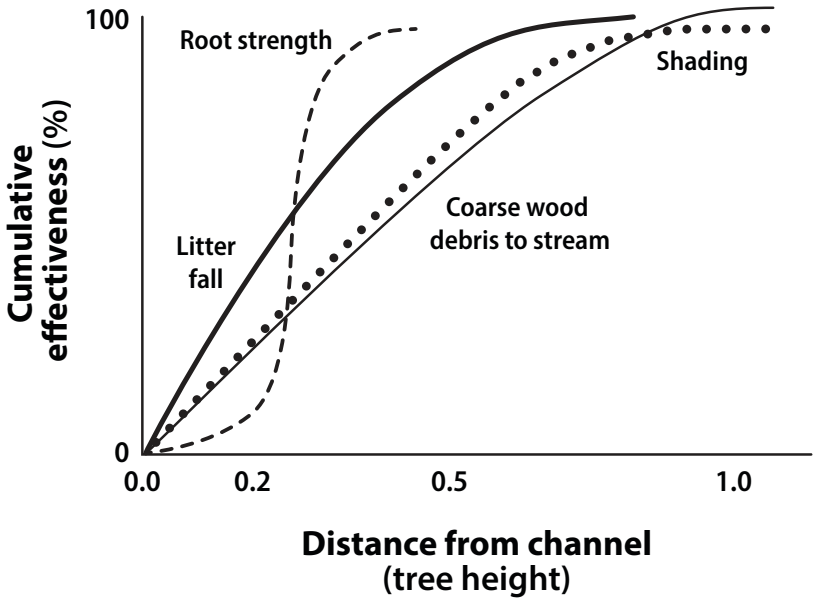


Figure 2.1. The "FEMAT Curves" (FEMAT 1993): a generalized conceptual model describing contributions of key riparian ecosystem functions to aquatic ecosystems as the distance from a stream channel increases. "Tree height" refers to average height of the tallest dominant tree (200 years old or greater); 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).

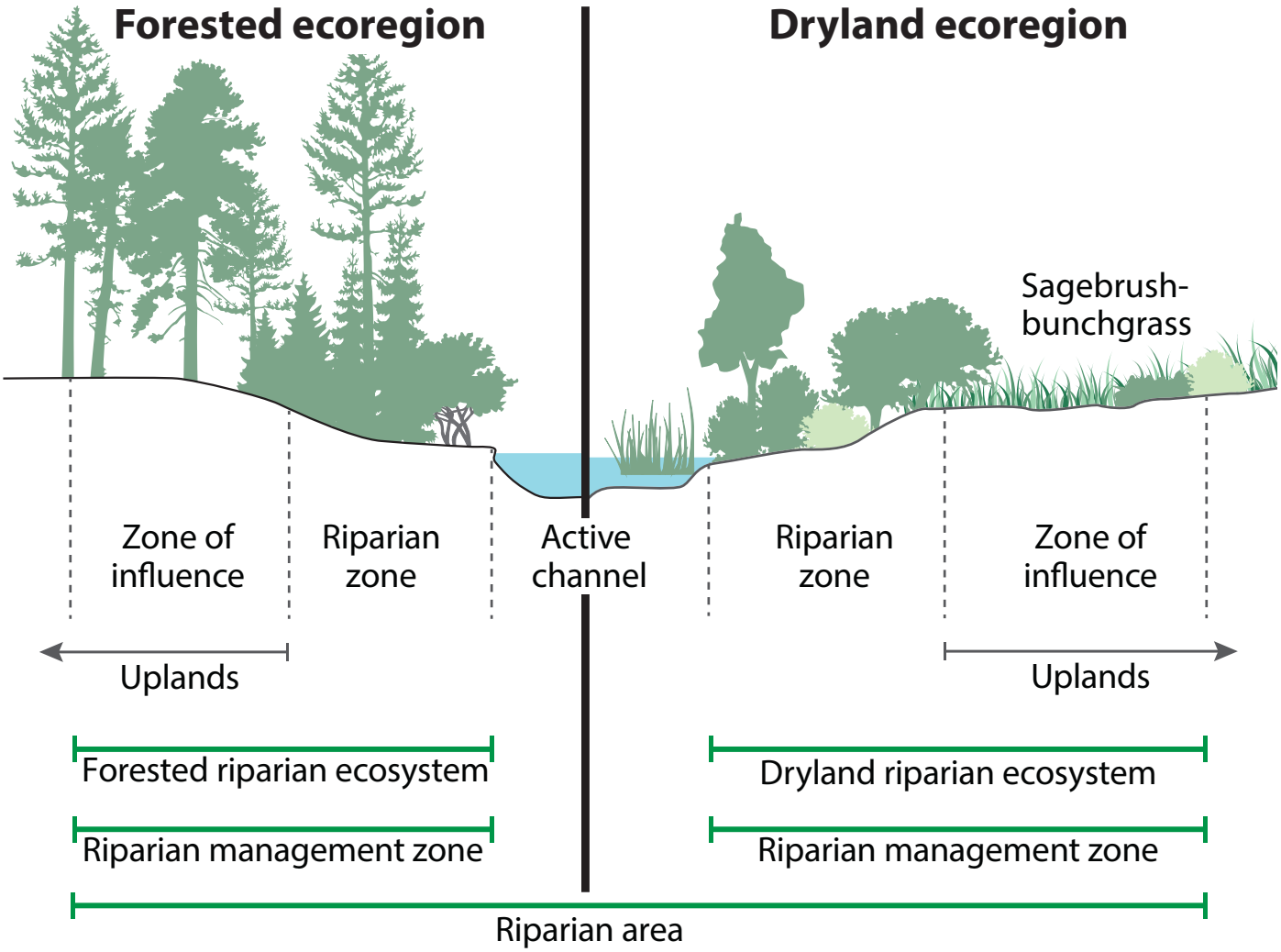


Figure 2.2. The diagram depicts the riparian management zone (RMZ) for both forested (left) and dryland (right) ecoregions. The RMZ is coincident with the riparian ecosystem, *which consists of the* riparian zone *(riparian vegetative community) and the* zone of influence. *The* riparian zone *extends 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.

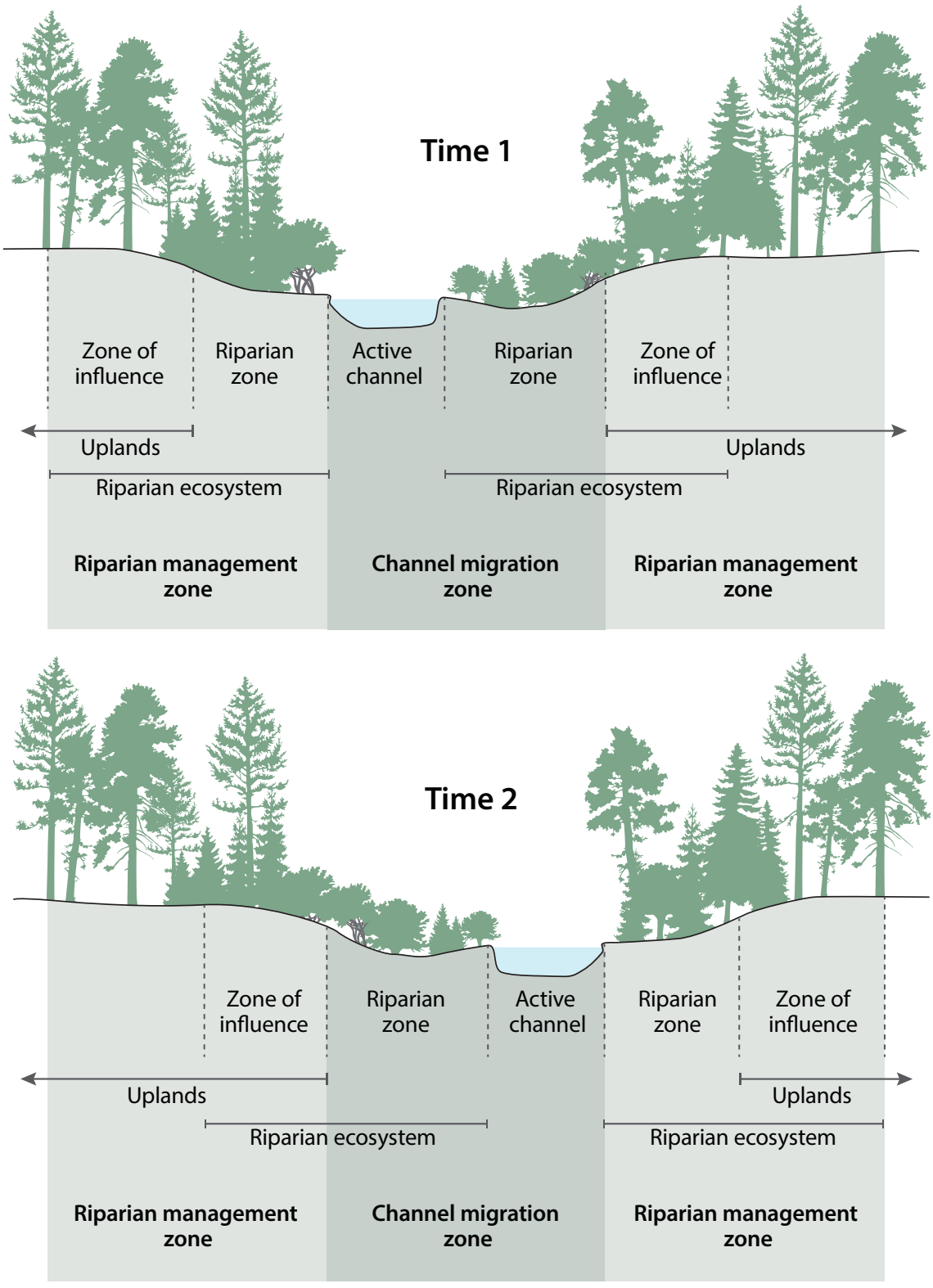


Figure 2.3. This diagram depicts the spatial relationship between the riparian management zone (RMZ) and channel migration zone (CMZ) over time. As the active channel moves laterally within the CMZ, the riparian ecosystem moves with it. As a result, when considering the establishment of an RMZ, delineation 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.

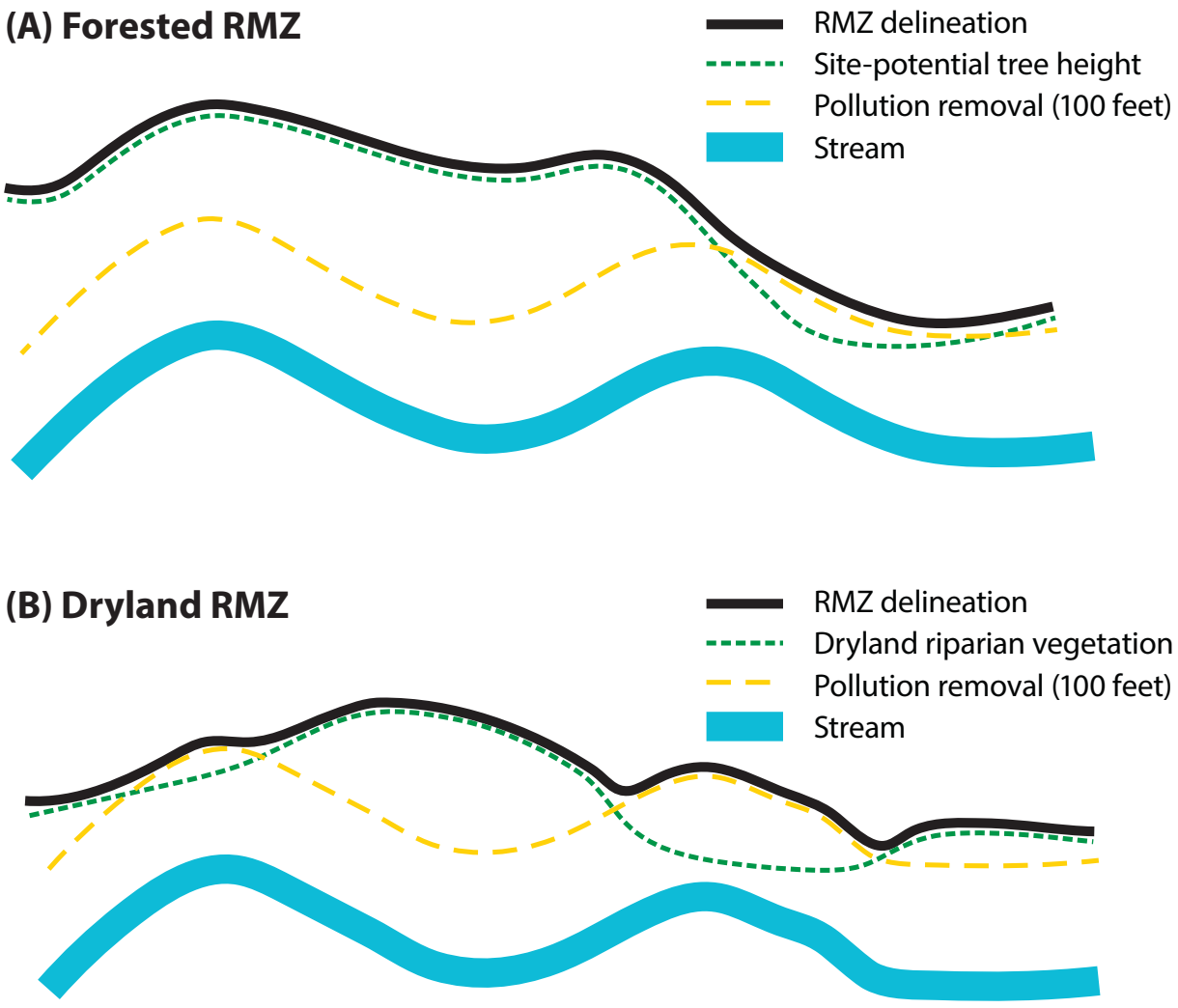


Figure 2.4. Aerial view of variable width RMZ delineation process for forested (A) and dryland (B) systems.

- *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.

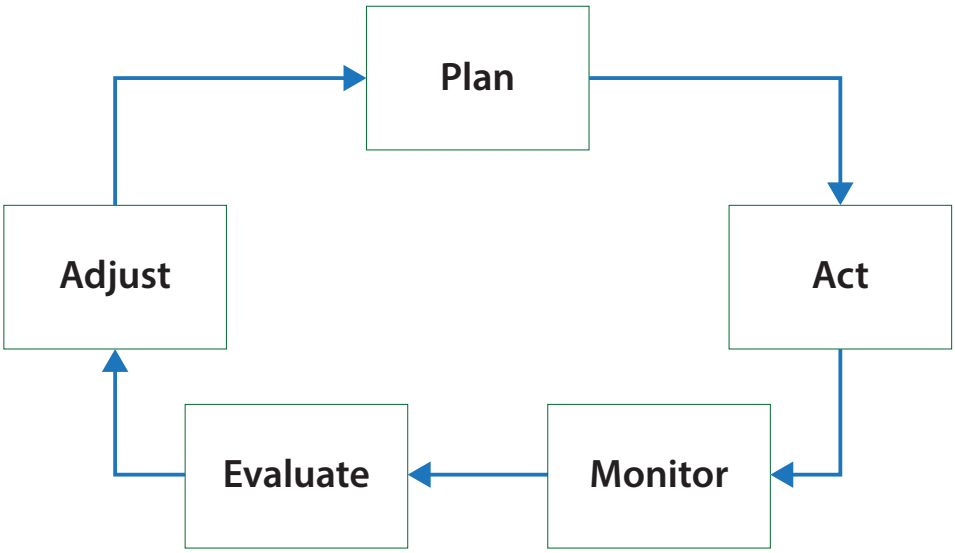


Figure 5.1. A simple depiction of the adaptive management cycle (modified from Bormann et al. 1994).

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.

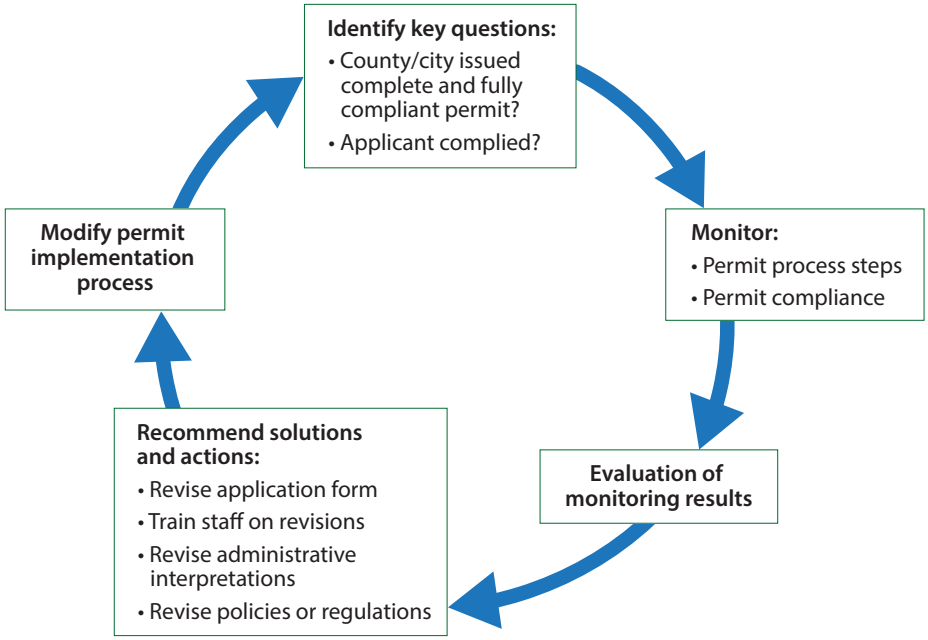


Figure 5.2. Depiction of the adaptive management cycle specific to permit compliance.

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.

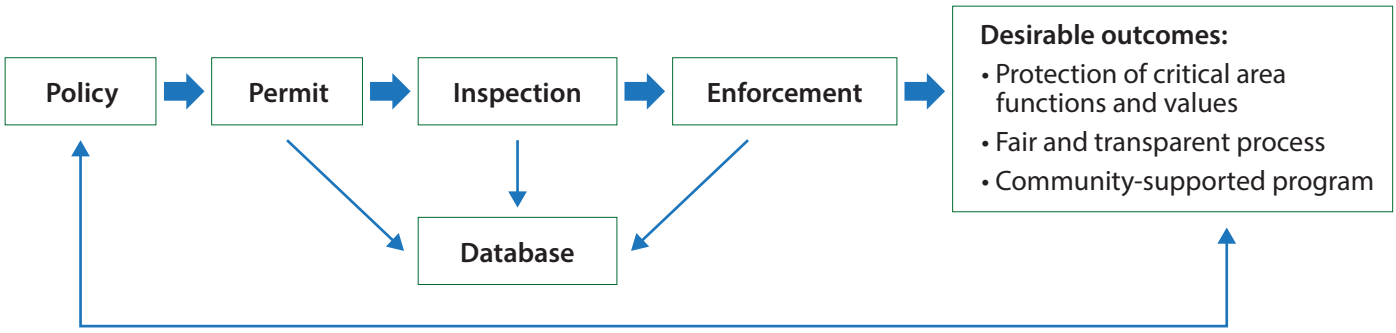


Figure 5.3. One system of permit accountability that includes implementation monitoring of internal permit processes, inspection for permit compliance, a database from which to judge outcomes, and a feedback loop connecting outcomes with policy intent.

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.

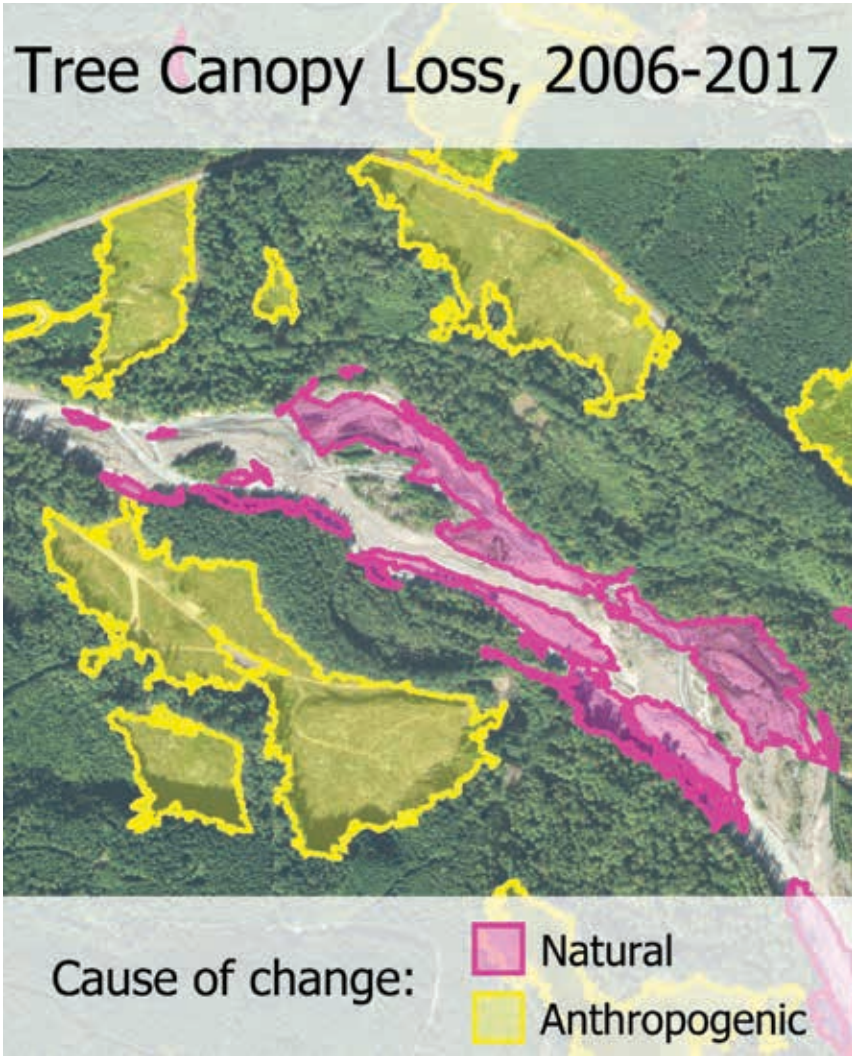
One goal of the pilot project was to answer several related sets of questions:

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

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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.

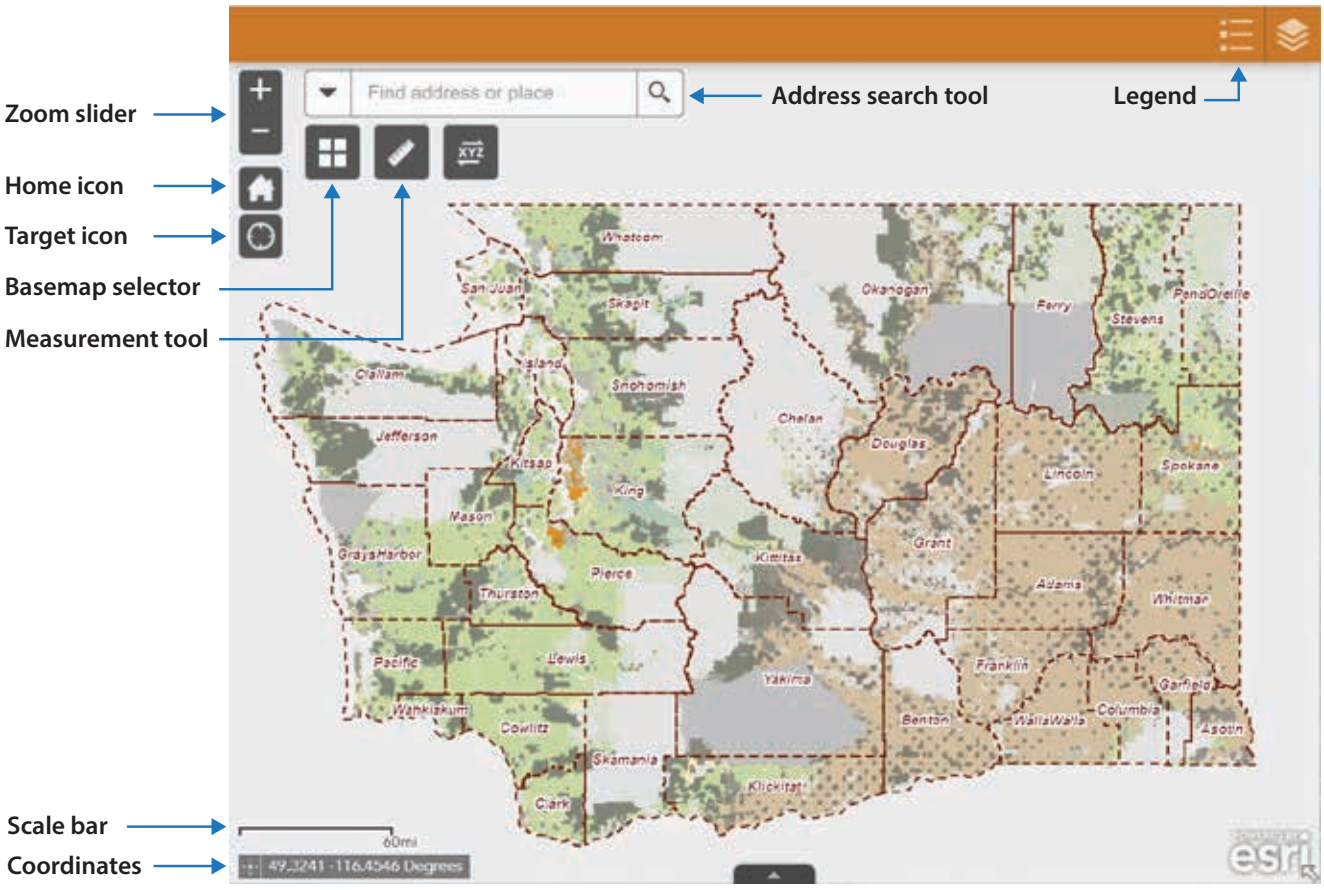

Figure A1. Tools available on the SPTH200 and RMZ Online Map.

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).

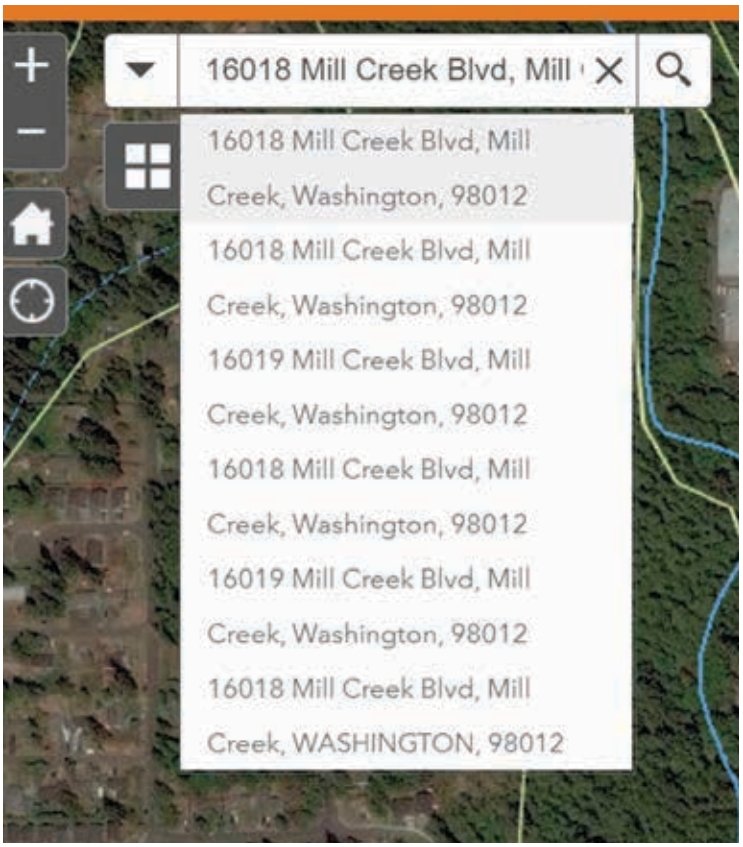

Figure A2. Using the Address Search tool.

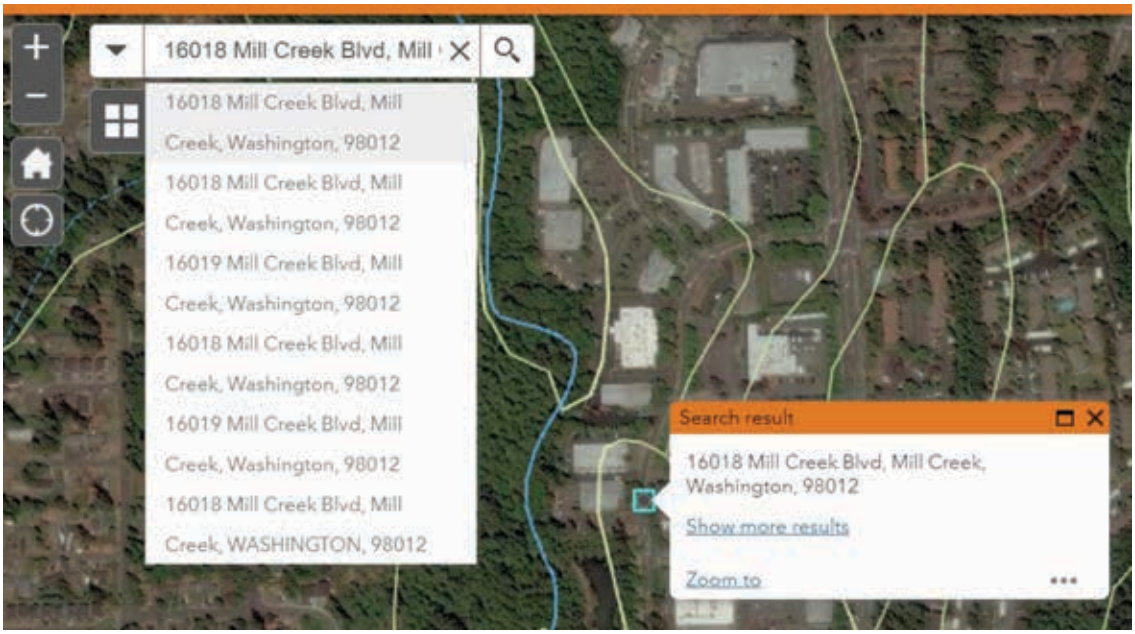

Figure A3. Zoomed in aerial image of the site address.

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.

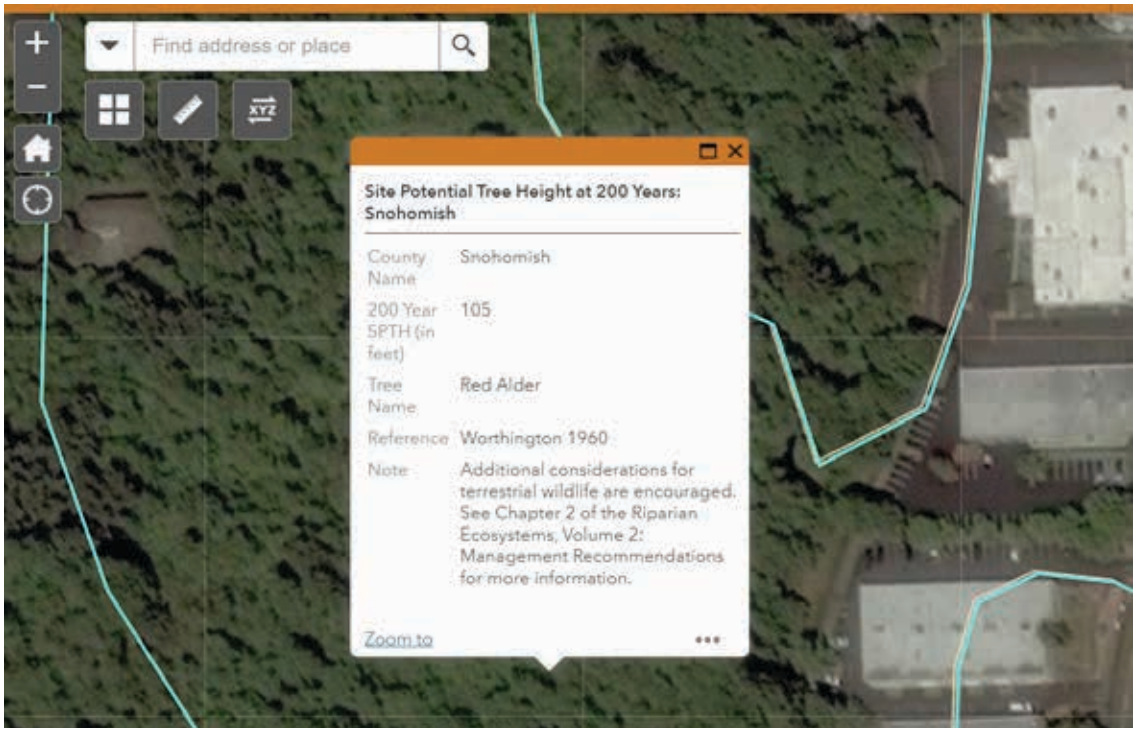

Figure A5. Bringing up the $SPTH_{200}$ information at the project site.

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.

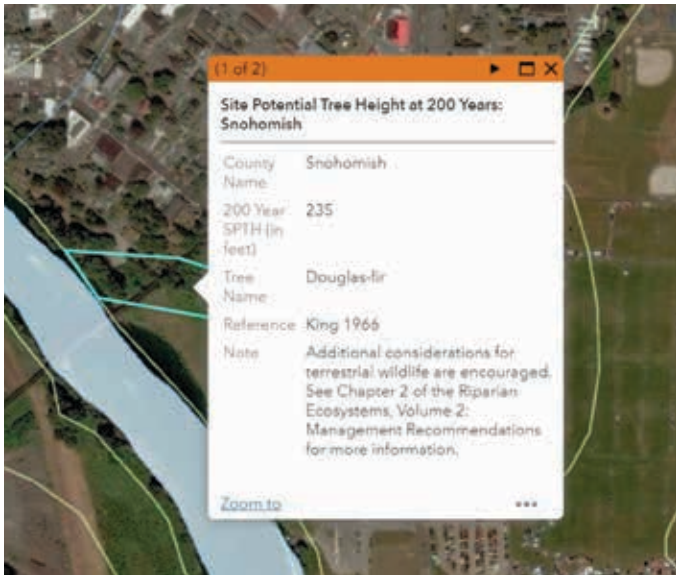

Figure A6a. SPTH information for the first of multiple tree species at a given site.

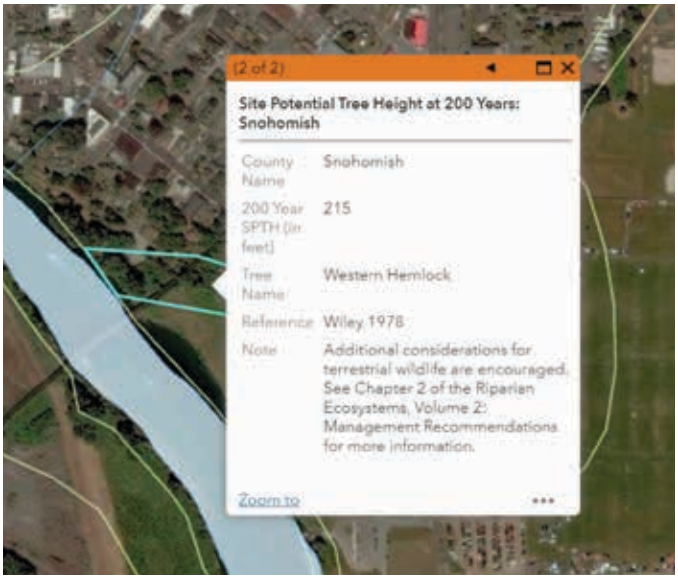

Figure A6b. $SPTH_{200}$ information for the second of multiple tree species at a given site.

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

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

August 30. 2024

Chris Pasinetti, Community Development Director
1309 Myrtle Avenue
Enumclaw, WA 98022

RE: Submittal ID 2024-S-7309, case #2022-C-195, WDFW comments regarding Enumclaw's draft Comprehensive Plan

Dear Mr. Pasinetti,

On behalf of the Washington Department of Fish and Wildlife (WDFW), thank you for the opportunity to comment on Enumclaw's draft Comprehensive Plan as part of the current periodic update. Within the State of Washington's land use decision-making framework, WDFW is considered 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 Comprehensive Plan language.

Policy Number	Policy Language (with WDFW suggestions in red)	WDFW Comment
Land Use		
Policy LU-1.11 Page LU-7	Consider development regulations that encourage walking. A. Consider reducing or eliminating parking requirements, while balancing the needs of commuters, tourists and local businesses. B. Consider zoning which permits proximity between houses of worship, residences, schools and neighborhood commercial businesses.	Open spaces should be designated, protected and connected. We propose that, along with requiring open space set-asides, site plans should demonstrate active efforts to connect these open spaces with others in the surrounding area. This open space corridor connection could serve pedestrian opportunities and wildlife habitat connectivity simultaneously. Additionally, open spaces are climate-resilient assets that can serve as community spaces. All development within dense or populated areas should strive for open

	C. Require site plans demonstrate an effort to connect newly constructed open spaces with adjacent open spaces.	space retention, creation, and *connection* for the benefit of people and the environment.
Goal LU–1 Page LU-7 Suggested Policy	Review development standards and regulations to ensure they possess an appropriate level of flexibility to promote efficient use of buildable lands, balanced with the need for predictable decision-making and environmental protection.	We suggest the addition of this policy to highlight the need for flexibility within developmental regulations to address environmental protection standards. Some examples of development standards that incorporate this include: • Flexible subdivision design, such as cluster development or conservation subdivisions. • Flexibility in lot size and configuration, including on-site density transfers to accommodate habitat patches and corridors. More examples can be found in WDFW's Landscape Planning for Washington's Wildlife.
Goal LU–2 Annexations Page LU-7 Suggested Policy	Protect, enhance, and preserve wetlands, riparian corridors, and open space corridors by avoiding these areas for annexation into Enumclaw's UGA, ensuring these areas can continue to serve essential functions for recreational and wildlife habitat corridor use.	Annexation must not diminish the functions stated in the adjacent policy. We suggest Enumclaw regularly update mapping information to clearly depict where open spaces, riparian corridors, and other critical areas are located to avoid these areas for annexation. Resources to help address this goal include WDFW's Priority Habitats and Species (PHS) mapping information, found on our website (link).
Goal LU-7 Page LU-10 Suggested Policy	To the greatest extent feasible, require new development and redevelopment to incorporate Low Impact Development (LID) techniques to enhance city-wide stormwater management. These practices shall improve water flow and quality while also delivering cost savings through ecosystem services.	As well as salmon recovery advantages, constructed wetlands and other green infrastructure projects planted with native trees and grasses can provide co-benefits that traditional gray infrastructure do not, including providing pollution filtration, mitigating emissions (carbon sequestration), and creating recreational opportunities (seasonal trails and picnic spots). Resources include U.S. Environmental Protection Agency - LID resources page as well as the Olympia Rain Garden Incentive Program, Puget Sound Green Stormwater Infrastructure Incentives Programs, Green Stormwater Infrastructure Assistance Programs Guidebook, and the Rain Garden Handbook for Western Washington. While these are generally small-scale projects, the cumulative impact of widespread implementation can be significant, especially in regard to watershed-wide salmon recovery goals.

Suggested Policy	Encourage energy-saving construction and building operation practices and the use of energy-conserving materials in all new construction and redevelopment of buildings.	Many sections within this Land Use element would benefit from the adjacent policy addition to ensure awareness of state-required energy efficiency standards. The Sustainable Development Code website is a great resource in outlining how to remove code barriers, create incentives, and fill regulatory gaps in pursuit of this policy's goals. See the city of Issaquah and the city of Bellevue's clean building incentive programs that aim to assist applicants reach these standards.
Transportation		
Policy TR-1.4 Page TR-3	Provide development incentives for the installation of elements that encourage transit, pedestrian, and bicycle usage and safe wildlife movement.	When discussing transportation in an area such as Enumclaw, wildlife movement must be planned in tandem with other transportation-related endeavors. We suggest including the adjacent addition in order to avoid an increase in safety concerns as it relates to wildlife collisions and additional wildlife conflict situations, as well as to facilitate habitat corridor linkages. To address this goal, we suggest Enumclaw: - Create a list of potential high-collision areas, taking note of all wildlife (including smaller animals such as frogs). - Employ wide bridges instead of culverts to facilitate wildlife passage under roads (which could also facilitate pedestrian and bicycle movement). - Increase the width and vegetation in right-of-way areas adjacent to pedestrian or recreational trail areas. As population densities increase, it is crucial to plan for wildlife movement now in order to avoid major conflict in the future, especially in rural areas that are in close proximity to urban areas or in areas slated for future growth. For additional resources, see The Washington Wildlife Habitat Connectivity Working Group, WSDOT's Reducing the risk of wildlife collisions website as well as Wildlife Habitat Connectivity Consideration in Fish Barrier Removal Projects, Montana Fish, Wildlife, and Parks' How to Build Fence with Wildlife in Mind, and WDFW's website.

Policy TR-2.2 Page TR 3-4	The following Transportation investments should have the highest funding priority: • Facilities and services necessary to keep local Levels of Service from falling below established minimum standards. • Facilities and services necessary to serve growth centers and areas experiencing significant development activity. • Multimodal Improvements that complete gaps, increase safety and the mobility of ~~both~~ freight, wildlife, and people, and those which are unlikely to occur as a result of new development. • Pedestrian improvements indicated on the safe walking route/ priority pedestrian route map/ active transportation network.	See comments above. Additionally, aligning pedestrian trail needs with wildlife corridor linkages would expand project eligibility for diverse funding opportunities and grant programs.
Policy TR 2.5 Page TR-4	Prepare a map illustrating desired safe walking routes to assist in prioritizing on and off-street improvements to the pedestrian system and develop a combined comprehensive trails and bicycle master plan.	We strongly encourage the consideration of wildlife movement within the early stages of development for this master plan. See comments above.
Policy TR-5.2 Page TR-5	Minimize stormwater runoff from impervious surfaces by incorporating best practices for low impact development and fish passage improvements in the construction, redevelopment, and retrofitting of transportation facilities.	We greatly appreciate the inclusion of this policy. See resources in comments related to Policy TR-1.4 above. We recommend utilizing these techniques in all stages of infrastructure use, as outlined in the adjacent policy edit.
Goal TR-5 Page TR-5	Integrate wildlife collision and habitat corridor data into future master plans to effectively	See comments above.

Suggested Policy	promote healthy and connected wildlife populations, while also reducing risks to public safety.	
Policy TR-7.2 Page TR-6	Consider new partnerships and innovative financing methods to fund and construct citywide transportation system improvements.	As stated above, aligning pedestrian trail needs with wildlife corridor linkages would expand project eligibility for diverse funding opportunities and grant programs. Similarly, culverts replaced for fish passage needs could also open opportunities for wildlife and pedestrian connection if culverts are replaced with larger underpasses. See WSDOT's Wildlife Habitat Connectivity Consideration in Fish Barrier Removal Projects for more information.
Housing		
Policy H-1.6 Page H-3	Enhance the appearance of and maintain public spaces in residential areas.	See comments in relation to Policy LU-1.11 above. Public spaces that are connected to adjacent open/public spaces can help facilitate pedestrian and wildlife corridor usage.
Goal H-1 Page H-3 Suggested Policy	Require, to the greatest extent feasible, the development of efficient and environmentally sensitive housing practices to minimize the impacts of infrastructure on natural resources and to address state energy efficiency, carbon reduction, and salmon recovery goals.	We suggest requiring these standards to the greatest extent feasible in order to meet salmon recovery (RCW 36.70A.172), energy efficiency, and other state requirements.
Goal H-1 Page H-3 Suggested Policy	Address the need for flexibility within developmental regulations to address environmental protection standards by updating regulations to include: • Flexible subdivision design, such as cluster development or conservation subdivisions. • Flexibility in lot size and configuration, including on-site density transfers to accommodate habitat patches and corridors.	These suggestions come from WDFW's Landscape Planning for Washington's Wildlife, which outlines that all landscapes, from the human-dominated (e.g., urban) to the relatively undisturbed (e.g., managed forests), can contribute to maintaining ecological health that benefits people and wildlife.

Policy H-2.6 Page H-4	Consider an incentive program in which developers would be allowed to deviate from the underlying zoning district's development standards if a portion of the units that are provided in the project are affordable to households making less than 80% of the City's AMI. The incentive program should not result in projects that consist primarily of affordable units. Possible incentives could include: • Additional dwelling units. • Increase in building height. • Reduced parking requirements. • ~~Reduced open space requirements.~~ • Increase in building lot coverage. • Reduce building lot sizes.	We strongly advise against using reduced open space requirements as an incentive, particularly for affordable housing initiatives. Open spaces are vital for community engagement, recreation, climate mitigation, and environmental health. Reducing access to these essential areas to promote affordable housing could adversely affect the well-being of an already vulnerable population.
Natural Environment + Climate Resilience		
Policy NE-1.2 Page NE-4	Encourage corridor development for pedestrian and wildlife routes.	See regulatory change suggestions in comments above in relation to Policy LU-1.11.
Policy NE-2.1 Page NE-4	Enhance all City parks and recreational facilities and programs with ecological process education. A. Consider as necessary municipal ordinances... B. Maintain land use regulations that include provisions for... C. Promote the creation and protection of wildlife habitat attributes in all spaces through educational efforts and community involvement.	For information on implementing wildlife habitat attributes in all public spaces, see WDFW's Habitat at Home resource as well as WDFW's Landscape Planning for Washington's Wildlife, especially "Chapter 6: Implementation through Comprehensive Plans, Development Regulations, and Incentive Programs," page 6-1. Some additional resources include the Trust for Public Lands, the NRPA Safe Routes to Parks Action Framework (which provides professionals with a "how-to" guide to implement Safe Routes to Parks strategies), and the Sustainable Development Code website.

Policy NE-3.3 Page NE-4	Avoid placing hazardous land uses and essential public facilities in the 500 year flood plain to increase their climate resiliency.	We greatly appreciate this policy as FEMA FIRM maps do not take climate change projections into consideration. As a result, projects relying solely on 100-year floodplain measurements may underestimate their actual flood risk.
Goal NE-5 Page NE-5 Suggested Policy	Carefully consider the ecosystem services and climate mitigation functions provided by critical areas in assessing project plans, especially if impact to these critical areas is proposed.	It is important to highlight the ecosystem services provided by natural resources. Protecting and restoring natural assets is often more cost-effective than engineered solutions. See FEMA's guide *Building Community Resilience with Nature-based Solutions*, as well as software to track these resources from Natural Capital Project. Furthermore, see Kitsap County's approach to quantifying ecosystem services through their Kitsap Natural Resource Asset Management Project.
Goal NE – 6 Page NE-5 Suggested Policy	Protect and restore watershed-scale processes to maximize ecological benefits, ecosystem services, and climate resilience by coordinating with adjacent jurisdictions.	Successful restoration, salmon recovery, and the functioning of healthy ecosystem processes cannot be accomplished without large-scale planning and coordination.
Policy NE-6.3 Page NE-6	Support enhancement of water quality through corrective and preventative methods including requiring best management practices (BMPs) and Low Impact Development (LID) methods, as well as offering education, planning, regulation, and enforcement~~,~~ incentives.	See resources in relation to Goal LU-7 above. Additionally, because of Enumclaw's geographic location near key salmon-bearing streams that offer slower, off-channel habitat for federally 'threatened' salmonid populations, it is critical that city regulations reflect salmon-recovery goals. Enumclaw is obligated (interlocal agreement, RCW 36.70A.172) to protect, preserve, and enhance this habitat.
Policy NE-12.3 Page NE-8	Consider developing an urban forestry program to address drought resistant species, preservation of significant trees and increase canopy.	In order to pursue this policy's goals, we recommend Enumclaw strive to create a tree canopy assessment, followed by a tree canopy plan in order to assess trends, set goals, and measure progress towards those goals. **This plan should also measure how well the City's tree-related ordinances are functioning in retaining trees on the landscape.** It may not be enough to rely on ordinances if there is not a system in place to track cumulative impacts over time. This plan could help the city pursue the adjacent policy's goals, including increasing property values, reducing stormwater runoff and erosion,

		improving air quality, and reducing energy used for heating and cooling. Resources: • City of Tacoma is a great resource for exploring how tree canopy plans can become a community effort, how data can be presented, and how to track canopy loss/gain. • Data resources include the USDA website, WDFW's change detection tree canopy data, the Puget Sound Washington Urban Canopy Project, and the WA DNR website. • Example ordinances and plans can be found on the MRSC website. • Funding resources can be found on the DNR website (*Commissioner Franz Announces $8 Million in Urban Forestry Grants*). • Discover the value of the benefits provided by individual trees around your home and in your community with the National Tree Benefit Calculator. See also the city of Everett's Tree Keeper website.
Parks, Recreation, and Open Space		
Policy PK-1.1 Page PK-4	The priorities for acquisition of park land are as follows in order of priority: A. Land in developing areas as necessary to meet minimum adopted levels of service for neighborhood and community park land; B. Trail corridors identified in the Park Plan or identified as areas with frequent wildlife collisions; and, C. Open space areas, wildlife corridors, historic structures or areas and view corridors that contribute to or enhance the unique character of Enumclaw.	Trail corridors should consider wildlife movement when prioritizing areas for acquisition. See comments in relation to Policy TR-1.4 above.
Policy PK-5.2 Page PK-6	Trail systems should be separated from vehicle travel lanes by a planter strip to improve the user experience. Ideally, trails shall have vegetative buffers that serve	See comments in relation to Policy TR-1.4 above.

	aesthetic, safety, and wildlife corridor habitat purposes.	
Suggested Policy	Protect and increase tree canopy cover to boost carbon sequestration, reduce heat islands, and improve air quality, prioritizing overburdened communities.	See resources in comments above in relation to Policy NE-12.3.
Suggested Policy	Calculate the ecosystem services parks and open spaces provide in order to better assess cost benefits.	See resources in comments above in relation to Policy NE-5.
Utilities		
Policy U-10 Page U-6 Suggested Policy	To the greatest extent feasible, restrict sewer system placement within frequently flooded areas.	The State Department of Health adopted rules establishing public health standards for location, design, installation, operation, maintenance, and monitoring of onsite sewage systems (OSS), including the responsibility of jurisdictions to identify any areas where OSS could pose an increased public health risk. The list of areas to identify includes frequently flooded areas. For assessing future climate-related flooding conditions, see Climate Mapping for a Resilient Washington, as well as FEMA's Resilience Analysis and Planning Tool (RAPT) for resources in visualizing these hazard areas.
Policy U-7 Page U-6 Suggested Policy	Support the benefits provided by healthy, connected floodplains and riparian systems, such as water attenuation, pollution filtration, and drought resistance.	Natural water infiltration and attenuation processes help retain, cool, and filter water. Additionally, we recommend incorporating Riparian Management Zones (RMZs) into Enumclaw's Critical Area Ordinance update to help address this goal. RMZs should be designated and protected as a critical area and replace outdated 'stream buffer' terminology. These areas "are disproportionately important, relative to area, for aquatic species (e.g., salmon) and terrestrial wildlife," as stated in WDFW's Riparian Ecosystems, Volume 2: Management Recommendations and supported by WDFW's BAS which highlights key ecosystem service benefits RMZs provide. Please see WDFW's checklist to compare Enumclaw's current Critical Areas Ordinance to agency priorities.

Capital Facilities		
Goal CF-1 Page CF-6	Identify and prioritize stormwater retrofits to address impaired watershed processes and reduce effective impervious surface areas.	As much of Enumclaw's stormwater drains into salmon-bearing streams, such as Newaukum Creek, it is important to highlight the work that is being done to ensure corrections are planned for the problem areas identified on page CF-8 of this element. Additionally, combining stormwater projects with salmon recovery opens up new avenues for grant funding opportunities.
Policy CF-4.2 Page CF-9	At a minimum, the criteria for siting essential public facilities shall include the existing conditional use permit requirements for those facilities that present siting difficulties. Included in the review shall be an environmental analysis, either through the established NEPA or SEPA procedures, to include analysis of likely impacts related to climate change, local economic development, equity, and public health impacts.	We appreciate the consideration for climate change within this policy as it relates to siting essential public facilities. Given that capital facilities represent significant public investments, it is prudent to ensure that facilities are designed and sited to be resilient to climate impacts. Local governments should review their capital facilities plans in the context of climate change projections to ensure that planned facilities will be resilient throughout their intended lifespan and make changes as needed.

Please see the Sound Choices Checklist for additional guidance for other elements in the Comprehensive Plan.

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 me or our Regional Land Use Lead, Morgan Krueger (morgan.krueger@dfw.wa.gov).

Sincerely,

Timothy Stapleton

Washington Department of Fish and Wildlife
Region 4 – Habitat Program Manager

CC:
Morgan Krueger, Regional Land Use Lead (Morgan.Krueger@dfw.wa.gov)
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State of Washington
Department of Fish and Wildlife, Region 4
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August 30, 2024

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RE: Submittal ID 2024-S-7309, WDFW comments regarding Enumclaw's draft Critical Area Ordinance

Dear Mr. Pasinetti,

On behalf of the Washington Department of Fish and Wildlife (WDFW), thank you for the opportunity to comment on Enumclaw's draft Critical Area Ordinance (CAO) as part of the current periodic update. Within the State of Washington's land use decision-making framework, WDFW is considered 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 CAO language.

Policy Number	Policy Language (with WDFW suggestions in red)	WDFW Comment
19.02.010 Policy, goals, purpose, and intent Page 2	General comment.	This section seems to repeat much of the same information in sections A-D. For reference, see Black Diamond's Sensitive Areas code: 19.10.01 - Purpose. As shown, this section of Black Diamond's code accurately and succinctly covers the need to utilize best available science (WAC 365-195-900), give special consideration to conservation and protection of anadromous fisheries (as required by RCW 36.70A.172),

		achieve 'no net loss' standards (WAC 365-190-080), protect public safety, etc. This section should also clearly outline the five types of critical areas required to be included within this section of municipal code (wetlands, areas of critical recharging effect on aquifers used for potable water, fish and wildlife habitat conservation areas, frequently flooded areas, and geologically hazardous areas).
19.02.010 (A) Policy, goals, purpose, and intent Page 2	1. ~~Avoid or minimize damage to critical areas wherever possible~~ Follow the correct mitigation sequencing when impacts to critical areas are proposed;	We suggest any section that mentions mitigation reference the required mitigation sequence as outlined in WAC 197-11-768.
19.02.010 (A) Policy, goals, purpose, and intent Page 2	6. Achieve no net loss of wetland function and value by requiring restoration or enhancement of degraded wetlands or creation of new wetlands to offset losses that are unavoidable;	We recommend no net loss language be covered earlier, encompassing all critical areas and not just wetlands, as required by WAC 365-190-080.
19.02.010 (B) Policy, goals, purpose, and intent Page 3	4. Allow modification and/or obliteration of low function and value wetland, stream, and wildlife habitats in conjunction with off-site mitigation and restoration in designated areas where the addition of created and/or enhanced habitats will increase fish and wildlife production, public benefits, and economic viability in the city limits and urban growth areas; and	We do not recommend allowing the removal of critical area habitat with the intent to replace the functions and values elsewhere. Streams and wildlife habitat functions are predominately place-based. Removing these critical areas from an environment will often result in a net loss of ecological values and functions.
19.02.010 (B) Policy, goals, purpose, and intent Page 3	5. ~~Prevent cumulative adverse environmental impacts to water quality, wetlands, and fish and wildlife habitat, and the overall net loss of wetlands, frequently flooded areas, and habitat conservation areas~~ Prevent a net loss of ecological values and functions for all critical areas.	In this section of Enumclaw's municipal code, it seems there is confusion over 'net loss.' As described in WAC 365-190-080, no net loss applies to overall ecological values and functions. Stated within the adjacent policy, net loss seems to refer to an amount of area lost. Specifying no net loss for ecological values and functions encompasses all losses that may impact critical areas, including but not limited to surface area loss.
19.02.010 (C)	1. Defining, designating, and classifying ~~ecologically sensitive and hazardous~~	As mentioned above, we strongly recommend this section of code clearly

Policy, goals, purpose, and intent Page 3	~~areas to be regulated in the city~~ critical areas as; • Wetlands; • Critical aquifer recharge areas; • Fish and wildlife habitat conservation areas; • Frequently flooded areas and; • Geologically hazardous areas	define what critical areas are, as stated in WAC 365-196-830.
19.02.010 (D) Policy, goals, purpose, and intent Page 4	In addition, it is the intent of the city that activities in or affecting wetlands not threaten public safety, cause nuisances, or destroy or degrade natural wetland functions and values by:	As outlined in our Riparian Management Zone Checklist for Critical Areas Ordinances, we suggest including within this section the intent to protect all key riparian ecosystem functions (i.e., shade, root strength, nutrient input, wood input, and pollution control).
19.02.020 Applicability, regulated activities, and exempt activities. Page 5	A. All regulated activities shall be subject to the provisions of this chapter, except those activities... In the event of any conflict between these regulations and any other regulations, the more restrictive shall apply.	It is crucial that there is a provision within this chapter that stipulates what will happen in the event of conflicting code provisions. It is commonplace that the more restrictive regulation shall apply.
19.02.020 Applicability, regulated activities, and exempt activities. Page 5	B. All exempted activities shall use reasonable methods to avoid potential impacts to critical areas. By finding that an activity proposed within a critical area or its associated buffer is exempt from the provisions of this chapter, the administrator is not granting permission to degrade a critical area or ignore risk from natural hazards. Any incidental damage to, or alteration of, a critical area that is not a necessary outcome of the exempted activity shall be restored, rehabilitated, or replaced at the responsible party's expense and result in no net loss to ecological values and functions.	It is important that no net loss language is repeated here to ensure state law is met in the outcome of these projects.
19.02.020 (B) Applicability, regulated activities, and exempt activities.	11. Public and private pedestrian trails, except in wetlands, are subject to the following: f. Require impacts and disturbances from recreational trails and interpretive	We recommend including the adjacent provision when assessing the impacts that pedestrian trails will have on critical areas. WDFW's Priority Habitats and Species program outlined the areas and management recommendations to consider

Page 8	facilities are minimized to the extent practicable, informed by Priority Habitats and Species data and management recommendations	in order to accurately protect these resources.
19.02.020 (B).12.b. Applicability, regulated activities, and exempt activities. Page 9	(2) Tree cutting shall be limited to pruning and crown thinning, unless otherwise justified by a qualified professional. Where pruning or crown thinning is not sufficient to address the hazard, trees should be removed or converted to wildlife snags;	We greatly appreciate the inclusion of snag creation within this section. If needed, see the resources on our webpage (link).
19.02.030 Exceptions. Page 11	A. Exception – Subdivisions with Substantial Completion of Infrastructure. A building permit application shall not be denied under this chapter if there has been substantial completion of the infrastructure of the plat within which the subject property of the permit is specifically located; however, a floodplain development permit is required, and the completed infrastructure cannot adversely impact critical area habitat or endangered species. A determination of substantial completion shall be based on the administrator's assessment of existing constructed infrastructure such as streets, utilities, and drainage improvements. 1. Typically "substantial completion" means the amount of construction within a particular project area has impacted critical areas to the maximum extent that would be attributable to the project actions and on-site mitigation is neither economically nor ecologically viable. 2. The administrator will confer with the city manager, the city's risk management specialist, and the city attorney regarding the consequences of a decision to deny a building permit for a project with a valid clearing and grading permit, approved site plans,	I have not encountered a section of code like this before and am unclear on its intended application. Is this a provision that Enumclaw commonly utilizes, and could you provide some context on its practical use?

	and an authorization to proceed with construction.	
19.02.030 Exceptions. Page 11	B. Exception – Reasonable Use. "Reasonable use" exceptions do not apply within shoreline jurisdiction or within areas of special flood hazard. The intent of reasonable use is meant for the construction of single-family homes or individual projects, not commercial developments, subdivisions, or similar large-scale projects.	We encourage Enumclaw to further specify the original intent for 'reasonable use.'
19.02.050 Finding of fact. Page 14	General comment.	We recommend this section, which defines the five types of critical areas, come earlier within this chapter.
19.02.060 Frequently flooded areas. Page 14	...The best available information for flood hazard area identification as outlined in subsection (C)(1) of this section shall be the basis for regulation until a new FIRM is issued that incorporates data utilized under subsection (C)(1) of this section.	FEMA's Flood Insurance Rate Map (FIRM) modeling does not take climate change projections into consideration. We suggest Enumclaw supplement FIRM maps with regulations that consider climate change projections. For example, King County regulations place 'Flood Protection Elevations' three feet above base flood elevation for development within flood-prone areas. For assessing future conditions, see Climate Mapping for a Resilient Washington, as well as FEMA's Resilience Analysis and Planning Tool (RAPT).
19.02.100 Fish and wildlife conservation areas – Habitat types and buffer widths. Page 26	A. Finding of Fact. There are eight types of habitat listed in ~~WAC 365-190-080(5)~~ WAC 365-190-130 to be considered for designation~~ed~~ as fish and wildlife habitat conservation areas (FWHCAs). ~~In addition, there are six considerations to be factored into the designation process. Within t~~The urban growth boundary within the city of Enumclaw ~~and its urban growth areas there are only~~ encompasses ~~two types of habitat present that will be classified or designated as fish and wildlife habitat conservation areas~~ the following types of FWHCAs:~~. The two~~	WAC 365-190-130 is the correct section of WAC referenced here. We also recommend accurately assessing the types of FWHCAs present within Enumclaw. Including WDFW's Priority Habitats and Species (PHS) information is strongly recommended, as this is the largest database in the state for important habitats, species, and mapped location data of their occurrences. PHS information is already required in Enumclaw's code for critical area reports. Additionally, we recommend classifying riparian management zones (RMZs) as a type of FWHCA in order to stay current with

	~~types are stream habitat and buffers (riparian areas) adjacent to regulated streams or water bodies.~~ (a) Areas where endangered, threatened, and sensitive species have a primary association; (b) The approximate location and extent of habitat conservation areas are shown on the following map adopted by the City, as revised: Washington Department of Fish and Wildlife Priority Habitat and Species maps; (c) Areas in which state-listed priority species are found, have a primary association with, or contain suitable habitat for said listed species, as listed on the Washington Department of Fish and Wildlife's Priority Habitats and Species list; (d) Stream corridors and riparian management zones designated on the City critical areas map (e) Habitats and species of local importance, as determined locally; (f) Naturally occurring ponds under 20 acres and their submerged aquatic beds that provide fish or wildlife habitat; (g) Waters of the state;	Best Available Science (BAS) (Riparian Ecosystems, Vol. 1) as required by WAC 365-195-900. This BAS replaces stream buffer widths with RMZs measured by the Site Potential Tree Height at 200 years ($SPTH_{200}$). See Riparian Ecosystems, Vol. 2 for management recommendations. Vol. 2 also provides specific resources on how to determine RMZ widths, specifying that RMZs should be at least 100 feet wide to effectively remove pollution. In reviewing the current scientific literature (Vol. 1), we found no evidence that full riparian ecosystem functions 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.
19.02.100 (B) Fish and wildlife conservation areas – Habitat types and buffer widths. Page 27	6. The location of all ~~fish-bearing~~ streams within 200 feet of the project site, corresponding buffers, and the high water mark shall be identified on a site plan that shall be included in the critical areas report.	It is crucial that ***all*** streams are mapped and protected as critical areas. Identifying streams within 200 feet of the project site is also recommended, as construction and long-term outcomes of newly constructed projects may negatively impact adjacent critical areas not necessarily located on-site.
19.02.100 (C) Fish and wildlife conservation areas – Habitat types and buffer widths. Page 27	Stream Type.	As outlined in comments above (19.02.100 (A)), all streams should be protected without bias for fish presence. See Anacortes municipal code for reference: 19.70.330

19.02.100 (C) Fish and wildlife conservation areas – Habitat types and buffer widths. Page 28	~~5. Type O for watercourses that do not have enough flow energy to scour a stream channel to mineral soil or bedrock and that do not have fish use. This latter type is sometimes referred to as a swale or drainage swale~~	Any naturally occurring watercourse must be considered and regulated as a critical area, whether that be a stream or wetland.
19.02.100 (D) Fish and wildlife conservation areas – Habitat types and buffer widths. Page 28	Stream Buffer.	We suggest this section incorporate BAS by referencing RMZs instead of 'stream buffers.' Using stagnant stream buffer widths without considering site-specific characteristics results in a net loss of ecological values and functions. At a minimum, all streams should have an RMZ of 100 feet in order for pollution removal. Type Ns and Np waters within this table are listed as having buffers far below this minimum (30 feet and 60 feet, respectively). Other buffers listed in this table may result in degraded riparian areas, as all ecosystem functions and values are not being accounted for (i.e. shade, root strength, nutrient input, wood input and pollution control). Please see above comments, as well as RMZ mapping resources: • RMZ web app map • RMZ downloads for jurisdiction mapping purposes We also recommend using WDFW's RMZ checklist as a tool to supplement Enumclaw's current CAO with these suggestions. The checklist addendum provides code language used by other local jurisdictions.
19.02.100 (D) Fish and wildlife conservation areas – Habitat types and buffer widths. Page 28	~~Water Type O is not a DNR classification, but has been adopted into this chapter to provide regulatory guidance for vegetated swales. The city will not impose a buffer requirement on water Type O unless the administrator is convinced, on the basis of available field data and personal knowledge, that a buffer is needed to protect downstream critical areas from a risk of~~	As stated above, any naturally occurring watercourse must be considered and regulated as a critical area, whether that be a stream or wetland, and requires corresponding buffers to ensure no net loss of that critical area's ecological values and functions.

	~~significant adverse impact due to on-site water quality degradation.~~	
19.02.100 Fish and wildlife conservation areas – Habitat types and buffer widths. Page 28	E. Other Habitat areas. Protection standards for fish and wildlife other than ~~streams and~~ lake~~s~~ are~~a~~ as follows:	WDFW's PHS program encompasses all the RMZ recommendations given here. If needed, Enumclaw could include stream provisions within this section. The city of Burlington has adopted our science in a similar way, stating 'refer to WDFW's recommendations' within their stream section of code.
19.02.120 Critical areas maps and databases. Page 29	C. The approximate location and extent of habitat conservation area-associated critical areas are shown on the following map adopted by the City, as revised: Washington Department of Fish and Wildlife Priority Habitat and Species maps	As noted above, this map encompasses the largest database in the state for important habitats, species, and mapped location data of their occurrences.
19.02.140 (D) Application.	1. The administrator, when requested by the applicant, may waive the delineation of the boundary requirement for the applicant and, in lieu of delineation by the applicant, perform the delineation. a. All wetland delineations will be completed in accordance with... b. All RMZ delineations will be completed in accordance with WDFW's Riparian Ecosystems, Volume 2: Management Recommendations, as amended.	As stated above, BAS dictates that RMZs are measured using the $SPTH_{200}$ methodology.
19.02.160 (A).1 Criteria for permit review, approval, denial, and issuance.	A. A permit shall only be granted if the permit, as conditioned, is consistent with the purposes and intent of this chapter. Additionally, permits shall only be granted if: 1. A proposed action follows the proper mitigation sequence outlined in 19.02.230 ~~:~~ ~~a. Avoids significant adverse impacts to critical areas; or~~	We strongly recommend using succinct, legally accurate language, such as utilizing the mitigation sequence section of code.

	~~b. Takes affirmative and appropriate measures to minimize significant adverse impacts to critical areas; or~~ ~~c. Mitigates (compensates for) unavoidable significant adverse impacts to critical areas; and~~ ~~d. Assures no net loss of wetland function and value;~~	
19.02.190 Critical area development standards. Page 37	A. Area of Special Flood Hazard – Development Standards.	We encourage Enumclaw to consult the National Flood Insurance Program Flood Damage Prevention Ordinance, Washington Model (Revised 12/09/2019). It is advised that this section of code have its own chapter. As stated within this model, "This ordinance, as developed by FEMA and the Washington Department of Ecology, supersedes previous versions and includes all the minimum standards required as a condition of participation in the NFIP. It will be used by FEMA and state staff as the basis for providing technical assistance and compliance reviews during the Community Assistance Contact (CAC) and Community Assistance Visit (CAV) process to ensure federal and state law are met."
19.02.190 Critical area development standards. Page 37	A. Area of Special Flood Hazard – Development Standards. In all areas of special flood hazard where base flood elevation data has been provided as set forth in EMC 19.02.060(B)(1)(a), Basis for Establishing the Areas of Special Flood Hazard, or EMC 19.02.060(C)(1), Uses of Other Base Flood Data, the following standards are required:	How is this section of code limiting development with special flood hazard areas? It is crucial that allowances for development within these areas are construed narrowly and only when all other options have been exhausted. Additionally, and as stated above, FEMA's Flood Insurance Rate Map (FIRM) modeling does not take climate change projections into consideration. We suggest Enumclaw supplement FIRM maps with regulations that consider climate change projections. For example, King County regulations place 'Flood Protection Elevations' three feet above base flood elevation for development within flood-prone areas.

19.02.190 (A).6 Critical area development standards. Page 37	a. In AE and A1-30 zones or other A zoned areas where the BFE has been determined or can be reasonably obtained, new construction or substantial improvement of any residential structure shall have the lowest floor, including basement, elevated one foot or more above base flood elevation. Mechanical equipment and utilities shall be waterproof or elevated at least one foot above the BFE.	As stated above, one foot is often insufficient. Stricter regulations should apply.
19.02.210 Critical area tracts and easements. Page 47	A. Critical Area Management Tracts. As a condition of any permit, the city shall ~~may~~ require the permit holder to create a separate critical area management tract containing the areas determined to be critical areas. Critical area management tracts are legally created tracts containing critical areas, and compensation areas that shall remain undeveloped in perpetuity, except for allowed activities pursuant to this chapter...	It is crucial that the city maintains a record of all critical areas found through project applications and protects them in perpetuity. Compiling data gathered by consultants for all projects that impact critical areas can be a cost-effective way for a city to update critical area maps.
19.02.210 Critical area tracts and easements. Page 47	C. Marking During Construction. The location of the outer extent of the critical area buffer and the areas to be disturbed pursuant to an approved permit shall be marked in the field to prevent unnecessary disturbance by individuals and equipment during the development or construction of the permitted activity. Such field markings shall be approved by the city prior to the commencement of permitted activities. Such field markings shall be maintained throughout the duration of the permit.	The critical area *buffer* must not be disturbed, which protects and provides key ecological functions and values to the critical area.
19.02.230 Mitigation sequencing – Decision criteria. Page 48	A. Eligibility for Reasonable Use Exception Application.	This seems out of place, as reasonable use was discussed earlier in this chapter.

19.02.230 Mitigation sequencing – Decision criteria. Page 48	D. Mitigation of Unavoidable Critical Area Impacts as Part of a Reasonable Use Exception.	As noted above, reasonable use was already addressed earlier in this chapter. Additionally, no impact on critical areas can result in a net loss of ecological values and functions. If on-site mitigation is infeasible, a pathway must be given for off-site in order to achieve this requirement.
19.02.250 Critical area impact mitigation. Page 51	C. The overall goal of any critical areas mitigation project designed and implemented to compensate for wetland or fish and wildlife habitat conservation area impacts shall be no net loss of habitat (wetland, stream, riparian area, buffer, pond, etc.) functions and values and to strive for a net resource gain in habitat functions and values over present conditions. Compensation should be completed, whenever it is feasible, prior to any critical area alteration.	We greatly appreciate the intent for net ecological gain within this section.
19.02.250 Critical area impact mitigation. Page 52	F. Type and Location of Mitigation. Unless it is demonstrated that a higher level of ecological functioning would result from an alternate approach, compensatory mitigation for ecological functions shall be:	We recommend making it clearer in this section that on-site, in-kind compensatory mitigation is preferred and shall be considered first.
Appendix C Mitigation plan requirements. Page 62	A. Baseline Information. A written assessment and accompanying maps drawn to an appropriate scale of the: 1. Impacted wetland including, at a minimum, wetland delineation; existing wetland acreage; vegetative, faunal, and hydrologic characteristics; soil and substrate conditions; topographic elevations; 2. Impacted wetland functions and values shall be described using the system approved by the administrator; and 3. Compensation site, if different from the impacted wetland site, including at a minimum: existing acreage; vegetative, faunal and hydrologic conditions; relationship within	It seems as though wetlands are the only critical area with specific mitigation requirements within this chapter. We strongly recommend provisions for mitigation impacts to RMZs that similarly ensure no net loss of these critical area values and functions.

	watershed and to existing water bodies; soil and substrate conditions; topographic elevations; existing and proposed adjacent site conditions; buffers; and ownership.	
Appendix D Definitions.	"Hazard tree" is defined as a threat to life, property, or public safety. Require that the method of hazard tree removal not adversely affect riparian ecosystem functions to the extent practicable, encourage the creation of snags (Priority Habitat features) rather than complete tree removal, involve avoidance and minimization of damage to remaining trees and vegetation within the RMZ, and require a qualified arborist to evaluate requests for hazard tree removal.	Hazard tree is mentioned in 19.02.020 Applicability, regulated activities, and exempt activities, and should be defined for clarity. This suggestion comes from section N. of WDFW's Riparian Management Zone Checklist for Critical Areas Ordinances.
Appendix D Definitions.	"Riparian management zone" (RMZ) means an 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 channel migration zone (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.	As mentioned above, to implement Best Available Science, we recommend replacing stream buffer terminology with Riparian Management Zone. We appreciate Enumclaw's inclusion of the channel migration zone already within this draft.

Thank you for taking the time to consider our recommendations to better reflect the best available science for fish and wildlife habitats 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 me or our Regional Land Use Lead, Morgan Krueger (morgan.krueger@dfw.wa.gov).

Sincerely,

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