Synthesis of Riparian Buffer Best Available Science: Informing Variable-Width Buffers in the Lower Snoqualmie Valley

May 2019

King County

Department of Natural Resources and Parks
Water and Land Resources Division
Rural and Regional Services Section
King Street Center, KSC-NR-0600
201 South Jackson Street, Suite 600
Seattle, WA 98104
206-477-4800 TTY Relay: 711

Alternate Formats Available

Synthesis of Riparian Buffer Best Available Science: Informing Variable-Width Buffers in the Lower Snoqualmie Valley

Prepared for:

King County

Submitted by:

Josh Kubo[1], Michael Thai[1], Kollin Higgins[1], and Beth leDoux[2]
[1] Science and Technical Support Section
[2] Rural and Regional Services Section
King County Water and Land Resources Division
Department of Natural Resources and Parks

Funded in part by:

This project has been funded wholly or in part by the United States Environmental Protection Agency under assistance agreement PC-01J22301 through the Washington Department of Fish and Wildlife. The contents of this document do not necessarily reflect the views and policies of the Environmental Protection Agency or the Washington Department of Fish and Wildlife, nor does mention of trade names or commercial products constitute endorsement or recommendation for use.

King County
Department of
Natural Resources and Parks
Water and Land Resources Division

Acknowledgements

The authors would like to thank all the internal and external reviewers that made this product much better than the original draft. A special thanks goes to the Buffer Task Force members for their countless hours of hard work to integrate salmon and riparian habitat needs with agricultural interests so that we can find a path forward that respects everyone's interests.

Buffer Task Force Members:

Matt Baerwalde - Snoqualmie Tribe
Preston Drew – Citizens Alliance for Property Rights
Erin Erickson – Snoqualmie Valley Preservation Alliance
Wayne Gullstad – Snoqualmie Valley Farmer
Chris LaPointe – Stewardship Partners
Kurt Nelson – Tulalip Tribes
Elissa Ostergaard – Snoqualmie Watershed Forum
Lara Thomas – City of Duvall
Steve VanEss – Snoqualmie Valley Farmer
Daryl Williams - Tulalip Tribes

We would also like to give special thanks to the members of King County who helped with the review of this paper - Joan Lee (Manager, Rural and Regional Services Section Manager), Janne Kaje (Supervisor Regional Partnerships Unit), Richard Martin (Environmental Programs Managing Supervisor), Josh Latterell (Manager, Science and Technical Support Section), Kate OLaughlin (Senior Ecologist).

We would also like to thank our funders who generously supported this idea - United States Environmental Protection Agency through the Washington Department of Fish and Wildlife.

Citation

King County. 2019. Synthesis of Riparian Best Available Science to Inform Variable-Width Buffers in the Lower Snoqualmie Valley. Prepared by Josh Kubo, Michael Thai, Beth leDoux, and Kollin Higgins, Water and Land Resources Division. Seattle, Washington.

Contents

Figures

Tables

EXECUTIVE SUMMARY

Background

Chinook salmon habitat recovery has been a priority for King County for the past two decades and the signing of the 2005 Snohomish River Basin Salmon Conservation Plan (Salmon Plan) signified a strong commitment to that effort. A primary basin-wide recommendation of the Salmon Plan is to restore, enhance, and protect vegetated riparian areas, with mostly trees, at a width of 150 feet along salmon bearing streams and rivers to improve water quality and restore habitat for salmon. These vegetated riparian areas are commonly referred to as buffers.

King County, like other local jurisdictions in the Puget Sound Region, has overlapping and sometimes conflicting mandates to support the recovery of salmonids listed under the Endangered Species Act (ESA), to work toward equity and restorative justice with our tribal partners, while also maintaining a healthy, viable agricultural industry. A rapidly growing regional population coupled with an increased interest in local food and food security have amplified the need to resolve longstanding conflicts. The conflict is particularly acute in larger river floodplains, like the Snoqualmie Valley, that are both critical for salmon recovery and productive agricultural areas. In the last several years, intensive efforts have been initiated to integrate these mandates in ways that balance the needs for both salmon and farms.

Recent analyses for King County's ongoing Snoqualmie Fish, Farm, Flood initiative, noted the potential of riparian restoration actions for salmon recovery—if fully implemented — to displace hundreds or even thousands of acres of agricultural land in the Snoqualmie Agriculture Production District (APD). The Salmon Plan's uniform 150-foot buffer recommendation for salmon bearing streams does not prioritize specific riparian functions or consider the size of the water course and their relative salmon habitat value. Farmers in the valley have expressed concerns that the existing "one-buffer-size-fits-all" riparian restoration approach currently described in the Salmon Plan would ultimately take too much land out of production, does not account for the needs of existing agricultural uses, and does not provide clear rationale for why 150-foot wide riparian areas are needed on very small water courses. Moving forward, more clarity, prioritization, and flexibility is needed in order to achieve both riparian restoration and agriculture goals in the Lower Snoqualmie valley.

Buffer Task Force Goal

In an attempt to address these issues, the Fish, Farm, Flood initiative established a Buffer Task Force to evaluate how riparian plantings can be implemented in a manner that is supportive of improving salmonid habitat and accounts for the concerns of the agricultural community. The overarching goal of the Buffer Task Force is to make recommendations during the next phase of the Fish, Farm, Flood effort by creating a decision framework that describes potential variable-width riparian buffers along watercourses in the Snoqualmie Valley APD and associated benefits or impacts. The underlying basis for this effort is to prevent the cumulative result of riparian restoration from causing an unacceptable reduction in the available acres for growing food or otherwise damaging agricultural productivity. Ultimately, the Buffer Task Force will create a decision framework that will evaluate watercourses in the Snoqualmie Valley APD and determine appropriately-sized buffers that provide habitat benefits through specific functions while minimizing complications for landowners.

Purpose of this Report

The purpose of this document is to support the Buffer Task Force decision framework by summarizing the body of scientific knowledge on the functions provided by riparian buffers pertinent to watercourses in the Snoqualmie Valley APD.

This document synthesizes scientific evidence on how the buffer characteristics, such as width, length, tree size, and connectivity influence riparian functions and habitat for salmonids. This information is organized by six key habitat functions that provide benefits to salmonids including:

- water quality (nutrients, sediment, and pollution),
- water temperature,
- microclimate,
- large wood,
- erosion and bank stability, and
- invertebrate prey and leaf-litter detritus.

This synthesis highlights the following critical findings relevant to the goal of developing riparian buffers with variable characteristics, which support the aforementioned ecological functions. This report presents key findings for each ecological function to help with aligning Snoqualmie Valley watercourse types with potential riparian buffer width, length, and composition characteristics.

1. Riparian buffer characteristics and considerations for water quality: nutrients, sediment, and pesticides:
    - Low-gradient areas have higher removal efficacies of suspended solids, nutrients, and pesticides, compared to higher gradient areas.
    - Soils with higher clay content have greater potential for nutrient and pesticide removal.
    - Woody vegetation including shrubs and trees have higher removal efficacies of nutrients and pesticides compared to grasses.

- Long-continuous buffers have greater nutrient and pesticide uptake compared to fragmented buffers; narrower buffer that are long-continuous are more effective than wide-fragmented buffers.
- Straightened watercourses require wider, longer, and more continuous riparian buffers to compensate for lost capacity in aquatic in-stream microbial processing.

2. Riparian buffer characteristics and considerations for water temperature:
   - Small and medium watercourses are most susceptible to temperature fluctuations and provide the greatest potential for shading benefits among watercourse sizes.
   - Riparian vegetation height and density significantly influence watercourse shading.
   - Riparian buffer length accounts for a majority of temperature variation (the longer the buffer length, the greater the shading benefit).
   - Narrow-dense riparian buffers are most effective for shading on east-west oriented watercourses.
   - Wider-taller buffer width are needed for shading on north-south oriented watercourses.
   - Straightened channels may only require dense and overhanging buffers at relatively narrow widths to provide shade benefits.
   - Larger waterways require tall, dense, and wide riparian buffers to shade waterbodies.
3. Riparian buffer characteristics and considerations for riparian corridor microclimate:
   - Riparian buffer width, length, and continuity helps protect and maintain microclimate presence from surrounding landscape climate conditions.
   - Riparian areas closer to watercourses protect stream center microclimate and riparian areas further from watercourses protect off stream microclimate.
   - The ability of microclimate conditions to buffer water temperatures decreases with increasing watercourse width.
4. Riparian buffer characteristics and considerations for large wood recruitment and retention:
   - Primary wood input among mainstem and large watercourses comes from bank erosion.
   - Areas of channel migration require wide buffers to provide continual wood sources.
   - Large channels require relatively larger wood (i.e., tall and wide) to remain stable and influence channel and habitat forming processes.

- Coniferous trees provide long-term habitat benefits and deciduous provides short-term benefits.
- Armoring shifts wood input drivers from erosion to windthrow and tree mortality; large wood source distance from windthrow and mortality is based on max tree height (potential fall distance).
- Size of habitat-forming wood is relatively smaller in small and medium watercourses.
- Small and medium watercourses receive a greater proportion of wood inputs from shorter source distances (closer to watercourses).
- Hardwoods generally contribute more large wood in smaller channels.
- Primary wood inputs among high-gradient watercourses comes from debris flows, landslides, and windthrow (greater source distances than bank erosion).
- High-gradient tributaries contribute to instream wood which is transported downstream.

5. Riparian buffer characteristics and considerations for erosion and bank stability:
    - Trees and shrubs provide the greatest bank stabilization for large watercourses.
    - Trees are more effective than shrubs or grasses on steep banks.
    - Maximum root strength and depth can be achieved at around ½ site potential tree height.
    - Grass and shrubs may be suitable vegetation for small and medium watercourses which have relatively less-steep banks.
    - Small and medium channelized watercourses may require trees, rather than grass or shrubs due to related bank steepness.
    - Bank erosion commonly occurs on the outside of river bends; outside bends with riparian vegetation can significantly decrease erosion during storm events.
    - The denser vegetation is along outside bends, the more effective riparian vegetation is at reducing erosion impacts.
6. Riparian buffer characteristics and considerations for invertebrate prey and litter-detritus inputs:
    - Relative contribution and role of litter and detrital inputs tends to decrease from small streams to large streams.
    - Riparian corridor length and continuity may be the primary drivers of macroinvertebrate structure and diversity.
    - Percentage of tree coverage in a riparian corridor is positively related to stream invertebrate community structure and diversity.
    - Deciduous trees provide seasonal pulse inputs and conifer trees provide year-round inputs.

Recommendations

By organizing the riparian buffer literature by function and watercourse type, we recommend that the Buffer Task Force take the following actions:

Recommendation 1
Determine how the functions from this paper should be prioritized among watercourses across the Snoqualmie Valley landscape.

Recommendation 2
Use the key findings from this document to help determine where it is important to have larger riparian buffers and where smaller buffers are appropriate with the goal of benefiting Chinook salmon, while reducing impacts to agriculture in the Valley.

These actions, as indicated by evidence presented in this report, will produce a framework that evaluates the benefits and costs of variable width buffers for different types of watercourses in the lower Snoqualmie Valley.

This page intentionally left blank.

1.0 INTRODUCTION

1.1 Problem statement

King County, like other local jurisdictions in the Puget Sound Region, has overlapping and sometimes conflicting mandates to support the recovery of salmonids listed under the Endangered Species Act (ESA), to work toward equity and restorative justice with our tribal partners, while also maintaining a healthy, viable agricultural industry. A rapidly growing regional population coupled with an increased interest in local food and food security have amplified the need to resolve longstanding conflicts. The conflict is particularly acute in larger river floodplains that are both critical for salmon recovery and productive agricultural areas. In the last several years, intensive efforts have been initiated to integrate these mandates in ways that balance the needs for both salmon and farms.

The Snohomish Basin Salmon Conservation Plan (Salmon Plan) recommends a buffer width of 150 feet along all fish bearing watercourses to restore riparian functions and improve degraded water quality based on a previous review of the best available science (BAS), modeling, and an assumption that it would not be possible to get the best (old growth trees), widest (300 feet plus) riparian areas in the time frame needed for salmon recovery (Snohomish Basin Salmonid Recovery Technical Committee 2004). The Salmon Plan prioritizes riparian plantings with a goal of 150-foot buffers along 65-85% of total stream length based on fish use. For example, the plan recommends that at least 85% of the mainstem Snoqualmie River should have an intact riparian area of mostly trees, commonly referred to as a buffer, while 65% of length in smaller watercourses should be buffered. The percentage targets highlight that plantings are critical to the survival of salmon but do not aim for 100% planting of the length of the watercourses in the Snoqualmie Valley. It was recognized that conversion of the land from agricultural to other uses posed a threat to salmon recovery.

During King County's Snoqualmie Valley Fish, Farm, Flood (FFF) discussions in 2015-2017 (Phase 1), the potential of salmon recovery riparian restoration actions to displace hundreds or even several thousands of acres of agricultural lands raised questions about whether a more nuanced approach to riparian buffer restoration might afford the ability to achieve the vision of recovering salmon while sustaining farming in the Valley: in other words, how much restoration is needed where and in what priority.

Participants in the FFF effort of 2015-2017 realized the need for an analysis of and conversation about ways to improve riparian buffer restoration that improve riparian functions on different types of watercourses for salmon recovery and water quality, while also reducing potential adverse impacts to agriculture. Therefore, the FFF Phase 1 recognized that a more balanced approach to buffers is needed and recommended creating a Buffer Task Force to review the science and explore opportunities for variable-width buffers. This paper, along with a companion document, *Riparian Buffers in Agriculture Settings*, represents the first step towards that goal.

Currently, there are two main approaches to riparian revegetation: voluntary plantings, and plantings done as mitigation to an action on the landscape. While riparian buffers planted for mitigation are prescribed via regulations, voluntary plantings seek to plant 150-foot riparian buffers wherever possible.

The direct loss of actively farmed and potentially farmable acres is not the only way that riparian restoration can affect agriculture. Riparian buffers can also complicate field drainage maintenance, harbor wildlife that may damage crops, create obstructions to flood flows, and shade crops. Conversely, riparian buffers may offer benefits to agriculture, including shade for livestock, reduced bank erosion, and habitat for pollinators.

The Snoqualmie Valley Agricultural Production District (Snoqualmie APD) contains more than 150 miles of watercourses, most of which are used by anadromous salmonids to some degree. Approximately half of the total length is comprised of small tributaries, which many are actively maintained for agricultural drainage. An analysis of Geographic Information System (GIS) data during FFF Phase 1 in 2014 showed that in the Snoqualmie APD, 57% of the land within 150 feet of watercourses is in active agricultural use. Most of the land is next to very small tributaries rather than larger streams or rivers (King County, *unpublished data*).

Riparian conditions in the Snoqualmie APD are heavily degraded. Analyses of 2014 riparian conditions in the Snoqualmie APD, during Phase 1 of FFF, indicated that 150-foot buffers on all salmon bearing watercourses in the Snoqualmie APD would affect approximately 4,800 acres of land, or one third of the Snoqualmie APD. While only about 2,400 (50%) of the 4,800 acres was currently in production, this represents about one fourth of all the actively farmed land in the APD (approximately 9,400 acres). Removing this percentage of farmed acreage within the Snoqualmie APD would have significant and long-lasting impacts on the Valley's agricultural economy, and planting this many acres would be very expensive.

Riparian buffers are critical for salmon habitat and in some cases they can complicate farming. Both salmon recovery partners and local landowners recognize that the one-size 150-foot buffer approach of the Salmon Plan does not take into account the relative importance of different watercourses for salmon or the individual requirements of specific agricultural lands. The ecological benefits to salmon recovery in the mainstem Snoqualmie are greater than those in constructed drainage watercourses. Therefore, the FFF Phase 1 recognized that a more intentional approach to buffers is needed and recommended creating a Buffer Task Force to review the science and explore opportunities for variable-width buffers. This paper, along with a companion document, *Riparian Buffers in Agriculture Settings*, represents the first step towards that goal.

1.2 Purpose and goal

We summarized scientific literature to assist King County and FFF participants with making recommendations for variable-width buffer sizes in the Snoqualmie APD. The hope is that this document provides scientific information allowing local governments and stakeholders to align policies and interests with riparian science to best support outcomes in the Snoqualmie Valley for riparian plantings.

Many syntheses of peer reviewed journal articles have been completed for riparian buffer widths, including the recent, regional and extensive Washington State Department of Fish and Wildlife Best Available Science (WDFW-BAS) report titled "Riparian Ecosystems, Volume 1: Science Syntheses and Management Implications." The WDFW-BAS was the foundation for the FFF Buffer Task Force Best Available Science (FFF-BAS) synthesis work. The WDFW –BAS report determined that the larger the vegetated riparian buffer, the greater the protection to aquatic systems. The FFF-BAS synthesis builds on the WDFW-BAS work by further exploring how narrow, wide, and variable-width riparian buffers differ in ecological function and salmonid recovery benefits. The FFF- BAS synthesis identifies a range of buffer widths that balances ecological benefits and practical land management issues.

The ecological benefits analyzed in the FFF-BAS are based on the functions provided by riparian areas. This document summarizes the scientific literature on riparian buffers and discusses the relationships between ecological functions (e.g. erosion control, water quality, or large wood recruitment) and buffer width, length, composition, density, height, continuity, and other factors. A better understanding of the relationships between these riparian buffer attributes and related ecological functions is critical to the development of riparian buffer recommendations.

The overarching goal of the Buffer Task Force is to recommend variable-width buffers along watercourses in the Snoqualmie Valley APD that will support salmon recovery without cumulatively impacting the available acres for growing food or otherwise damaging agricultural productivity. The authors acknowledge there are ecological tradeoffs and uncertainties associated with reducing buffer widths from the larger riparian buffers recommended in the Salmon Recovery Plan and WDFW-BAS document. The work of the Buffer Task Force is to use the findings of this synthesis, including any implicit assumptions and limitations, to recommend riparian buffers across the various watercourses types in the Snoqualmie Valley while being thoughtful and respectful of the needs of landowners in supporting a healthy and viable agricultural base.

2.0 BACKGROUND

2.1 Ecological and geographic context of the Snoqualmie Valley

The Snoqualmie River watershed includes two distinctly different geomorphic areas including, the Puget Lowland and the Middle Cascade Range (Montgomery et al. 2003). The Middle Cascade Range includes the high elevation, steep topography area above Snoqualmie Falls. The headwaters of the Snoqualmie River are located in the alpine lakes of the Cascade Mountains. There are three forks (North, Middle and South) of the Snoqualmie River that flow from the lower slopes of the Cascades. Near the City of Snoqualmie and North Bend, the forks merge to form the Snoqualmie River. Approximately two miles downstream from North Bend, the Snoqualmie River plummets over Snoqualmie Falls, a natural barrier to anadromous salmon. At this point, the topography transitions from the higher and steeper elevations to a flat, alluvial valley bottom called the Puget Lowland (Bethel 2004).

Below the falls, the Lower Snoqualmie River Valley is characterized by a broad valley-wide floodplain with several higher gradient tributaries flowing into the meandering mainstem (Figure 1). This valley was carved by glaciers retreating and advancing, not by the Snoqualmie River itself. Due to its low gradient and geomorphology, the Snoqualmie River historically migrated across the floodplain as a single channel through lateral channel migration (eroding the banks), versus highly braided channels as seen in the higher gradient Tolt or Skykomish rivers. The remaining portions of this report focus on the floodplain area below the falls and any description of the Snoqualmie River refers to this lower area of the river.

The two largest tributaries, the Tolt and Raging rivers, supply large amounts of coarse gravel into the Snoqualmie River at their mouths, creating alluvial mainstem reaches with slightly steeper gradients than the other reaches of the lower Snoqualmie. In both locations, the transport capacity of the Snoqualmie River can move the gravel about six miles downstream from the mouths of the Raging and Tolt rivers. The supply of gravel from these tributaries make these reaches of the Snoqualmie River and lower reaches of the Tolt and Raging rivers the most important for spawning and early rearing by Chinook salmon in the entire Snoqualmie watershed (Snohomish Basin Salmonid Recovery Technical Committee 2004).

Outside of these alluvial reaches, the Snoqualmie River lacks the power to move coarse sediment, therefore sand and finer sediment are suspended in the water column. During floods, when the river overtops its banks, the velocity decreases resulting in sands and suspended sediment settling out, generally near the top of the bank. Over time, sand and silt deposited on the floodplain immediately next to the channel forms natural levees. These natural levees are higher in elevation than in the areas of the floodplain farther from the river. As a result, large areas of the floodplain have very poor drainage. This phenomenon created large wetlands in the floodplain prior to European settlement (Collins and Sheikh 2002, Bethel 2004). In many locations, this natural pattern of deposition has continued on top of constructed revetments and levees.

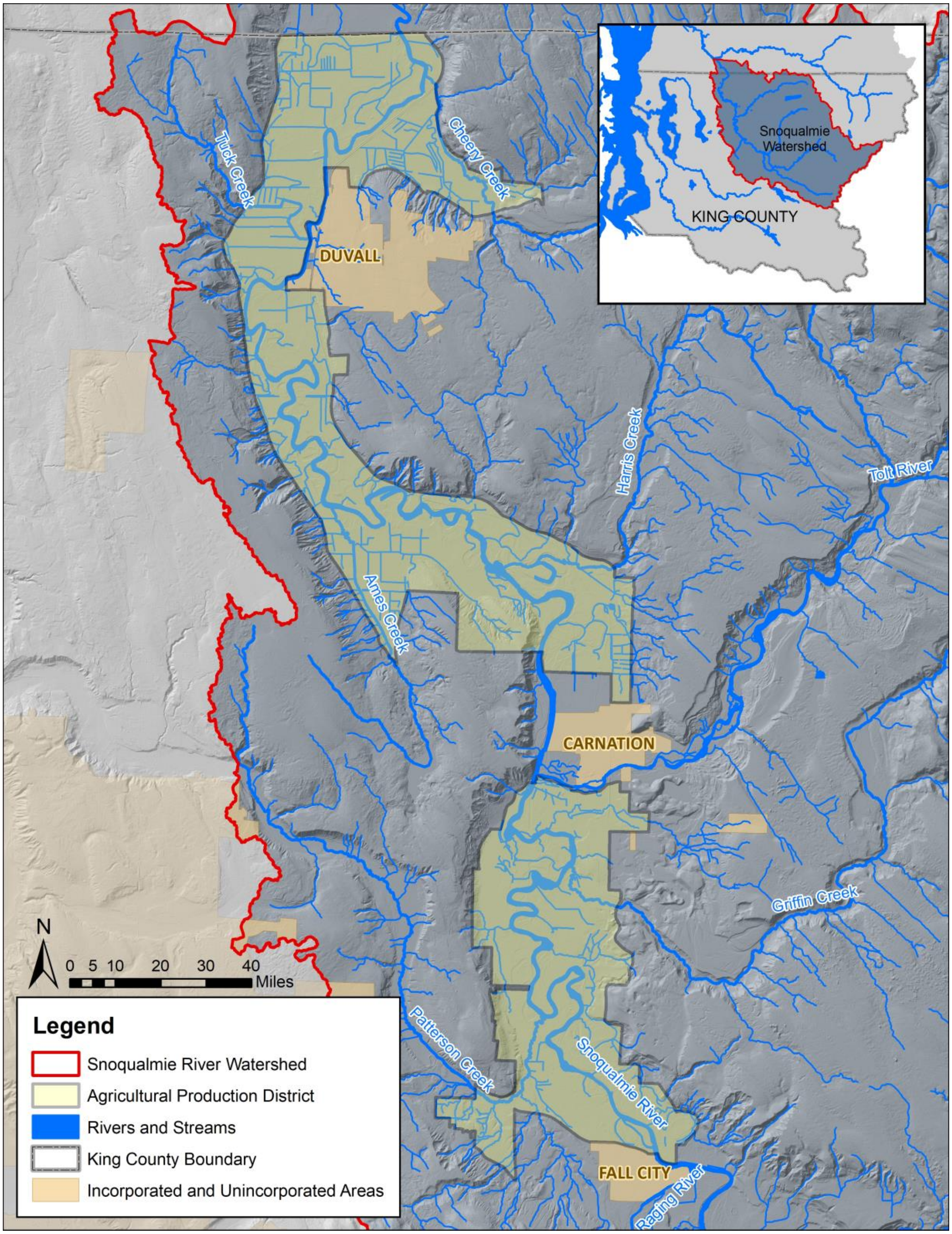


Figure 1. Area map of the Lower Snoqualmie River Valley.

2.1.1 Mainstem river (Snoqualmie)

For this paper, riparian buffers refer to the vegetated area of land immediately adjacent to stream channels. The Snoqualmie Valley floodplain vegetation prior to 1870 was composed of a mixed species forest with large areas of marsh or wetland connected to the mainstem, frequent tributary streams, and multiple abandoned or semi-abandoned river channels (e.g., oxbows) (Figure 2;(Collins and Sheikh 2002)). The northern portion of the Snoqualmie Valley, near the City of Duvall, was predominantly scrub-shrub wetlands while the southern portion of the valley was predominantly forested floodplain. The trees in the forested floodplain were mainly hardwoods including big leaf maple (*Acer macrophyllum*), black cottonwood (*Populus trichocarpa*), red alder (*Alnus rubra*), pacific crabapple (*Pyrus fusca*) and willow (*Salix spp*.) (Collins and Sheikh 2002). The forested floodplain also included conifers, at a much smaller proportion (~20%), including western red cedar (*Thuja plicata*) and Sitka spruce (*Picea sitchensis*)(Collins and Sheikh 2002). Wetland areas were composed of dense shrubs and small trees with a few very large conifers. These wetland areas remained relatively stable or undisturbed due to the Snoqualmie's natural ability to create levees on its banks that slowed or stalled surface runoff during major rain events and floods.

The land bordering the river was forested, with hardwoods dominating the riparian buffers. While conifer frequency was low (<10% of stems), they provided more than 40% of the basal area (amount of area occupied by tree stems) due to their large size. These conifers were estimated to have provided half of the large wood among river channels (Collins and Sheikh 2002). The riparian buffer area persisted over time due to the slow channel migration, the stabilizing effects of large conifers along the banks, as well as stable "key" logs within the channel (Collins and Sheikh 2002, King County 2011).

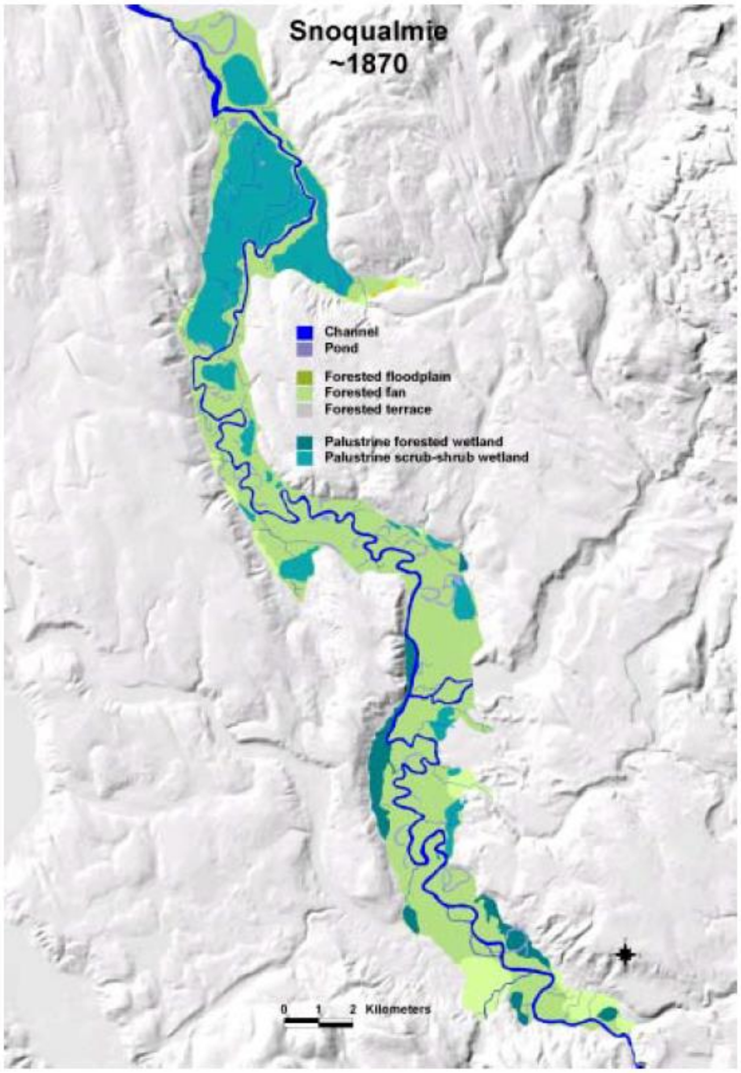


Figure 2. Map of the Historic Vegetation Communities (From Collins and Sheikh 2002)

By 1936, the hydrology and land cover across the valley floodplain had been extensively modified. Roads had been constructed near the river and a railroad ran along the east valley wall (this is now the Snoqualmie Valley Trail). Channel cleaning had removed at least several hundred logs from the river to improve river navigation for large vessels (Collins and Sheikh 2002). However, records describing log snagging from this time period are incomplete and the number of logs removed from the river is likely much larger.

Most riparian buffer areas were cleared for agriculture, channel re-alignment, local bank stabilization, and levee construction (King County 2011). These activities straightened channels and armored banks resulting in decreased river complexity and vegetated cover (King County 2011). The majority of land currently in agricultural production had been cleared and drained by 1930s (Bethel 2004). Extensive drainage systems were constructed to support farming of the rich alluvial soils. As the areas next to the river were some of the highest ground in the valley, agricultural infrastructure was constructed in the riparian buffers of the river.

After the 1930s, development along the rivers dramatically increased, mostly concentrated within the Raging River and Tolt River alluvial fans (Collins and Sheikh 2002). The riparian areas within these alluvial fans are important in maintaining diverse salmon habitat. Bank stabilization within these alluvial reaches significantly diminished riparian river interactions by decreasing channel migration into the riparian area, halting large-wood recruitment/delivery, and decreasing river complexity. Although specific riparian buffer estimates are not available, Collins and Sheikh were able to map approximate land cover within the floodplain from historical data (~1870) and found that by 2000 forest cover had declined by >80% and wetland cover had decreased by >80%. This loss of forest cover—along with channel cleaning and declining instream wood loading—highlights the importance of re-establishing and maintaining riparian buffers that provide ecological functions to the Snoqualmie River valley. Reductions in forest cover and subsequent young forest stand age has resulted in current large wood recruitment among watercourses being dominated by smaller, less mature trees. Smaller trees are more readily transported downstream and thus less likely to provide long-term habitat benefits.

Bank conditions across the lower Snoqualmie River are considerably modified from conditions that existed prior to European settlement. Armoring for levees and revetments degraded shoreline conditions and decreased floodplain connectivity throughout the Snoqualmie River watershed (Snohomish Basin Salmonid Recovery Technical Committee 2004, Snohomish Basin Salmon Recovery Forum 2005). More than 40% of the banks across the lower Snoqualmie River have been confined by bank armoring, generally concentrated along outside bends where channel migration is more common (Gersib et al. 1999, Collins and Sheikh 2002). In one study of the Snoqualmie River between the mouths of the Raging and Tolt rivers, roughly 60% of the outside bends had been armored (Higgins 2016). Subsequently, more than 70% of floodplain connectivity has been altered from historic conditions (Gersib et al. 1999, Collins and Sheikh 2002) decreasing access to off-channel, side-channel, and floodplain habitats for salmonids. Additionally, armored banks provide poor edge habitat conditions for juvenile salmonids (Knudsen and Dilley 1987, Beamer and Henderson 1998, Quigley and Harper 2004).

2.1.1.1 Summary of Snoqualmie River conditions

- Prior to 1870, the northern portion of the lower Snoqualmie River floodplain was dominated by wetlands and a scrub shrub forest and the southern portion was dominated by forested floodplains.
- There continues to be active channel migration in the alluvial reaches near the Raging and Tolt rivers.
- Outside of the major tributary alluvial reaches, sediment transport in the mainstem Snoqualmie River is limited to fine and coarse sands and silts.

- From 1870 on, most of the existing large wood was removed from the river channel to improve navigation and across the riparian buffer area for agriculture and development.
- By 1936, the addition of levees, revetments, and channel straightening changed the Snoqualmie River into a simplified, narrower channel. Much of the salmon habitat was eliminated and the opportunity for the river to migrate and create new habitat was diminished.
- Activities from 1870 forward had caused a reduction in the total amount of salmon habitat and the remaining habitat is reduced in quality.
- It is no longer practical to restore much of the previous scrub-shrub wetland areas back to pre-1870's conditions because this would require undoing large amounts of agricultural drainage.

2.1.2 Other rivers (Tolt and Raging)

The lowest 4,000-foot section of the Raging River is an alluvial fan. Under natural conditions, alluvial fans have high volumes of sediment deposits and active channel migration. The lower Raging River is entirely confined by levees constructed to protect development in and around Fall City. This creates a flume, where sediment and wood is funneled to the mouth and deposited into the Snoqualmie River.

The Tolt River at approximately 2.0 river miles upstream from its confluence with the Snoqualmie River transitions from a tributary valley into the floodplain of the mainstem Snoqualmie, creating a broad alluvial fan. The fan extends across the width of the Snoqualmie Valley forcing the Snoqualmie River against the west valley wall. The Tolt River levee system was constructed in the 1940s to protect the city of Carnation from flooding and channel migration, and extends from the confluence to river mile 1.7. Similar to the Raging, most sediment and wood is funneled downstream to be deposited in the Snoqualmie River.

2.1.2.1 Summary of Tolt and Raging Rivers

- The Tolt and Raging rivers deposit large sediment loads in the Snoqualmie River immediately downstream of their confluences.
- Levees and revetments along the lower sections of these rivers restrict sediment from spreading out into the floodplain and flushes them into the Snoqualmie River.
- The alluvial reaches of these major tributaries contain some of the most active channel migration areas of the Snoqualmie River floodplain.

2.1.3 Tributaries and unnamed watercourses

The larger tributaries of the lower Snoqualmie River include Ames Creek, Harris Creek, Griffin Creek, Patterson Creek, and Cherry Creek. Medium-sized streams include Tuck Creek, Weiss Creek, Langlois Creek, and Adair Creek. Most of the water courses in the Snoqualmie APD are small unnamed tributaries. These smaller tributaries run from steep hillside headwaters through incised ravine sections intersecting groundwater before meeting the valley floor and becoming low-gradient, low-velocity, and meandering channels across the floodplain. These tributaries provide sources of cool, clean perennial base flows which support lower stream reaches. As the tributaries meet the valley floor, the change in stream gradient creates small alluvial fans along the edge of the valley wall. These small alluvial fans provide most of the spawning habitats for coho salmon and steelhead trout in Snoqualmie APD—outside of the major rivers. All of these tributary characteristics are critically important for creating and maintaining high-quality rearing habitat for juvenile salmonids, while also providing limited adult spawning habitat.

After 1870, many floodplain wetlands and small stream channels were straightened and channelized to drain the floodplain for agriculture. Estimating the amount of habitat reduction related to these actions is challenging. Historic photographs showing a portion of Patterson Creek prior to straightening indicate that there has been a 30% reduction in channel length. The reduction in channel length reduced the total amount of fish habitat. It also reduced the quality of the remaining salmon habitat by simplifying the channels to uniform depths, minimizing woody cover, as well as limiting off-channel areas. The reduction in habitat quality and quality can affect stream productivity. Whitney and Bailey (Whitney and Bailey 1959) observed a >90% reduction in the number and biomass of small trout after channelization. Similarly, Gebhards (1970) found that fish production in modified channels in Idaho were 80 to 90% lower than before channelization. The reduction in length reduces nutrient retention, and temperature amelioration in riparian areas (Simpson et al. 1982).

2.1.3.1 Summary of tributaries and unnamed watercourses

- Most of the smaller streams in the Snoqualmie Valley descend steeply from uplands to the Snoqualmie floodplain. The streams coming off the valley wall are the primary sources of sediment in these streams.
- Alluvial fans form where steep ravines along the valley wall meet the floodplain of the Snoqualmie Valley, providing spawning habitat.
- Channelization/straightening of small stream channels as well as drainage of floodplain wetlands has reduced the overall amount of aquatic habitat and degraded much of the remaining habitat.

2.2 Snoqualmie River salmonids, Endangered Species Act, and salmonid conservation

The Snoqualmie River watershed supports the freshwater life stages of various salmonids, including wild populations of Chinook (*Oncorhynchus tshawytscha*), chum (*Oncorhynchus keta*), coho (*Oncorhynchus kisutch*), and pink salmon (*Oncorhynchus gorbuscha*); mountain whitefish (*Prosopium williamsoni*); as well as rainbow-steelhead (*Oncorhynchus mykiss*), cutthroat (*Oncorhynchus clarkii*), and non-native brook trout (*Salvelinus fontinalis*). The watershed is also in the range of native char, e.g., Dolly Varden (*Salvelinus malma*) and bull trout (*Salvelinus confluentus*). These anadromous salmonids are distributed throughout the lower Snoqualmie River watershed downstream of the Snoqualmie Falls.

Chinook salmon and bull trout were listed as threatened under the ESA in 1999 due to declining and depressed populations throughout the Puget Sound Region, including the Snoqualmie River. Additionally, Puget Sound steelhead trout were listed as threatened in 2007 due to similarly declining populations. These Puget Sound salmonid populations were considered threatened due to factors including excessive harvest, riverine habitat degradation, hatchery practices, altered flow regimes, ocean survival, and climate change (Lichatowich 1999, NMFS 1999, McElhany et al. 2000, Levin and Tolimieri 2001, Bisson et al. 2002, Snohomish Basin Salmon Recovery Forum 2005, Snoqualmie Watershed Forum 2016). Coho salmon, while not listed under the ESA, are classified as a species of concern due to broader Puget Sound declines. Within the Snohomish River Basin, salmonid habitat degradation has primarily occurred due to the construction of fish passage barriers, bank and floodplain modification, loss of wetlands, altered channel conditions including large wood removal, and altered riparian functions and conditions (Haring 2002).

In response to the federal ESA listing of Chinook salmon and bull trout, a salmon recovery planning effort was started in 1999 for the Snohomish River Basin. Through the evaluation and integration of basin locations, watershed conditions, and related salmonid use, the Snohomish Basin Salmon Recovery Technical Committee and Forum developed the 2005 Salmon Plan (Snohomish Basin Salmon Recovery Forum 2005). The 2005 Salmon Plan provided a guide for salmon conservation with specific strategies aimed at improving habitat conditions (i.e., habitat quality, quantity, and connectivity) to support viable salmonid population parameters (i.e., abundance, productivity, spatial structure, and diversity) (Snohomish Basin Salmon Recovery Forum 2005). Conservation efforts outlined in the 2005 Salmon Plan focused on restoring habitat forming processes of ESA-listed salmonids; additionally, restoration and protection strategies were structured to support healthy watershed conditions that would benefit various other salmonid species as well. Actions in the plan are expected to benefit coho salmon, and include a range of actions from programs to large restoration projects. The 2005 Salmon Plan also includes chapters on how hatchery and harvest management should change to support recovery.

2.2.1 Snoqualmie River Chinook freshwater life stages

Adult Chinook salmon generally migrate up the Snoqualmie River from September to November (Figure 3) and spawn in mainstem Snoqualmie River throughout the gravel deposits below the confluences of the Tolt River, Raging River and Tokul Creek. These gravel deposits and the related habitat forming processes occurring below the tributary confluences are critical for adult Chinook salmon spawning and early juvenile rearing. While Chinook and steelhead spawning is primarily concentrated in the Tolt and Raging Rivers they occasionally spawn in smaller streams. Spawning by other anadromous salmonids occurs across various other Snoqualmie tributaries, including but not limited to Cherry Creek, Tuck Creek, Harris Creek, Griffin Creek, Patterson Creek, Ames Creek, and Tokul Creek.

The quality and quantity of holding and spawning habitat across Snoqualmie River tributaries is inherently related to river and riparian conditions. For example, water temperatures experienced by adult salmonids during migration and spawning can significantly influence reproductive success as well as the production, development, and survival of juveniles. High water temperatures (e.g., above 23°C) can be lethal to salmonids and warm temperatures (e.g., 16-23°C) can cause significant sub-lethal effects such as increased susceptibility to disease, metabolic stress, developmental issues, and thermal blockages to migration (Hicks 2000). Sub-lethal high water temperatures can impact adult salmonids holding throughout the system as well as those actively migrating and spawning. Additionally, they can impact juvenile salmonids rearing in the river over the summer such as coho, steelhead and yearling Chinook (discussed below). Maintaining cool water temperatures is critical to supporting juvenile and adult Chinook salmon in the Snoqualmie River watershed.

Juvenile Chinook hatch from the aforementioned spawning grounds in late winter and then migrate and rear within mainstem, off-channel, tributary, and floodplain areas. The broad valley-wide floodplain extent and annual flooding frequency of the lower Snoqualmie River watershed allows juvenile Chinook to actively and passively distribute across all of these various aquatic habitats. Snoqualmie juvenile Chinook generally display two distinct rearing patterns including a sub-yearling and yearling life-history type (Figure 3). Juvenile Chinook characteristic of the sub-yearling type include fry and parr, which rear in freshwater habitats for several weeks to months and then migrate downstream to the estuary and ocean from March to June (Kubo et al. 2013). Riverine out-migration of sub-yearling Chinook tends to display two separate peaks with fry migrating in March and parr migrating in May and June. Juvenile Chinook characteristic of the yearling type generally remain in freshwater riverine habitats for an entire year and then migrate downstream during the following late winter and early spring. Among the sub-yearling and yearling life-history types, the greatest proportion of juvenile Chinook produced in the Snoqualmie River tend to out-migrate within their first year (Kubo et al. 2013). However, a proportion of yearling-type juvenile Chinook are consistently observed in the Snoqualmie River and small tributaries. While the proportion of juveniles displaying this extended freshwater residence is generally small, in some years juvenile yearling Chinook can contribute up to 46% of the out-migrating juveniles (Kubo et al. 2013), and can contribute up to 30% of the returning adults (SBSRTC, 1999). Yearling Chinook generally have greater marine survival compared to sub-yearling Chinook (Beamer et al. 2005) since marine survival is often size dependent (larger juveniles generally have greater survival rates) (Hunt 1969, Holtby et al. 1990). The yearling life-history type emphasizes the importance of year-round freshwater conditions and the importance of sustaining multiple life-histories in supporting abundant and productive Chinook populations. Diversity in rearing and migration within juvenile Chinook help to buffer inter-annual variability in freshwater and marine environmental conditions as well as variability in salmon population dynamics (Hilborn et al. 2003, Schindler et al. 2010).

Juvenile Chinook have been observed throughout the lower Snoqualmie River watershed (WSU and UW 2008, Berge et al. 2002, Kubo et al. 2013, King County 2017); however, juvenile Chinook abundance tends to be the greatest in the mainstem river, its off-channel where the water slacks and provides shelter from high flows, and larger tributaries. Aquatic habitats across the Snoqualmie River floodplain, including wetlands, oxbows, smaller tributaries, and modified watercourses, support juvenile Chinook, but these channel types tend to support relatively greater abundances of juvenile coho salmon than juvenile Chinook. Additionally, juvenile Chinook tend to primarily use freshwater habitats from late-winter to summer (aside from yearling Chinook as discussed above), while juvenile coho use these various habitats throughout the year due to a life-history predominately characteristic of extended freshwater rearing (i.e., at least one year of freshwater residence). The benefits of mainstem as well as off-channel, tributary, and floodplain habitats for salmonid growth and survival has been well documented (Groot and Margolis 1991, Sommer et al. 2001, Beamer et al. 2005, Jeffres et al. 2008, Rice et al. 2008, Quinn 2018a). These areas provide the food sources and habitat diversity needed to support juvenile Chinook survival during freshwater residence.

Factors such as channel migration, large wood recruitment, channel connectivity, and temperature conditions are essential to create and maintain freshwater salmonid habitats. For example, healthy riparian corridors contribute to fish productivity by providing large wood that creates pools and provide refuge during climatic extremes, cover from predators, and encourage habitat partitioning (McMahon and Hartman 1989, Reeves et al. 1997). Additionally, healthy riparian corridors can provide temperature moderation by insulating streams from solar and atmospheric radiation. The availability, diversity, connectivity, and distribution of habitats are directly related to well-functioning riverine, floodplain, and riparian conditions. Degradation of these conditions subsequently impacts juvenile Chinook growth and health as well as their survival. The quality and quantity of freshwater habitats are critical for the long-term viability of Snoqualmie River Chinook salmon.

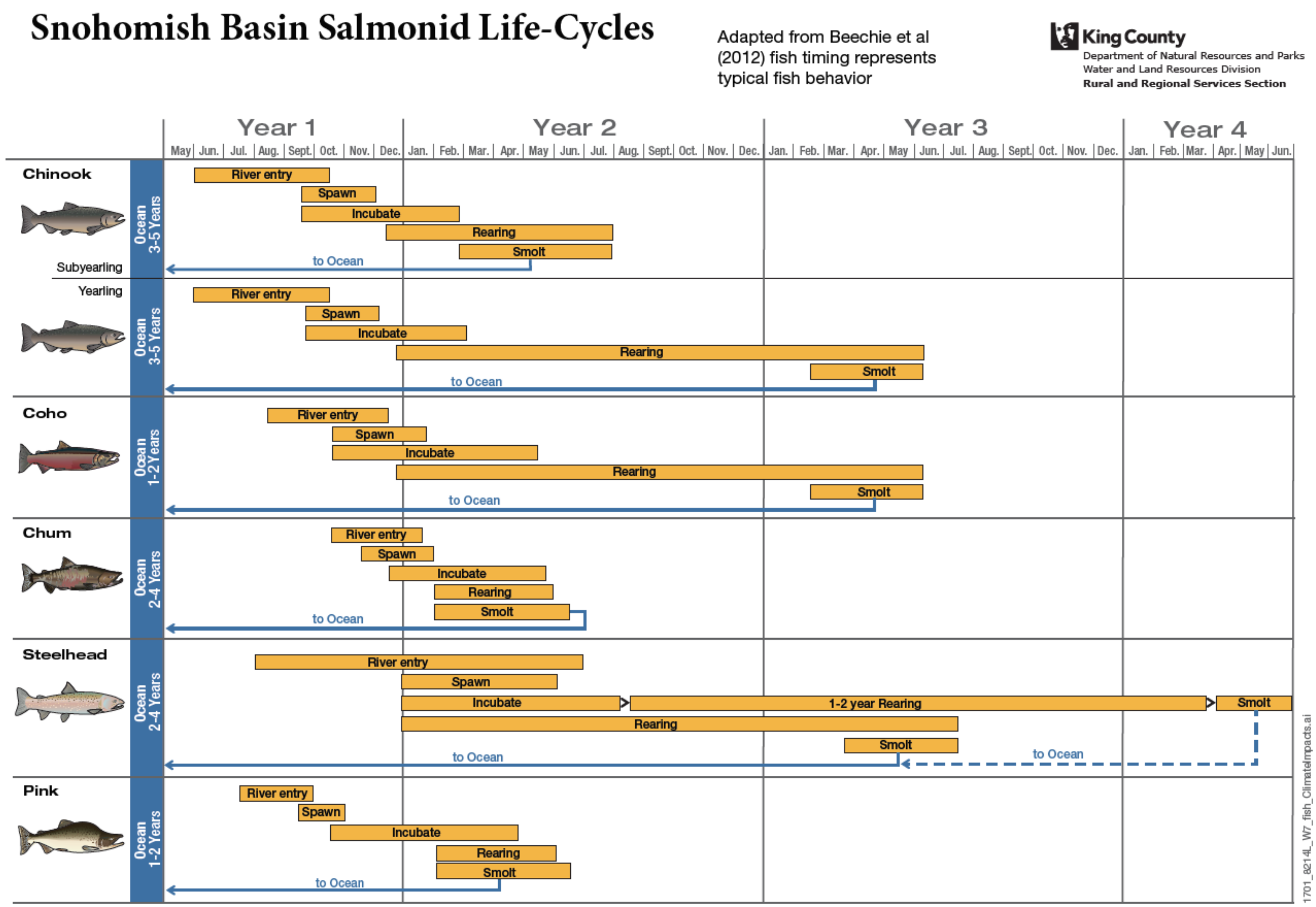


Figure 3. Salmonid Life-Cycles in the Snohomish River Basin.

2.3 Water quality

As noted earlier, according to 1936 aerial photographs, vegetation was cleared in much of the floodplain for development and agricultural production. This significantly influenced the water quality functions of riparian areas, such as instream temperature conditions. The lack of vegetation along watercourses eliminated or impaired crucial ecological functions (e.g., shade, nutrient uptake and processing, and sediment trapping) that protect water quality. The Snoqualmie River is known to be impaired for water temperature with other parameters, namely dissolved oxygen, fecal coliform, pH, and nutrients, being of concern. Currently, the Snoqualmie River has a Total Maximum Daily Load (TMDL) intended to protect and restore essential summer salmonid rearing habitat as well as salmonid migration and spawning (Kaje 2009, Stohr 2011). In larger tributaries within the APD, water temperature, dissolved oxygen, fecal coliform, pH and nutrients are either impaired or of concern, with very few exceptions (Kaje 2009). In some areas, changes in farming practices through recent decades have improved water quality but many agricultural watercourses remain degraded and do not meet Washington State standards (Kaje 2009, Stohr 2011).

Improving water quality requires a watershed wide effort because precipitation on land flows to watercourses, streams flow into each other, and smaller watercourses impact the water quality of the larger receiving watercourses. Reestablishing riparian vegetation along watercourses is the primary method used to protect and improve water quality in rural areas, where open channels are the primary method of surface water movement. The Snoqualmie floodplain has a few key features (e.g. low-gradient/flat-landscape and moderate to high clay content in soils) that have the ability to optimize the water quality effects of riparian vegetation when planted continuously along watercourses (see Section 3.2 for more details).

2.4 Regulatory and management

Over the last 50 years there has been a substantial increase in the recognition and consideration of environmental degradation related to land uses (e.g. urban development, agriculture, and forestry). In an effort to address the history of widespread environmental degradation, several environmental laws such as the National Environmental Protection Act (NEPA), the Clean Air Act, and the Clean Water Act (CWA) were created and led to the establishment of the Environmental Protection Agency. Further environmental regulations were created to help protect critical areas and the species who use them. The Coastal Zone Management Act (CMZ 1972) was created to protect and restore shoreline and coastal zones. The CMZ was quickly followed by the Endangered Species Act (ESA) in 1973, which aimed to conserve and protect endangered and threatened species and their habitats. These regulations help protect the most critical environmental resources and species and changed how land uses impact various landscapes.

With the formation and adoption of these federal regulations, state and local jurisdictions also began to pass policies and regulations to protect natural resources. Some of these regulations and policies include: Total Maximum Daily Loads (TMDLs) outlined in the CWA which aimed at setting regulatory limits on specific pollutants such as nutrients, fecal coliforms and temperature; local Critical Areas Ordinances (CAOs) focused on protecting sensitive areas, critical habitats, and environmental features from degradation; and the Forest and Fish Law passed in 1999 which provided a science-based set of forest practice regulations aimed to protect public resources such as fish habitat and water quality while maintaining a viable timber industry. All of these policies and regulations have helped to reduce environmental degradation as well as provide tools and support for environmental restoration and protection.

Many stakeholders, including tribes, local jurisdictions, state agencies, industries and private land owners recognize the impacts land use activities have on ecological resources and acknowledge that protecting those resources is good for everyone. Throughout the Puget Sound, including the Snoqualmie Valley, many residents have incorporated best management practices that reduce ecological impact and comply with regulations while maintaining economic opportunities.

3.0 RIPARIAN FUNCTIONS

3.1 Introduction

This report focuses on summarizing the primary physical and ecological functions riparian areas provide for salmonid habitat among low-gradient, floodplain valleys (comparable to the lower Snoqualmie River Valley). Regional information from forested catchments in the Pacific Northwest as well as national and global research was also incorporated when applicable.

Each function is framed to highlight its particular importance to salmonids, what controls the function (e.g. riparian vegetation characteristics, climate, and disturbance regimes), as well as the key guiding principles of how the function works. This framing structure aimed to help highlight how adjusting buffer characteristics including width, density, length, continuity, height, and species composition may improve or degrade a particular riparian function. When available, information that tied riparian buffer widths to given function percentages was noted and summarized.

Riparian functions included in this review are:

- Water quality:
    - Contaminants: nutrients, sediments, pesticides
    - Temperature
- Large wood
- Erosion and bank stability
- Microclimate
- Invertebrate prey and litter-detritus

Due to limited information on relationships between riparian characteristics and tributary junctions, aquatic habitat, and differential fish use (variation in fish distribution and abundance), these topics were only briefly mentioned in this report. There is relatively minimal information that ties these important ecological attributes directly to variable buffer widths.

<u>Tributary junctions</u> (such as where x creek joins y creek) are a unique habitat that support greater biological diversity and productivity than typical river banks (Rice et al. 2008). While the importance of tributary junctions for salmonids is becoming increasingly recognized, there is minimal information on the specific linkages between tributary junction aquatic habitats and riparian area characteristics. However, due to the significance of tributary junctions for salmonid habitats, it is likely that healthy riparian coverage in these areas is critical.

High quality <u>aquatic habitat</u> is also important for salmonid growth, productivity, and survival. The literature shows relationships between riparian conditions and aquatic habitats; however, how these relationships change with buffer width has not been thoroughly described. The quality and functionality of aquatic habitat relies on several factors aside from solely riparian conditions such as channel characteristics, hydrologic regimes, sediment dynamics, as well as watershed and landscape patterns and processes. For the purpose of this document, aquatic habitat will not be evaluated as an individual riparian function, but rather as the result of all riparian functions. For example, riparian functions operating at high levels would likely support healthy aquatic habitats which would intern support juvenile and adult salmonids.

Differential fish use has been thoroughly tied to riparian presence/absence; however, similar to aquatic habitat, several factors aside from just riparian condition play into why fish may or may not be found in any particular watercourse. For example, a fish passage barrier may limit fish from accessing high quality habitat. Similarly, the existing literature provides minimal information on the relationships between riparian buffer characteristics and differential fish use. Generally, the literature supports that forested riparian buffers compared to other land covers types along watercourses support higher fish species diversity and abundance. While riparian buffer presence/absence is clearly influential on fish use, minimal information indicates how different buffer sizes may affect the degree of fish use in any particular area.

3.2 Water quality contaminants – nutrients, sediment, pesticides

3.2.1 Importance to salmon

Nutrients

- Eutrophication is a result of excessive amounts of nutrients (primarily nitrogen and phosphorus) that can cause algal blooms and, ultimately, oxygen depletion, which kills fish and/or their primary food sources (i.e., plankton and invertebrates) (Mayer et al. 2007).

Sediment

- Increased concentrations of suspended solids within watercourses can cause reduced salmonid growth rates, acute salmonid mortality, and altered macroinvertebrate prey populations (Newcombe and Jensen 1996, Florsheim et al. 2008).

Pesticides

- Concentrations of pesticides and other chemicals from farm fields as well as other managed landscapes and runoff can negatively affect salmonid development, survival, reproductive potential, and lowers food availability (e.g. plankton and invertebrates) (Harris et al. 2008, Bereswill et al. 2012).

3.2.2 Drivers and controlling factors of water quality?

The primary pathway for nutrients, suspended solids and pesticides to enter watercourses is via overland or underground water flow. All can also enter via drift caused by wind. The following factors can impact nutrient uptake at multiple levels within the soil profile (e.g. surface water, shallow, and deep groundwater), the amount of sediment filtered out of overland flow, the filtering of windborne nutrients and pesticides, and the conditions for nutrient and pesticide processing (Osborne and Kovacic 1993, Mayer et al. 2007, Bentrup 2008, Zhang et al. 2010, Aguiar et al. 2015). This section is intended to provide a high level summary of the controlling factors of this riparian function. Further details can be found in the discussion section.

- Soil characteristics
  - Soil permeability – the speed at which water moves through the soil, vertically and laterally, impacts the uptake and processing of nutrients (specifically nitrogen) (Mayer et al. 2007, Sweeney and Newbold 2014). This is mostly influenced by soil type/composition (e.g. clay, silt, sand, gravel, etc.).
  - Soil chemistry – mainly the presence of decaying organic matter and anaerobic soils, which together cause microbial denitrification and can affect pesticide processing (Mayer et al. 2007, Aguiar et al. 2015).
- Vegetation – the type, density, and height of vegetation can influence how riparian areas filter out nutrients and pesticides as well as how subsurface characteristics like root density and depth can influence nutrient and pesticide uptake.
  - Riparian buffer width – buffer width influences the amount of vegetation that can interact with overland and groundwater flow to uptake nutrients and supports areas for nutrient and pesticide processing as well as sediment filtering.
  - Continuity of vegetation –gaps in buffers allow water carrying nutrients, sediment, and pesticides to freely flow into watercourses without passing through vegetated buffers (Scarsbrook and Halliday 1999, Bereswill et al. 2012).
  - Density – vegetation density affects the dynamics of overland water flow by decreasing velocities and increasing the amount of sediment deposition (and related nutrient/pesticide deposition) (Osborne and Kovacic 1993, Mayer et al. 2007, Zhang et al. 2010, Aguiar et al. 2015).
  - Composition (e.g., vegetation type) – trees generally remove more nutrients (e.g., nitrogen and phosphorus) and pesticides compared to grasses and shrubs (Foster et al. 2002, Zhang et al. 2010, Aguiar et al. 2015); grasses can effectively filter sediments that may include any sediment-bound nutrients and pesticides (Buffler et al. 2005).

  - Placement (e.g., proximity to pollutant source) – riparian vegetation closer to pollutant sources are more effective at intercepting pollutants than vegetation distant from sources (Norris 1993).
- Watercourse characteristics
  - Watercourse length –influences the amount of time a given watercourse can support microbial processing of nutrients and pesticides (e.g., short watercourses have less contact time for microbial processing compared to longer watercourses)(Scarsbrook and Halliday 1999, Vidon et al. 2010, Bereswill et al. 2012, Sweeney and Newbold 2014).
  - Flow path modification (e.g., drain tiles, pipes, straightening, channelization, etc.) – management actions like channelization and watercourse straightening reduce the length of a watercourse and subsequent microbial processing time/length; drain tiles and pipes influence the contact length/time of sub-surface waters with soils and the potential for nutrient and pesticide removal.
- Concentration and/or volume of pollutant – the concentration of nutrients and pesticides and the volume of sediment within runoff (i.e. riparian buffers have a finite capacity to uptake, process, and filter pollutants at any one time) (Mayer et al. 2007, Yuan et al. 2009).
- Slope – bank and valley slopes impact the velocity of water moving toward watercourses and can influence the speed at which nutrient uptake and processing, sediment filtering, and pesticide processing occurs within buffers.

3.2.3 Ranges of buffer widths for water quality in the literature

Seventeen references were reviewed which focused on riparian buffer effects on nutrient, sediment, and pesticide inputs to watercourses. References reported that riparian buffer widths which support greater than 50% of nutrient, sediment, and pesticide reduction were a minimum of 10 feet to 328 feet (Appendix I). Additionally, riparian buffer lengths that supported sediment and nutrient reduction were a minimum of 984 feet to 4,920 feet (Appendix I). It's worth noting that the upper limits of these riparian buffer widths and lengths represent the upper limits of what has been studied and do not necessarily represent the full extent of potential riparian buffer function.

3.2.4 Discussion

The literature identifies riparian buffer characteristics (e.g., vegetation composition and buffer length/continuity) as well as landscape characteristics (e.g., clay content in soils and low-gradient features) that are directly applicable to the Snoqualmie River floodplain and help to optimize the ability of riparian buffers to protect water quality.

Within the Snoqualmie floodplain, the clay-containing soils and low-gradient floodplain can allow for optimal removal of nutrients, pesticides, and sediments from water flowing toward watercourses, if the watercourses are adequately buffered. According to the NRCS Hydrologic Soil Groups, the soils within the Snoqualmie Agricultural Production District

(APD) are predominantly groups "B" and "C." These soil classifications are based on the soil's clay content, which correlates to how quickly water is absorbed by and moved through the soil profile and into the groundwater, also known as infiltration. Group "B" and "C" soils are described as having moderate infiltration capacity (i.e., moderately low run-off potential) and low infiltration capacity (i.e., moderately high run-off potential), respectively. Although water infiltration is important to lessen overland flow and increase overall soil drainage, soil that allows water to move quickly vertically and horizontally through its profile is not conducive to nutrient and pesticide processing, retention, and uptake (Vidon and Hill 2006, Sweeney and Newbold 2014, Hill 2018). Soils with higher clay content have greater potential for nutrients and pesticide compounds to bind to soil particles and to slow subsurface water flow, allowing nutrient uptake by plants. Secondly, the overall low-gradient of the Snoqualmie floodplain also slows down surface and subsurface water flow toward watercourses. Buffers within these low-gradient landscapes (< 5% slope) allow for higher uptake, processing, and binding of nutrients and pesticides and higher sediment filtration (Yuan et al. 2009). Finer sediments and lower gradients can create areas with favorable conditions, referred to as "hot spots," for denitrification and pesticide processing by helping to produce anoxic areas, maintain high concentrations of organic matter and high moisture content (Vidon et al. 2010). For example, processing "hot spots" may occur when microbial biomass accumulates on the surface where organic matter is decaying or in subsurface root zones where excess water and organic residues collect, accelerating the breakdown of pollutants (Vidon et al. 2010). While the clay-containing soils and low-gradient characteristics of the Snoqualmie floodplain are conducive to the removal of nutrients, pesticides, and sediments, microbial processing and plant uptake of pollutants can only be optimized when riparian buffers (including grass, shrubs, and trees) are integrated across the landscape.

Riparian characteristics such as vegetation composition and buffer length affect the ability of riparian buffers to maintain high water quality. Woody vegetation, particularly trees, are best at protecting water quality based on the parameters examined here (i.e., sediment, nutrients, and pesticides) (Mayer et al. 2007, Zhang et al. 2010). Grasses are able to improve water quality conditions (primarily through sediment removal); however, woody vegetation including shrubs and trees have been shown to have relatively higher removal efficacies of nutrients and pesticides (Foster et al. 2002, Zhang et al. 2010, Aguiar et al. 2015). Deeply-rooted plants, specifically trees, tap into lower subsurface water flows and therefore can intercept more nutrients and pesticides before they flow into watercourses (Aguiar et al. 2015). Continuous buffers help ensure water is not diverted along less resistant paths around buffer fragments, increasing the percentage of water interacting with the buffer's vegetation before entering watercourses and decreasing erosion caused by concentrated water flows (Bereswill et al. 2012). Studies have found a lack of association of buffer width on nutrient or pesticide removal when buffers are fragmented as water is diverted around buffers and not through them (Sweeney and Newbold 2014). Continuous buffers along watercourses directly correlate to more areas conducive to high uptake and processing (i.e., "hot spots"), where most of the nutrient and pesticide processing occurs (Vidon et al. 2010). Conceptually, there is more area and a greater probability for pollutant uptake and processing when continuous buffers are in place rather than fragmented buffers. For example, Bunzel et al. (2014) found that long/continuous buffers intercepted more water flow and reduced pesticide contamination with relatively less buffer width compared to fragmented buffers. Narrow buffers may be able to provide water quality protections if they are continuous and densely planted to prevent runoff from breaks in vegetation.

Instream processing of pollutants also greatly benefits from continuous long riparian buffers. Continuous, long buffers have a greater capacity to contribute organic matter to watercourses, specifically woody debris and litter-detritus, which increases the amount of surface area available for microbial processing of nutrients and pesticides. These processes require significant stream length and residence time. For example, Scarsbrook and Halliday (1999) found that a non-buffered agricultural watercourse entering into a fully forested reach did not show any significant evidence of nutrient processing until 600 meters into the forest. These results suggest that nutrient processing is limited in non-buffered agricultural watercourses and a significant length of riparian buffer is needed to restore nutrient processing. Thus, the importance of continuity and length is two-fold, in that these two factors in combination can drastically reduce the likelihood of nutrients and pesticides entering watercourses and can increase the ability for streams to process the amount of instream nutrients. As previously mentioned, stream length and residence time is important for microbial processing of nutrients and pesticides. Management actions like channelization and watercourse straightening can result in decreased channel length, which minimizes the amount of time a given watercourse can process nutrients and pesticides. Watercourses across the lower Snoqualmie River valley that have been straightened and channelized may require relatively wider, longer, and more continuous riparian buffers to compensate for lost capacity in aquatic in-channel microbial processing. This may help to optimize the potential of riparian areas to remove/treat nutrients and pesticides prior to entering watercourses.

3.3 Water temperature/riparian shade

3.3.1 Importance to salmon

- As a cold-blooded species, salmonid's metabolic and physiological processes are greatly affected by water temperature. There is a strong association between water temperature and salmonid geographic distribution, spawning times, growth rates, egg development and survival, competitive interactions, life stage survival, and behavior (Quinn 2018a).
- High water temperatures are of predominant concern:
    - A temperature range of 23 - 25°C (~73 - 77°F) or higher is usually lethal in seconds to hours for salmonids and their life stages (Hicks 2000).
    - Temperatures of 16 - 23°C (~61 - 73°F) can cause significant sub-lethal effects such as increased susceptibility to disease, metabolic stress, developmental issues, and blockage of migration, which can influence survival during spawning development, and rearing (Hicks 2000).

3.3.2 Drivers and controlling factors of temperature

- Climatic drivers (Sullivan and Adams 1991, Poole and Berman 2001, Isaak et al. 2012)
    - Direct, uninterrupted sunlight (e.g., short-wave radiation emitted by sun that does not pass through other objects, such as trees) is the primary source of heating in most stream environments (Poole and Berman 2001, Johnson et al. 2003).
    - Atmospheric radiation/air temperature (e.g., long-wave radiation absorbed and emitted by the atmosphere) - air temperature and can influence long-term stream temperature trends and inter-annual variability (Isaak et al. 2012).
    - Wind speed influences the amount of time for heat exchange between the atmosphere and water surface (e.g., reduced wind speed can trap air against the water surface and decrease heat exchange to the water surface) (Naiman et al. 1992).
    - Precipitation acts as a source of thermal input (e.g., cooler rain) as well as a water volume input.
- Riparian buffer characteristics
    - Vegetation presence and topography – daily and seasonal temperature fluxes are controlled by relative water surface shading influenced by topography (channel banks and hills/mountains) and riparian vegetation (Steinblums 1977, Beschta et al. 1987).
    - Buffer density/height – the amount of solar radiation transmitted through a forest canopy depends on the density and height of vegetation (e.g., taller and denser vegetation can provide relatively greater shade than short and less-dense vegetation) (Vezina and Pech 1964, Reifsnyder and Lull 1965, Black et al. 1991, DeWalle 2010).
    - Buffer length and continuity – the greater the continuous length of stream that is buffered with vegetation that provides shade, the more effective the buffer is at controlling temperature (Barton et al. 1985, Rutherford et al. 2004, Cole and Newton 2013). Vegetation can reduce wind speed that traps air against the water surface and decreases heat exchange to the water surface (Naiman et al. 1992).
- Channel/Watercourse characteristics
    - Stream width – determines the amount of shade that can be provided by topography and riparian vegetation (e.g., narrower streams are easier to shade) (Cole and Newton 2013, Goss et al. 2014, Quinn 2018b).
    - Stream velocity – lower velocity streams are more susceptible to heating from direct solar radiation (Rutherford et al. 2004, Cole and Newton 2013, Quinn 2018b).

- Stream volume/size – water temperature is proportional to heat energy (e.g., solar radiation energy added to a stream) divided by water volume (e.g., discharge-flow of a stream); streams with less volume are more sensitive to thermal inputs (Poole and Berman 2001).
- Substrate composition and color – in-stream substrate that is dense, large, and dark in color absorbs and retains more heat, which allows streams to stay at higher temperatures for longer periods of time (Cole and Newton 2013).
- Stream aspect – the orientation of a watercourse can affect the amount of direct solar radiation reaching the water's surface (Johnson 1971, Davies et al. 2004).

- Microclimate – affects air temperatures, which are strongly correlated with stream temperatures, within the riparian area (see Microclimate section).
- Tributary inputs – the volume and related temperature of water inputs from tributaries can influence water temperatures in receiving waterbodies (e.g., cooler tributaries can create mainstem areas of lower temperatures) (Poole and Berman 2001).
- Hyporheic exchange and groundwater inflow – can help control/maintain water temperatures if enough groundwater is interacting with the stream's surface water (Rutherford et al. 2004, Gomi et al. 2006, Quinn 2018b).

3.3.3 Ranges of buffer widths for temperature in the literature

Eighteen references that focused on riparian buffer effects on stream shading and temperature were reviewed, some of which were review articles. Riparian buffer widths that provided significant shading and moderated instream temperatures were a minimum of 5 feet to 225 feet (Appendix I). Additionally, riparian buffer lengths that supported temperature moderation were a minimum of 328 feet to 8,202 feet (Appendix I). It's worth noting that the upper limits of these riparian buffer widths and lengths represent the upper limits of what has been studied and do not necessarily represent the full extent of potential riparian buffer function.

3.3.4 Discussion

In some watercourses, temperature will be the principal ecological concern to keep downstream habitat viable for salmonid spawning and rearing. For example, smaller watercourses are more susceptible to temperature fluctuations and priority management actions may focus on minimizing temperature spikes to lessen potential impacts to downstream water temperatures (Davies et al. 2004, Cole and Newton 2013, Quinn 2018b). Within smaller watercourses, it may only be necessary for the riparian buffers to be wide enough to create significant shading (Brazier and Brown 1973). Thus, smaller watercourses in the Snoqualmie River valley, such as agricultural-maintained channels, may only require dense and overhanging buffers at relatively narrow widths to provide shade benefits. These buffer characteristics reflect finding from Benedict and Shaw (2012), which indicated that narrow and dense buffers reduce air temperature and create effective shade along agricultural watercourses. Narrow-dense riparian buffers may be most effective on east-west oriented smaller watercourses, where the amount of shading from vegetation on south-banks can be significantly more than that of north-banks. Modelled results from DeWalle (2010) indicated that east-west oriented small streams can achieve relatively greater shading at narrower buffer widths, compared to north-south oriented streams (DeWalle 2010). These observations also suggest that wider, denser, and taller riparian buffers are needed to provide shading benefits on smaller, north-south oriented watercourses.

While smaller watercourses have the greatest cumulative stream length to moderate water temperature, riparian buffers along larger watercourses can also support shading benefits. In addition to watercourse orientation, the width of a given watercourse can influence the effectiveness of riparian buffer characteristics. As watercourse size increases, the shaded area from riparian and topographic vegetation is reduced, which can influence the sensitivity of a watercourse to thermal inputs (Cristea and Janisch 2007, DeWalle 2010). Since riparian vegetation height and density influence the percentage of watercourse shading, larger watercourses across the Snoqualmie River valley (e.g., large tributaries and mainstem channels) likely need wide, tall, and dense riparian buffers to support shading benefits. Additionally, while smaller east-west oriented watercourses can achieve shading through relatively narrow-dense vegetation, larger east-west oriented watercourses may require wider and taller buffers to achieve effective shade. For example, Cristea and Janisch (2007) found that effective shade declined significantly in east-west oriented watercourses for channel widths greater than ~10 meters (33 feet).

Riparian buffers help to maintain cooler water temperatures by limiting heat exchange between watercourses and solar-atmospheric radiation (Rutherford et al. 2004, Cole and Newton 2013, Goss et al. 2014). Additionally, riparian buffers help to maintain cooler water temperatures by insulating thermal inputs from groundwater mixing, streambed heat conduction, tributary inputs, and hyporheic exchange. Restoring overall temperature regimes for streams that were previously not buffered can take a significant amount of "buffered" stream time (4 hours travel time) or length (up to 3900 feet within a buffered reach) (Rutherford et al. 2004). As Cole and Newton (2013) demonstrated, direct solar radiation warmed watercourses faster than various other mechanisms within shaded forested reaches could cool them (cooling through groundwater mixing, streambed heat conduction, tributary inputs, and hyporheic exchange). Therefore, it is critical to shade as much of the length of the watercourse as possible to decrease the surface area exposed to direct solar radiation. Barton et al. (1985) established that buffer strip length accounted for 77% of the temperature variation within their study of 40 streams and determined that shading 80% of the stream length (33 foot-wide buffer along both sides of the stream, in their case) maintained stream temperatures indistinguishable from a fully forested system. These studies, and others, highlight the importance of buffer length/continuity in regulating overall temperature regimes within stream networks.

While temperature regulation is of predominant concern within the Snoqualmie River Valley, "extreme shading" (i.e,. blocking more than 80% of direct solar radiation) should be considered when thinking about riparian buffer design (Bottom et al. 1985) (Figure 4).

Some direct solar radiation is critical for primary production of algae—one of the main drivers of animal production in freshwater ecosystems (Brett et al. 2017). Thus, riparian cover that can provide optimal shade levels without impacting primary production may only require ~85% canopy cover (Cristea and Janisch 2007). Shade as an ecological function driving water temperature is critical in all watercourses but given the frequency and cumulative stream length of smaller watercourses, it may be most helpful to prioritize smaller watercourses to achieve temperature-related shading benefits. A suitable temperature regime is critical to the long-term viability of salmonid populations.

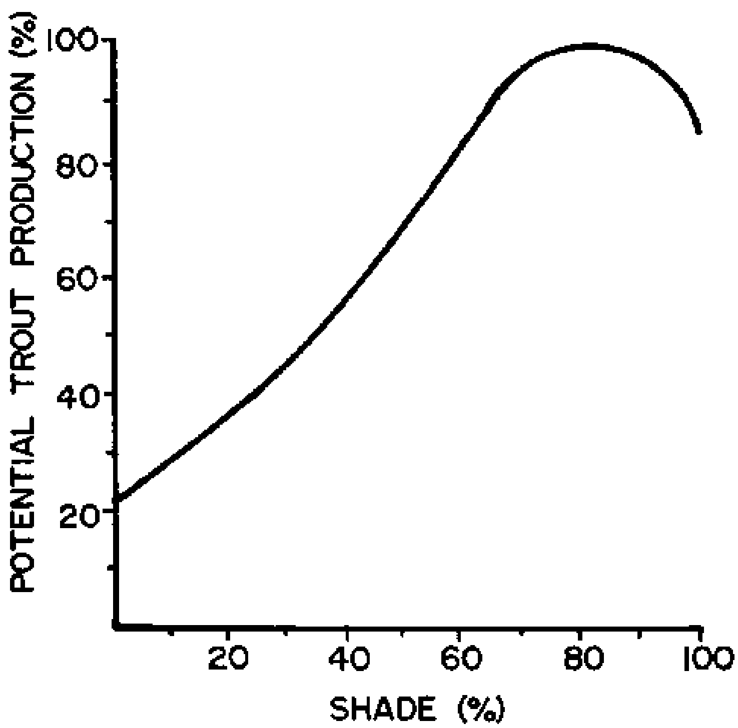


Figure 4. Trout Production in Relation to Surface Shading of Small Streams (Riparian Habitat Committee 1979)(From Bottom et al. 1985).

3.4 Riparian corridor microclimate

- Microclimate can generally be referred to as the climate at relatively smaller scales, such as 0.001 meters to 1,000 meters (Oke 2002). This phenomena is produced by a combination of variables including sunlight exposure, wind exposure (i.e., magnitude and direction), precipitation, and moisture content (i.e., air and soil), all of which help to control air and soil temperatures (Davies-Colley et al. 2000). For example, a riparian buffer can create a microclimate that moderates temperatures around a watercourse, shielding the area from temperature extremes from other nearby landscape areas.

3.4.1 Importance to salmon

- Maintaining a microclimate throughout a riparian buffer can increase the potential of a buffer to control stream temperatures and seasonal shifts in stream temperature extremes.
  - Deviating seasonal temperature may negatively impact salmonid behavior such as triggering early migrations (Macdonald et al. 2003).
  - See Water Temperature/Riparian Shade Function Framing section for more details on the effects of significant stream warming on salmonids.

3.4.2 Drivers and controlling factors of microclimate

- Solar radiation – the amount of solar radiation reaching the forest floor can affect most components of microclimate by influencing the thermal and moisture environments under the forest canopy (Moore et al. 2005).
- Cover/shade in riparian buffers –influence all of the microclimate components and is provided by vegetation and topography.
  - Trees, depending on their height and density, can create enough shade and canopy cover to influence microclimate (Moore et al. 2005, Olson et al. 2007).
  - Topography such as valley walls or surrounding mountains and hills can provide more complete shading of streams and riparian areas than vegetation alone, which can have a relatively larger impact on microclimate (Moore et al. 2005, Reeves et al. 2018).
- Riparian vegetation characteristics (Chen et al. 1993, Chen et al. 1995, Brosofske et al. 1997, Moore et al. 2005, Rykken et al. 2007)
  - Riparian buffer width – decreases in buffer width minimize the degree of protection for microclimate over and immediately connected to the stream as well as within the riparian buffer.
  - Riparian buffer length/continuity – the more continuous a buffer, the larger microclimate area that is protected due to reduced edge effects.
    - Edge effects are how the climate outside of the riparian buffer affects the microclimate along the edge of the buffer; increased buffer fragmentation results in increased edge effects.
- Open water surfaces – produce locally cool and moist conditions over and immediately next to the stream by producing water vapor and absorbing latent heat (Moore et al. 2005, Olson et al. 2007, Rykken et al. 2007, Reeves et al. 2018).
- Wind speed – can cause the mixing of air from outside of the riparian buffer, influencing all of the microclimate components within the riparian buffer; increased buffer fragmentation increases the area where wind and edge effects can influence microclimate conditions
- Macroclimate (the overall weather pattern and climate of an area) – can influence precipitation, humidity/moisture, air temperatures, and wind patterns which

directly influence the extent and degree of microclimate conditions within a riparian buffer (Olson et al. 2007).

3.4.3 Ranges of buffer widths for microclimate in the literature

Eight references focused on microclimate in riparian buffers, some of which were review articles. Riparian buffer widths which support microclimate conditions were a minimum of 50 feet to 328 feet (Appendix I). It's worth noting that the upper limit of these riparian buffer widths represent the upper limit of what has been studied and does not necessarily represent the full extent of potential riparian buffer function.

3.4.4 Discussion

Microclimates are known to extend 98-196 feet from streams and vary in intensity (Brosofske et al. 1997). Studies tend to focus on two areas of microclimate influence: referred to here as "stream-center microclimate" – an area directly over and immediately connected to the stream with strong microclimate characteristics (Anderson et al. 2007, Olson et al. 2007, Rykken et al. 2007) and "off-stream microclimate" – the area away from the stream within the riparian buffer that still has detectable characteristics of a microclimate (Brosofske et al. 1997, Moore et al. 2005, Reeves et al. 2016). Studies that measured the entirety of the microclimate gradient find the strongest effects over and directly connected to streams, 33-66 feet into the riparian area (Moore et al. 2005, Olson et al. 2007). Watercourses exert an influence on riparian microclimate, specifically on air temperature and relative humidity that create a climate different than that of the surrounding forest (Rykken et al. 2007). Microclimates slowly degrade as the distance from the watercourse increases, a phenomena known as the "edge effect," and is caused by the climate in the surrounding landscape pushing into the riparian buffer (Chen et al. 1993, Rykken et al. 2007). Physical edge effects include changes in air temperature, soil temperature, relative humidity, air flow, and light intensity (Chen et al. 1995). The stream center microclimate area is the strongest portion of the riparian microclimate and can dampen edge effects. Riparian buffer widths protective of the stream center microclimate generally fall within the lower to middle half of the reported buffer width range (48-98 feet, see Appendix I for more details) (Anderson et al. 2007, Olson et al. 2007, Rykken et al. 2007). Riparian buffer widths protective of both the stream center microclimate in addition to the off-stream microclimate (i.e., the entirety of the riparian microclimate) fall within the middle to upper end of the range (148- 225 feet range) (Brosofske et al. 1997, Moore et al. 2005, Reeves et al. 2016).

Much of the published research has focused on the spatial extent of microclimates and how wide riparian buffers should be to protect its entirety. Research suggests that microclimate extent and presence is related to the width and composition of riparian buffers (Brosofske et al. 1997, Moore et al. 2005, Olson et al. 2007, Rykken et al. 2007, Reeves et al. 2018). Consequently, it has been suggested that a buffer width of one to two site potential tree heights can protect the entirety of microclimate conditions (Reeves et al. 2016, Reeves et al. 2018). The inclusion of a second tree height in the buffer distance is aimed at protecting and enhancing the microclimate within the first tree height distance (Reeves et al. 2016).

Protecting the entirety of the microclimate gradient creates more certainty that a given riparian buffer will be able to support microclimate conditions and benefits. The microclimate in riparian areas is directly related to plant growth rates and overall productivity, microbial activity related to decomposition, denitrification, and other chemical processes, as well as stream temperature (Brosofske et al. 1997, Moore et al. 2005). Narrower buffers would provide partial protection to microclimate, but have a greater risk of being compromised by natural processes such as windthrow, which changes the extent and composition of riparian areas (Moore et al. 2005). Based on management goals, buffers can be protective of the entirety of the microclimate gradient or the most prominently affected areas (e.g., stream center microclimate), with the latter strategy potentially reducing riparian microclimate conditions further away from a watercourse. Riparian buffer length and continuity helps protect microclimate conditions, with fragmentation resulting in "edge effects". Fragmented riparian buffers allow more buffer edges to be prone to "edge effects", or outside climate, and riparian continuity helps to support microclimate preservation. Additionally, the relative width of watercourses influences the effectiveness and influence of microclimate conditions. The ability of microclimate conditions to buffer water temperatures decreases with increasing watercourse width, such that larger watercourses (e.g., Snoqualmie River) are relatively less sensitive to microclimate conditions compared to smaller watercourses (e.g., small tributaries and floodplain channels).

3.5 Large wood (recruitment and retention)

3.5.1 Importance to salmon

- Habitat – large wood (e.g., fallen trees in a watercourse) supports the formation, maintenance, and function of critical aquatic salmon habitat features, including pools, back eddies, side channels, alcoves, riffles, debris jams, as well as gravel and sand bars (Harmon et al. 1986b, Bisson 1987, Bilby and Ward 1991, Spence et al. 1996, Bilby and Bisson 1998).
    - Large wood significantly influences biological productivity (Franklin et al. 1982, Sedell and Swanson 1982, Sedell and Froggatt 1984).
    - Up to 50% of the aquatic habitat in streams is provided or controlled by large wood (Swanson and Lienkaemper 1978).
    - Large wood also provides macroinvertebrate habitat (Triska 1984).
- Refugia – large wood provides refuge for salmonids from extreme temperature conditions during the summer (i.e., it promotes hyporheic exchange which provides cool water) and from high flow conditions during winter by dissipating hydraulic energy (Everest and Chapman 1972, Bilby 1984, Murphy et al. 1984, Stanford and Ward 1988, Jackson and Sturm 2002, Johnson 2004).
- Cover – large wood provides cover from predators (Bilby 1984, Harmon et al. 1986b, Everett and Ruiz 1993, Nielsen et al. 1994).

- Channel morphology – large wood can influence geomorphic processes such as sediment transport, storage, and sorting (Nanson 1981, Swanson and Lienkaemper 1982, Gurnell et al. 2001, Gurnell and Petts 2002) as well as influence stream morphology and channel form (Bisson 1987, Montgomery et al. 1995, Spence et al. 1996, Beechie and Sibley 1997, Montgomery and Buffington 1997, Bisson and Bilby 1998).
    - Can cause and prevent lateral channel migration as well as influence the formation of side channels, gravel bars, and mid-channel islands (Keller and Swanson 1979, Nakamura and Swanson 1993).
    - Sediment movement is important for maintaining and expanding spawning areas; large wood can stabilize gravel deposits and reduce channel bed movement, helping to minimize scour impacts on salmon redds. It can also cause local scour around new deposits (Montgomery et al. 1996).
- Vegetation establishment – large wood provides sites for vegetation colonization, forest island growth and coalescence, and forest floodplain development (Fetherston et al. 1995, Bilby and Bisson 1998).
- Bank stabilization – large wood can stabilize banks, decreasing erosion (Beeson and Doyle 1995, Gurnell et al. 2002a, Micheli et al. 2004).

3.5.2 Drivers and controlling factors of large wood

The driving/controlling factors listed below influence large wood recruitment and retention across watercourses.

- Channel/watercourse characteristics
    - Channel width and size (Harmon et al. 1986a, Lienkaemper and Swanson 1987, Bilby and Ward 1989, Murphy and Koski 1989, Montgomery et al. 1995, Beechie and Sibley 1997, Bilby and Bisson 1998, Beechie et al. 2000, Gurnell et al. 2002a, Rosenfeld and Huato 2003, Booth and Fox 2004, Spies et al. 2013, Johnson et al. 2015, Wohl et al. 2019)
        - Related to the primary disturbance regime influencing wood recruitment (e.g., channel migration in large channels vs. windthrow in small channels).
        - Correlated to the size of wood necessary to influence aquatic ecosystems (e.g., stable habitat forming wood is relatively smaller in small watercourses, compared to large watercourses).
    - Channel planform (i.e., sinuosity, braiding, anastomosing) and network complexity (i.e., number of channels, branches, and confluences) (Piégay and Gurnell 1997, Gurnell et al. 2002a, Spies et al. 2013, Johnson et al. 2015, Wohl et al. 2019)
        - Influences the degree of disturbance (e.g., slow recruitment from a low-gradient sinuous channel vs. frequent recruitment in a braided high-gradient channel).

        - Influences the locations and ability for watercourses to retain wood (e.g., braided and multi-branching channels provide more location for instream wood to stabilize).
    - Channel slope and gradient (Gurnell et al. 1995, Beechie and Sibley 1997)
        - Influences the degree that large wood influences habitat formation (e.g., large wood is more likely to influence habitat formation in high gradient watercourses).
    - Stream discharge (Lienkaemper and Swanson 1987, Gurnell et al. 1995)
        - Influences the potential for wood displacement (e.g., higher flows can dislodge wood) and habitat formation (e.g., the degree of erosion and accretion).
        - Influences wood movement from floodplain areas (e.g., higher flows can carry fallen wood throughout a floodplain toward watercourses as well as move wood from within watercourses to floodplain areas).
- Disturbance regime – how trees end up in watercourses
    - Fluvial processes - channel migration, channel avulsion, and flooding influence erosion and subsequent wood recruitment (Harmon et al. 1986a, Lienkaemper and Swanson 1987, Grant and Swanson 1995, Latterell and Naiman 2007, Naiman et al. 2010, Johnston et al. 2011, Wohl et al. 2019).
    - Landscape processes – mass movement processes including soil creep, slumping, earthflows, debris flows, avalanches, and landslides provide episodic sources of large wood recruitment (Harmon et al. 1986a, McDade et al. 1990, Grant and Swanson 1995).
    - Tree mortality - disease (e.g., decay and root rot), windthrow (uprooting and snapping trees and branches), insects, fire, beavers, suppression and competition influence the frequency, location, and degree of large wood recruitment (Swanson and Lienkaemper 1978, Harmon et al. 1986a, Bisson 1987, Lienkaemper and Swanson 1987, Maser et al. 1988, McDade et al. 1990, Pollock et al. 2003, Naiman et al. 2010).
- Riparian vegetation characteristics (Harmon et al. 1986a, Murphy and Koski 1989, McDade et al. 1990, Robison and Beschta 1990, Bilby and Ward 1991, Rot et al. 2000, Gurnell et al. 2002a, Welty et al. 2002a, Sobota 2003, Johnson et al. 2015)
    - Riparian buffer width and source distance – the width of a buffer determines the distance of potential recruitment (i.e., wide buffers, compared to narrow buffers, can provide a greater source area for potential wood recruitment by maximizing tree falling distance as well as flood transport).
    - Composition (e.g., hardwood vs. conifer)
        - Conifers have a greater source distance compared to hardwoods due to relatively taller height potentials (e.g., conifers are generally taller at maturity resulting in a greater fall distance).
        - Hardwoods provide near-term recruitment due to shorter life expectancies (influencing potential for mortality related recruitment)

and conifers provide long-term recruitment due to longer life expectancies.

- Wood condition (i.e., size, shape, density, age, and species) - influences the likelihood of remaining in a watercourse and forming habitats (Harmon et al. 1986a, Lienkaemper and Swanson 1987, Bilby and Wasserman 1989, Beechie et al. 2000, Rot et al. 2000, Gurnell et al. 2002a).
    - Older trees provide relatively taller and larger diameter wood than younger trees (e.g., taller trees generally have greater weights, lengths, and densities).
    - Greater weight of old, large trees can counteract hydrologic displacement and greater density of old, large trees can counteract buoyancy forces.
    - Greater lengths and rootwad size associated with old-large trees increases the chance of large wood getting jammed, lodged, and snagged within a watercourse or against other wood.
    - Coniferous trees are more decay resistant compared to deciduous trees due to the relative size and density of conifer tree species.
- Sediment dynamics and transport regime (Gurnell et al. 1995, Gurnell et al. 2002a)– influences large wood storage dynamics (e.g., ability to remain in a watercourse), potential habitat formation (e.g., amount of sediment deposition), as well as channel stability (e.g., avulsion and migration rates).

3.5.3 Ranges of buffer widths for large wood in the literature

Twenty-three references detail the relationships between large wood recruitment and the relative distance that large wood can be recruited from (i.e., representative of riparian buffer widths). References reported that greater than 50% of large wood can be recruited at a minimum of 13 feet to 213 feet (Appendix I). It's worth noting that the upper limit of these riparian buffer widths represent the upper limit of what has been studied and does not necessarily represent the full extent of potential riparian buffer function.

3.5.4 Discussion

Mainstem channels, large tributaries, and alluvial reaches

Bank erosion is the primary source of large wood recruitment along alluvial mainstem channels (Murphy and Koski 1989, Latterell and Naiman 2007, Naiman et al. 2010), such as alluvial reaches of the Snoqualmie, Tolt, and Raging rivers. The majority of large wood in alluvial reaches is recruited through lateral channel migration from nearby stream riparian areas (i.e., relatively close riparian source distances) (Murphy and Koski 1989, Benda et al. 2002, Spies et al. 2013). While near-stream wood recruitment may suggest narrow buffer widths, active channel migration throughout alluvial reaches supports the need for relatively wider buffer corridors. Specifically, migrating channels require a wide riparian buffer to maintain a continuum of near-stream recruitment as the channel continues to migrate into riparian areas. Wide riparian buffers along alluvial reaches of the mainstem

Snoqualmie, Tolt and Raging Rivers would support the long-term input of near-stream wood and give riparian trees an opportunity to grow and reach mature size classes critical for in-channel retention.

The retention of large wood in larger channels such as the mainstem of the Snoqualmie, Tolt, and Raging rivers is dependent on the relative size of large wood pieces as well as the presence of large wood jams. In larger channels, wood needs to be large enough in size and weight to counteract hydrologic displacement and to get successfully lodged among channel features and within log jams (Harmon et al. 1986a, McDade et al. 1990). For example, large wood of greater widths and lengths have generally greater densities, which helps to counteract buoyancy forces, and also have a greater likelihood of getting wedged and snagged on bars, bank margins, as well as wood jams. Since large channels require relatively larger wood to remain stable and influence channel processes, consideration of stage age and stand type may be beneficial for determining riparian buffer widths (McDade et al. 1990, Welty et al. 2002b). Coniferous trees are more likely to be larger at maturity, less likely to float downstream, and more decay resistant compared to deciduous trees, which allows coniferous large wood to provide long-term habitat benefits (Harmon et al. 1986a, Spies et al. 2013). The lower Snoqualmie River floodplain was historically dominated by deciduous trees with relatively fewer coniferous trees; however, these large coniferous trees likely comprised much of the large wood actually retained in the Snoqualmie River (Collins and Sheikh 2002). Additionally, coniferous trees moving downstream from high-gradient areas above Snoqualmie Falls were likely to support instream large wood retained in the lower Snoqualmie River. In order to optimize the recruitment of mature, large coniferous trees, buffer widths along large channels should be wide enough to include areas of the floodplain where the river could migrate as well as areas where fallen trees could enter the river (i.e., source distance from a channel). Conifers generally have greater source distance than hardwoods (Figure 5) and source distance tends to be correlated with tree height since taller trees are more likely to reach the river from a greater distance compared to shorter trees (McDade et al. 1990, Robison and Beschta 1990). A riparian corridor width based on the potential tree heights of mature conifer species would integrate stand age and type to allow for riparian trees to be recruited at their maximum source distance (Spies et al. 2013, Reeves et al. 2018).

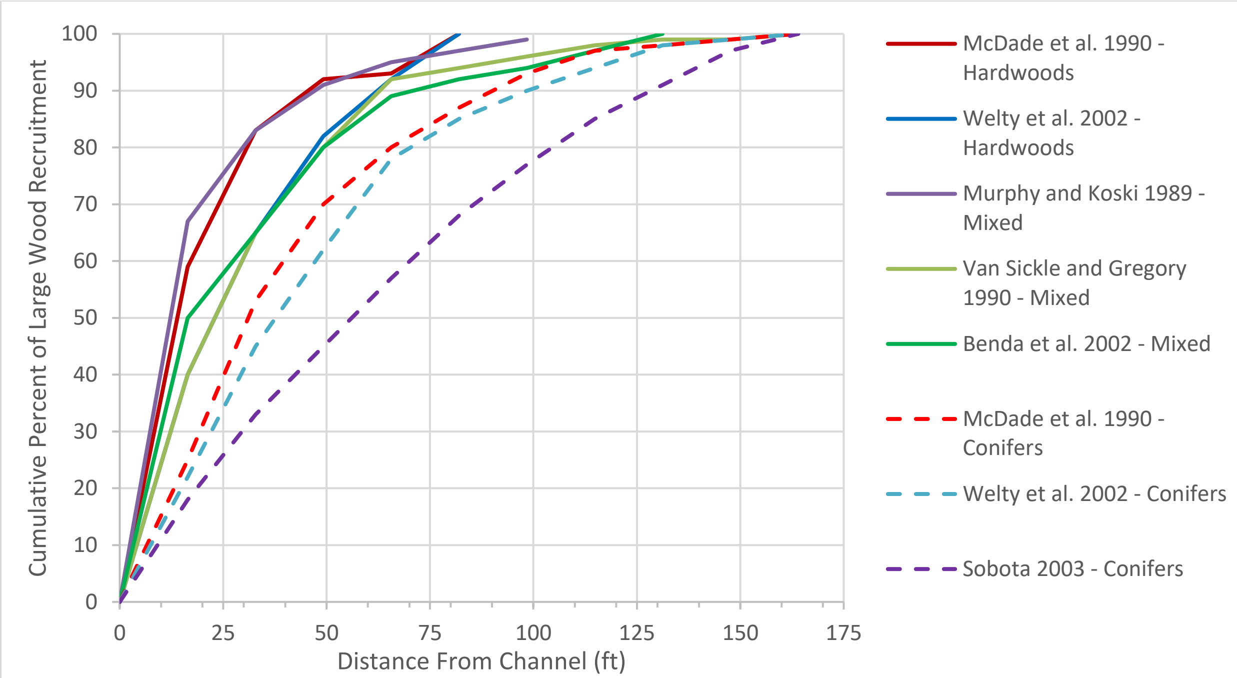


Figure 5. Large Wood Cumulative Recruitment Source Distances (adapted from Murphy and Koski 1989, McDade et al. 1990, Van Sickle and Gregory 1990, Welty et al. 2002, Subota 2003)

Focusing on coniferous species and their related site-potential tree height is informative for buffer width determination; however, consideration of stand composition is also necessary for near- and long-term large wood benefits (Sickle and Gregory 1990). Recruited hardwoods are able to provide considerable short-term benefits (Andrus et al. 1988, Beechie et al. 2000) and recruited conifers can provide long-term benefits upwards of twice as long as hardwoods (Andrus et al. 1988, Beechie et al. 2000). Inputs from hardwoods contribute to near-term wood recruitment since they grow relatively quicker than conifers, generally have a shorter life expectancies (influencing frequency of mortality related recruitment), are more characteristic of complex-branched canopies (influencing the likelihood of windthrow and breakage), and have relatively shorter recruitment distances compared to conifers (due to a greater likelihood of growing near a stream edge) (Andrus et al. 1988, McDade et al. 1990, Beechie et al. 2000, Hyatt and Naiman 2001, Benda et al. 2002, Collins and Montgomery 2002, Gurnell et al. 2002a, Welty et al. 2002b, Sobota 2003). As previously mentioned, the lower Snoqualmie River floodplain was historically dominated by deciduous trees (Collins and Sheikh 2002), which supports the likelihood of wide-spread deciduous tree recruitment. Thus, a riparian corridor based on mature conifer site potential tree height (optimizing potential recruitment distance) that also integrates a variety of conifers and hardwood species (supporting near- and long-term benefits) may adequately support large wood recruitment functions across the mainstem of the Snoqualmie, Tolt, and Raging rivers.

Since bank erosion is likely the primary source of large wood recruitment in mainstem alluvial reaches of the Snoqualmie, Tolt, and Raging rivers, bank and channel conditions should be considered when determining riparian buffer widths. Channel and bank alterations such as bank armoring, channelization, and wood removal significantly impair channel migration processes and subsequently influence the potential for large wood recruitment via erosional processes. Bank armoring subsequently results in a shift from wood inputs driven by erosion to inputs from windthrow and tree mortality. Since wood recruitment by windthrow and tree mortality have a source distance related to tree height (i.e., potential fall-source distance), mainstem areas where channel migration is limited due to bank armoring may need riparian buffers as wide as the site potential tree height for conifer species.

Floodplain channels, small tributaries, and maintained small channels

The smaller channel across the lower Snoqualmie River Valley may include floodplain, tributary, and maintained small channels. Large wood in smaller channels generally controls rather than responds to hydrological and sediment transfer characteristics (Gurnell et al. 2002a), and large wood is more likely to influence geomorphic functions in small and moderate channels (Booth and Fox 2004). The size of habitat-forming and stable large wood scales down with stream size, with smaller stream channels having greater proportions of stable large wood at relatively smaller size classes, compared to large stream channels. Smaller channels generally receive more large wood through windthrow, tree mortality (e.g., suppression, disease, insects, etc.), and beaver activity rather than by lateral channel migration or a channel avulsions (Fox 2001, Pollock et al. 2003). Smaller channels also receive a greater proportion of overall wood inputs from relatively shorter source distances, compared to larger channels (Lienkaemper and Swanson 1987, Murphy and Koski 1989). Relatively smaller habitat forming wood pieces as well as relative shorter wood source distances suggests that smaller riparian buffers along smaller channels may support wood recruitment processes.

Furthermore, a variety of vegetation types and age-classes can contribute to habitat-forming large wood across smaller channels. Hardwoods generally contribute more large wood in smaller channels (McDade et al. 1990) and a variety of smaller tree species are able to provide stable wood inputs for smaller channels. Rather than focusing on the site-potential tree height of large-mature coniferous trees for riparian buffer widths (as discussed for larger mainstem channels), relatively smaller riparian buffer widths based on deciduous trees and mixed composition vegetation may be sufficient to support wood recruitment in smaller floodplain, tributary, and maintained channels.

Large wood inputs within steeper gradient and bedrock channels (e.g., Tolt River, Raging River, valley-wall channel) generally have greater source distances than low-gradient channels. Upslope and episodic disturbances such as debris flows, landslides, and windthrow can contribute substantially to large wood in higher gradient small- and medium-sized streams (Reeves et al. 2003, Bigelow et al. 2007). Wood recruitment from these processes generally comes from greater source distances than bank erosion (Benda et al. 2002, Johnston et al. 2011). Additionally, valley-wall channels, steep gradient tributaries, and related alluvial fans can contribute significantly to instream wood transported to downstream reaches and mainstem channels. Subsequently, wide riparian buffers along higher gradient Snoqualmie valley tributaries may optimize upland wood recruitment processes as well as wood transport to downstream watercourses.

3.6 Erosion and bank stability (including channelization)

3.6.1 Importance to salmon

- Bank erosion can benefit aquatic habitats and biota (Junk et al. 1989, Bayley 1995, Wood and Armitage 1997, Florsheim et al. 2008, Quinn 2018b). Key benefits include:
    - Creates and maintains structural diversity of aquatic and riparian habitats; contributes coarse sediment to streambeds essential for benthic invertebrates and spawning salmon.
    - Influences changes in channel morphology and pattern (e.g., increased bed load and large wood recruitment from erosion can influence channel characteristics).
    - Sustains floodplain ecosystems by providing periodic erosion and sedimentation during floods that are important to floodplain and riparian soils and vegetation.
- Excessive bank erosion (i.e., outside of natural rates) can negatively impact aquatic life (Oregon-Washington Interagency Wildlife 1979, Theurer et al. 1985, Everest et al. 1987, Knutson and Naef 1997, Prevention 2005, EPA 2007, Hansen et al. 2010) by:
    - Increases bed sediment loads - smothering benthic habitats, suffocating fish egg and developing fry, decreasing benthic macroinvertebrate diversity
    - Increases turbidity - inhibiting fish feeding and growth, altering nutrient processing and primary productivity

3.6.2 Drivers and controlling factors of erosion and bank stability?

- Soil characteristics (e.g., cohesion, friction, soil moisture) (Hickin 1984, ASCE Task Committee on Hydraul. and Adjust. 1998, Fischer and Fischenich 2000, NRC 2002)
    - Non-cohesive soils (coarse grained soil like gravel and sand) = shallow depth of bank instability (shallow critical shear-stress zone).
    - Cohesive soils (fine grained soil like clay) = deeper depth of bank instability (deep critical shear-stress zone).
    - Poorly drained soils increase soil moisture, which reduces bank stability and leads to bank mass failure.

- Riparian vegetation characteristics
  - Presence - (Hickin 1984, Beeson and Doyle 1995, Knutson and Naef 1997, Naiman and Décamps 1997, ASCE Task Committee on Hydraul. and Adjust. 1998, Fischer and Fischenich 2000, Hairston-Strang and Adams 2000, Simon and Collison 2002, Micheli et al. 2004, Griffin et al. 2005, Pollen and Simon 2005, Langendoen et al. 2009, Hansen et al. 2010, Pollen-Bankhead and Simon 2010, Gorrick and Rodriguez 2012, Quinn 2018b)
    - Well-vegetated banks are 10 to 100 times less susceptible to fluvial erosion than unvegetated banks; the denser and more complete riparian vegetation is the more effective it is at stabilizing banks.
    - Deforested agricultural floodplains are more erodible than floodplains with a streamside forest (e.g., reaches of the central Sacramento River bordered by agriculture were 80-150% more erodible than reaches bordered by riparian forest across a 50-year period (Micheli et al. 2004)).
    - Vegetation increases soil strength due to adding tensile durability to the soil matrix, which enhances bank stability; vegetation dissipates the energy of water thereby suppressing the erosional processes that move sediment.
    - Spatial density of root networks physically restrain or bind soil particles preventing slumping and maintaining the structural integrity of the bank; deep roots permeate soil of streambanks and act as a composite material that enhances deep soil strength.
    - Exposed roots on the bank surface increase channel roughness, which dampens stream flow velocities, thereby reducing fluvial erosion.
    - Vegetation can be stabilizing or de-stabilizing (e.g., undercut or fallen trees can cause increased local erosion); Undercut or fallen trees can result in near-term de-stabilization and stream bank vegetation can result in long-term stabilization.
  - Composition - (Lyons et al. 2000b, Simon and Collison 2002, Polvi et al. 2014)
    - Grasses and willows can provide dense root systems providing greater shallow soil/bank reinforcement; trees can provide deep soil/bank reinforcement.
    - Trees can provide greater hydrologic effects (enhancing soil matrix suction) and total evaporation (transpiration and interception) than grasses/shrubs, which decreases likelihood of bank failure.
    - Grasses can support trees by providing additional root reinforcement.
    - Invasive species can outcompete native riparian plants and influence the ability of vegetation to provide streambank resistance to erosion (GRAF 1978, Schmidt and Allred 1999).
  - Size (ASCE Task Committee on Hydraul. and Adjust. 1998, Simon et al. 2006)

        - Weight of vegetation can increase the vertical shear stress near a streambank (increasing potential of mass failure).
        - Tall, stiff vegetation may impose destabilizing forces on streambanks during windstorms (increase likelihood of wind fall and disruption of bank soils).
    - Location (Abernethy and Rutherfurd 2000) - vegetation growing either on the face of the bank (between low flow and ordinary high water) or on the nearby floodplain has the greatest potential for bank reinforcement by growing close to potential failure plane locations.
- Neighboring land use - (Ice 1985, Everest et al. 1987, Lienkaemper and Swanson 1987, Cafferata 1992, Trimble and C. Mendel 1995, Knutson and Naef 1997, Nguyen et al. 1998, Parkyn 2004, Montgomery 2007)
    - Grazing animals and stock access can create unvegetated ramps along streambanks that enhance localized erosion and destabilize banks.
    - Soil erosion from conventional agriculture exceeds rates of natural erosion; exposed and compacted soils are highly susceptible to erosion by overland flow.
    - Land clearing and grading can increase sedimentation, destabilization, and erosion.
    - Impervious surfaces such as roads, buildings, and other infrastructure can impact hydrologic regimes, which influences flow conditions and resulting erosional processes.
- Bank slope, steepness, and armor (Hupp 1992, Davies-Colley 1997, Isenhart et al. 1997, Piegay and Bravard 1997, Trimble 1997, Watson et al. 1997, ASCE Task Committee on Hydraul. and Adjust. 1998, Burckhardt and Todd 1998)
    - Increased bank slope, height, and undercutting increases potential for mass failure.
    - Woody vegetation is more effective at stabilizing banks than grassy vegetation when banks are high and steep; grassy vegetation is more effective than woody vegetation when banks are low and less steep.
    - Channel bank infrastructure (hard structural elements) can increase bank stability. Bank infrastructure may increase localized stability but can also result in upstream/downstream erosional impacts.
- Erosional processes (Simon et al. 2000, Florsheim et al. 2008)
    - Fluvial Erosion (separation of sediments from a streambank's surface by the forces of flowing water) – may destabilize riparian vegetation by exposing plant roots or undercutting vegetation.
    - Mass Wasting Erosion (bank failure due to bank mass and gravitational forces) – combination of increased bank height and angle (from scour of streambed and bank toe) with increased gravitation forces on bank weight (from soil, water, and overlying vegetation).

    - Sediment transport and deposition – influences spatial and temporal patterns of erosional processes (e.g., sediment deposition can alter flow paths and related hydrologic forces that influence erosion).
- Large wood (Gurnell et al. 2002b, Florsheim et al. 2008)
    - Wood accumulation forms a debris line that protects the floodplain forest from erosion and slows cut-off processes.
    - Instream large wood or mid-channel gravel bars can divert flows toward a bank and increase erosion.
- Groundwater – shallow ground water in soil adds mass thereby increasing gravitational forces acting on a streambank (reducing cohesion and friction amongst soil particles) (Hickin 1984, ASCE Task Committee on Hydraul. and Adjust. 1998, NRC 2002)
- Hydrology (ASCE Task Committee on Hydraul. and Adjust. 1998, Rinaldi et al. 2004)
    - Bank failure often occurs shortly after flood waters recede because soils are at or near saturation and lateral support from flood water is removed.
    - Cycles of wet/dry increase desiccation cracking, which reduces bank stability.
    - Changes in hydrologic and climatic regimes (e.g., flood frequency, flood peaks, precipitation patterns) can increase the magnitude, frequency, and duration of erosional processes.
- Location in watercourses and watershed (Abernethy and Rutherfurd 1998, Quinn 2018b)
    - Bank erosion commonly occurs on the outside of river bends.
    - Bank sediment transfer in upper-watershed reaches is primarily due to windthrow, in mid-watershed reaches is due to direct scour, and in downstream reaches is predominantly due to mass failure.
- Channelization (i.e., watercourses that are straightened, deepened, widened, and leveed/revetted) (Karr and Schlosser 1977, Swales 1982, Allan and Flecker 1993, Malanson and Kupfer 1993, Magilligan and McDowell 1997, Trimble 1997, Hession et al. 2003, Sweeney et al. 2004, Allmendinger et al. 2005, Lewicki et al. 2007, Jackson et al. 2015)
    - Channelization contributes to channel erosion by increasing stream power (i.e., product of velocity, volume, and slope), leading to incision and eventual bank instability.
    - Channel widths are greater in forested areas than un-forested and grassy areas which influenced the capacity of channels; grassy vegetation increases channel narrowing and reduced channel capacity (grass cover tends to protect against surficial erosion encouraging deposition of sediment and permitting banks encroachment).

3.6.3 Ranges of buffer widths for erosion and bank stability in the literature

Seventeen references were reviewed which detailing relationships between riparian buffer widths and bank erosion/stability. Riparian buffer widths which support bank stability and minimize unnatural rates of erosion were a minimum of 10 feet to 164 feet (Appendix I). It's worth noting that the upper limit of these riparian buffer widths represent the upper limit of what has been studied and does not necessarily represent the full extent of potential riparian buffer function.

3.6.4 Discussion

The mechanisms of sediment input and erosional processes differ throughout a watershed (Abernethy and Rutherfurd 1998). For example, within upper reaches of the Snoqualmie watershed where channels are relatively smaller, such as valley-wall channels and headwater tributaries, downed trees from windthrow as well as debris flows and landslides are the primary mechanisms of bank sediment transfer where uprooting delivers sediment and exposes banks. Across relatively larger and higher-gradient tributaries such as the Tolt River, Raging River, and Tokul Creek, increased steam power (i.e., product of velocity, volume, and slope) results in direct scour and bank erosion. Additionally, in mainstem watercourses such as the Snoqualmie River, increased stream power (due to flow accumulated throughout the watershed) results in bank erosion along the meandering channel margins. Large and high-gradient tributaries can also act as primary sediment sources to the mainstem Snoqualmie River resulting in mainstem alluvial reaches with relatively higher gradients where increased channel migration and stream power localizes erosional processes. The presence or absence of riparian vegetation along mainstem and large tributary reaches is a primary factor influencing bank stability (Beeson and Doyle 1995, Naiman and Decamps 1997, ASCE Task Committee on Hydraul. and Adjust. 1998, Fischer and Fischenich 2000, Simon and Collison 2002). Subsequently, woody riparian vegetation will likely have the greatest impact on bank stability along these reaches by increasing hydraulic roughness and creating resistance to erosion. The ability for woody riparian vegetation to increase bank strength through root-soil matrix reinforcement will also decrease the likelihood of bank failure to hydraulic flow conditions.

Larger mainstem river reaches (e.g., Snoqualmie, Tolt, and Raging rivers) tend to have relatively steeper banks where woody vegetation is more effective in stabilizing eroding processes (Lyons et al. 2000a). In areas of mainstem river reaches where cohesive soils dominate (fine grained soils like clay), trees and woody vegetation may provide relatively greater reinforcement compared to grasses and shrubs. Areas dominated by cohesive soils tend to have relatively deep shear stress zones (critical mass failure depths) (ASCE Task Committee on Hydraul. and Adjust. 1998) and trees and woody vegetation are more likely to have root depths and root network strength capable of reaching and stabilizing shear stress zones (Simon and Collison 2002). This mechanical root reinforcement can be a significant factor improving bank stability. Since most of the Snoqualmie River floodplain has moderate to high clay content (discussed in *Section 3.2*), woody riparian vegetation in these areas may have the greatest benefit for stabilizing banks and minimizing unnatural rates of erosion. However, much of the lower mainstem Snoqualmie River has sheer stress zones below potential woody vegetation root depths due to relatively steep banks. In these areas, erosion and scour is focused at the toe of a bank below woody vegetation roots. Riparian vegetation in these areas will not be effective in stabilizing banks from erosion. In mainstem areas where root depths can reach shear stress zones (generally less steep banks), appropriate riparian buffer widths align with maximum root strength-depth. The depth of maximum root strength can be achieved at around ½ site potential tree heights (Figure 6). In the lower Snoqualmie River watershed, site potential tree heights would be based on Sitka spruce and Douglas fir, as they are the tallest conifers across the valley.

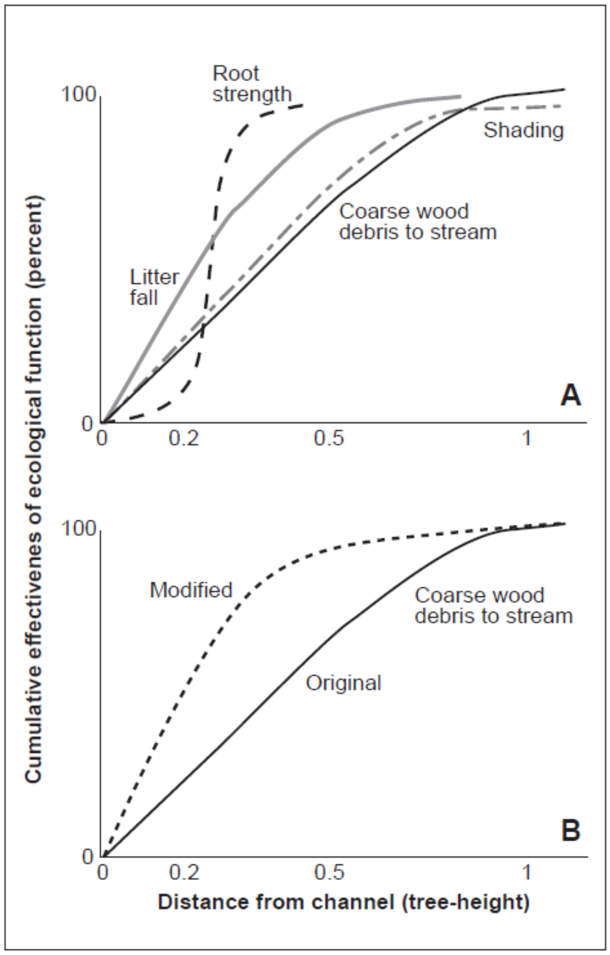


Figure 7-7—(A) Relation of distance from stream channel to cumulative effectiveness of riparian ecological functions (FEMAT 1993: V-27); (B) modified effectiveness curve for wood delivery to streams as a function of distance from the stream channel. The original curve was changed based on scientific literature developed since the original curve was portrayed in FEMAT (1993). Source: Spies et al. 2013.

Figure 6. Relation of Distance from Stream Channel to Cumulative Effectiveness of Riparian Ecological Functions (FEMAT 1993)

In addition to greater root depth and root network strength, riparian trees have relatively greater hydrologic effects (enhanced soil matrix suction) and total evaporation (transpiration and interception) compared to grasses and shrubs. Tree transpiration doesn't generally impact soil moisture till mid-spring; however, during and after this period the amount of water removed from near bank soils by trees can significantly reduce the likelihood of bank instability (ASCE Task Committee on Hydraul. and Adjust. 1998, Simon and Collison 2002). The influence of trees on soil moisture is especially apparent in areas of poor soil permeability (e.g., areas of high clay content). The hydrologic effects of trees are secondary to the mechanical effects of root reinforcement for bank stabilization; however, the combined effects can significantly increase bank stability. Additionally, the interception of rainfall by tree canopies as well as evapotranspiration from tree foliage can reduce the frequency of saturated soil conditions leading to bank collapse. Subsequently, tree coverage in areas of poor soil permeability may significantly help to decrease soil moisture and reduce the likelihood of bank instability. In addition to hydrologic and evaporative effects, exposed roots from trees and woody vegetation can also reduce erosion by increasing channel roughness and dampening stream flow velocities (Griffin et al. 2005, Gorrick and Rodriguez 2012).

Smaller watercourses throughout the Snoqualmie River floodplain may include floodplain-originating channels, low-order tributaries, and maintained watercourses. Grass and shrub vegetation may be suitable for providing adequate bank reinforcement in smaller watercourses, which have relatively less-steep banks (Lyons et al. 2000a). In areas that are not deeply-incised and which are dominated by non-cohesive soils (gravels and sand), grasses and shrubs can provide stabilization due to a relatively shallow shear stress zone among non-cohesive soils (ASCE Task Committee on Hydraul. and Adjust. 1998). Grasses and shrubs can provide dense root systems at relatively shallow depths, which provide soil/bank reinforcement (Quinn 2018b). However, grasses and shrubs along watercourses that are deeply incised may not be adequate to support bank reinforcement. Management actions like dredging and channelization can increase incision among smaller watercourses, which result in increased bank steepness and instability. Smaller watercourses within the lower Snoqualmie River Valley that have been dredged or channelized may require woody tree vegetation, rather than grass/shrubs, to optimize bank stabilization. Additionally, while grass and shrubs may provide bank reinforcement benefits for non-incised smaller watercourses, this vegetation can also result in channel narrowing which can increase stream power and lead to incision during storm events (Karr and Schlosser 1977, Malanson and Kupfer 1993). Since forested watercourses generally have wider channel widths than un-forested watercourses (Trimble 1997), integrating tree coverage with grass and shrub vegetation may optimize riparian bank reinforcement while minimizing potential channel narrowing.

Across watercourses, the benefits of riparian vegetation in stabilizing banks may be optimized on outside bends. Bank erosion commonly occurs on the outside of river bends (Quinn 2018b) and bends with riparian vegetation can significantly decrease erosion during storm events (Beeson and Doyle 1995). Additionally, the denser the vegetation is along outside bends, the more effective riparian vegetation is at reducing erosion impacts. While vegetation along outside bends will likely be recruited by channel migration, the potential of this wood to form accumulations along the bank may slow migration processes and provide additional stabilization from erosional forces. Wide riparian buffers around areas of higher channel migration (e.g., alluvial reaches) and on outside bends will help in maintaining near- and long-term natural bank stabilization (i.e., natural rates of erosion) as the channel continues to migrate into riparian areas.

3.7 Invertebrate prey and litter-detritus inputs

3.7.1 Importance to salmon?

- Food resources – benthic aquatic macroinvertebrates (e.g., aquatic insects, snails, worms, etc.) and terrestrial invertebrates (e.g., insects, spiders, arthropods, etc.) are the principle food resources for salmonids in streams and rivers (Allan 1981, Henry et al. 1985, Budd et al. 1987, Gregory et al. 1987, Barling and Moore 1994, Wipfli 1997, Baxter et al. 2005).
- Litter and detritus inputs - riparian vegetation provides a direct source of allochthonous (terrestrial and upstream origins) leaves, needles, branches, and woody debris for invertebrate communities (Fisher and Likens 1973, Parkyn 2004, Naiman et al. 2010).
    - Streams and rivers largely depend on allochthonous inputs for instream habitat diversity and food resources, which support microbes and macroinvertebrates (important instream food resources for salmonids) (Meehan et al. 1977, Maser and Sedell 1994, Naiman and Decamps 1997, Collier et al. 1998, Scarsbrook et al. 2001, Parkyn 2004).
- Terrestrial invertebrate habitat – riparian vegetation provides habitat and suitable microclimate conditions for terrestrial invertebrates and adult stages of aquatic insects (contributing significantly to salmonid diets) (Benke and Wallace 1990, Parkyn 2004).
- Biological and ecological indicators – macroinvertebrate community structure and diversity reflect water quality and ecosystem health (i.e., indicators for salmonid habitat and water quality conditions) (Edwards and Andersen 1984, Plafkin et al. 1989, Lenat 1993, Rosenberg and Resh 1993, Loeb and Resh 1994, Wallace and Webster 1996).

3.7.2 Drivers and controlling factors of invertebrate prey and litter-detritus?

- Channel/Watercourse characteristics
    - Habitat Complexity (i.e., variety of riparian and in-stream habitats and features) (Gregory et al. 1987, Wallace et al. 1995, Wallace and Webster 1996, Johnson et al. 2003)
        - Increased watercourse/habitat complexity increases benthic invertebrate diversity and increases organic matter retention (organic

        matter cannot serve as a nutritional resource for aquatic biota until it is retained within a stream).
        - Riparian habitat complexity increases terrestrial insect abundance and diversity.
    - Channel width, length, and size (Vannote et al. 1980, Conners and Naiman 1984, Cummins et al. 1989, Junk et al. 1989, Benfield 1997, Naiman and Decamps 1997, Wallace et al. 1997, Ward et al. 2002)
        - Relative fraction and importance of litter and detrital inputs decrease with increasing watercourse size (i.e., litter inputs per watercourse areas becomes progressively less from smaller to larger channels); An exception being floodplain channels where lateral inputs can be significant during flooding.
        - Litter and detritus provide primary food resources for lower aquatic food webs (e.g., microbes and macroinvertebrates) in smaller watercourses.
        - Large channels primarily have litter inputs from vertical sources (through direct litter fall) and smaller channels primarily have litter inputs through lateral sources (debris moving along bordering slopes); fewer vertical litter inputs in smaller channels is largely due to the minimal physical area for direct litter fall. Exceptions to these vertical and lateral input patterns occur among watercourses with engaged floodplains where lateral inputs during flood events can be significant.
- Riparian vegetation characteristics and season
    - Presence/Absence (Erman et al. 1977, Newbold et al. 1980, Gregory et al. 1987, Sweeney 1993, Davies and Nelson 1994, Quinn and Cooper 1997, Stewart et al. 2001, Reid et al. 2008)
        - Benthic macroinvertebrate diversity, abundance, growth, and reproduction are higher when riparian buffers are present.
        - The percent tree coverage in the riparian corridor is positively correlated with the amount of organic matter input (e.g., leaves, needles, and wood) as well as invertebrate community structure and diversity.
    - Buffer width and length (Campbell et al. 1992, Davies and Nelson 1994, Wallace and Webster 1996, Benfield 1997, Fischer and Fischenich 2000, Parkyn 2004, Wooster and DeBano 2006)
        - Benthic macroinvertebrate community structure and diversity increases with riparian buffer width and length (length may be the primary driver with width being secondary).
        - Longer-wider patches provide more organic matter inputs, stabilize more stream banks, provide more thermal buffering, and minimize sediment inputs, which all benefit macroinvertebrate communities.

        - Wider riparian widths provide greater sources of lateral litter and detritus inputs; lateral inputs can be greater than vertical inputs in steep slopes and in floodplains.
    - Continuity (i.e., degree of fragmentation) (Davies and Nelson 1994, Stewart et al. 2001, Harding et al. 2006, Wooster and DeBano 2006)
        - Increased riparian continuity (i.e., less fragmentation) increases macroinvertebrate community structure and diversity.
    - Composition (e.g., vegetation type) (Swanson and Lienkaemper 1982, Conners and Naiman 1984, Gregory et al. 1987, Campbell et al. 1992, Wallace and Webster 1996, Naiman and Decamps 1997, Fischer and Fischenich 2000, Urgenson et al. 2009, Bilby and Heffner 2016)
        - Influences the timing, duration, and distance of litter/detritus inputs (e.g., deciduous inputs primarily occur in autumn, deciduous trees provide relatively more pulsed inputs compared to conifers, and deciduous leaves generally travel farther than coniferous needles).
        - Determines the quality and quantity of litter/detritus food resources for macroinvertebrates (e.g., the quality of deciduous litter as a nutritional resource for microbial communities and macroinvertebrate consumers is higher than that of coniferous litter); Litter quality can be greater in native vs. invasive species (e.g., knotweed provides significantly less carbon and nitrogen than red alder and willow).
    - Age/Maturity (e.g., size) (Parkyn 2004, Duehr et al. 2006, Naiman et al. 2010, Bilby and Heffner 2016)
        - Older and taller trees can provide litter and detritus at greater distances (due to crown width and wind transport distance).
        - The amount of leaf litter inputted by riparian vegetation increases with riparian community age.
        - Macroinvertebrate community structure and diversity increases with riparian tree age.
- Neighboring land use (e.g., agriculture, forestry, urbanization) (Campbell et al. 1992, Weigel et al. 2000, Stewart et al. 2001, ZumBerge et al. 2003, Allan 2004, Death 2010, Gerth et al. 2017)
    - Bordering agricultural land use, deforestation, and urbanization decreases benthic macroinvertebrate community structure and diversity as well as decreases organic matter inputs.
- Temperature/Shade (Gregory et al. 1987, Quinn and Cooper 1997, Parkyn 2004, Rykken et al. 2007)
    - Increased benthic macroinvertebrate community structure and diversity is strongly linked to decreases in temperature associated with shade and microclimate conditions.
- Substrate composition (Gregory et al. 1987, Parkyn 2004, Duehr et al. 2006)

  - Benthic macroinvertebrates community diversity increases with substrate heterogeneity.
  - Sedimentation and decreased substrate stability may decrease the abundance of benthic macroinvertebrates.
  - Dredging and channelization minimizes substrate heterogeneity.
- Wind and riparian rlope (Reiser and Bjornn 1979, Benfield 1997, Scarsbrook et al. 2001, Bilby and Heffner 2016)
  - Terrestrial insects enter streams by falling or being blown off riparian vegetation; wind parallel to streams inhibits inputs and wind perpendicular to streams increases inputs.
  - Litter inputs increase with wind speed.
  - Lateral inputs of litter increases with slope.

3.7.3 Ranges of buffer widths for invertebrate prey and litter-detritus in the literature

Twenty one references were reviewed that detail relationships between riparian buffer widths and invertebrate prey, litter-detritus, and benthic macroinvertebrates. Riparian buffer widths that support invertebrate prey, litter-detritus inputs, as well as benthic invertebrate diversity and abundance were a minimum of 10 feet to 246 feet (Appendix I). Additionally, riparian buffer lengths that supported macroinvertebrate community structure and diversity were a minimum of 164 feet to 1,969 feet (Appendix I). It's worth noting that the upper limits of these riparian buffer widths and lengths represent the upper limits of what has been studied and do not necessarily represent the full extent of potential riparian buffer function.

3.7.4 Discussion

The presence or absence of riparian vegetation may be the most important factor altered by humans that affects the structure and function of stream macroinvertebrates (Sweeney 1993, Davies and Nelson 1994). Specific to riparian buffer dimensions, the length, width, and continuity of riparian corridors can influence stream macroinvertebrate community structure and diversity (Davies and Nelson 1994, Stewart et al. 2001, Parkyn 2004, Wooster and DeBano 2006). Within these riparian dimensions, riparian corridor length and continuity may be the primary drivers of macroinvertebrate structure and diversity. For example, the length of riparian corridor patches have been shown to have a stronger correlation to macroinvertebrate structure and diversity than solely corridor width (Wooster and DeBano 2006). Additionally, the continuity of riparian corridors (i.e., minimal fragmentation) has been found to be significantly related to benthic macroinvertebrate health (Davies and Nelson 1994, Stewart et al. 2001, Wooster and DeBano 2006). This doesn't negate the importance of riparian corridor width, but supports that length and continuity may be primary drivers influencing macroinvertebrate structure and diversity with width being a secondary driver. Riparian corridors that are relatively longer and wider can provide greater litter and detritus inputs, stabilize more stream banks, and minimize sediment inputs. Maximizing riparian corridor length and continuity may help to optimize riparian benefits to benthic macroinvertebrate communities.

Riparian buffer composition appears to be a significant factor influencing litter entering streams, either directly or through lateral transport from the forest floor (Naiman and Décamps 1997). The percentage of tree coverage in a riparian corridor is positively related to stream invertebrate community structure and diversity (Stewart et al. 2001, Reid et al. 2008) and the quality of deciduous litter as a nutritional resource for microbial communities and consumers is higher than that of coniferous litter (Gregory et al. 1987). Additionally, the composition of riparian vegetation influences the timing of food resource inputs into streams with deciduous vegetation providing generally more seasonally pulsed inputs than coniferous trees (Naiman and Decamps 1997). This information suggests that deciduous and coniferous vegetation throughout the Snoqualmie River valley may bolster the benefits of riparian vegetation for stream macroinvertebrates and that a high percentage of trees (compared to other vegetation) is needed in the riparian corridor to optimize inputs. A higher percentage of deciduous tree cover in riparian corridors throughout the Snoqualmie River Valley would provide better quality litter and the integration of coniferous trees would provide continual year-long litter and invertebrate inputs. This riparian composition aligns with historical tree extents in that the Lower Snoqualmie River floodplain was historically dominated by deciduous trees with relatively fewer coniferous trees (Collins and Sheikh 2002). In addition to tree type, the age of riparian vegetation also influences stream macroinvertebrates with generally older trees supporting greater macroinvertebrate diversity and richness (Duehr et al. 2006). Older and larger trees provide greater sources of litter and debris inputs with peak inputs occurring around 50-78 years and then declining after 100 years as Pacific Northwest forest communities shift from deciduous to coniferous trees (Bilby and Heffner 2016). Subsequently, mature deciduous and coniferous tree cover across riparian corridors are likely to optimize near- and long-term litter and invertebrate inputs.

The relative contribution and role of litter and detrital inputs tends to decrease from a small stream to a large stream (Vannote et al. 1980, Conners and Naiman 1984, Naiman and Décamps 1997). These litter and detritus inputs provide the basal food resources for food webs in many smaller low order streams, since the majority of the inputs are retained long enough be used by macroinvertebrates (Meehan et al. 1977, Conners and Naiman 1984, Cummins et al. 1989, Wallace and Webster 1996). Additionally, riparian vegetation along smaller stream systems contributes a significant source of terrestrial invertebrate food resources for fish and biota (Baxter et al. 2005). Stream width and watercourse size drives the relative contribution of vertical versus lateral inputs with smaller and narrower streams having little physical area for direct vertical litter fall and having more litter and detritus from lateral inputs (e.g., bordering slopes for debris movement and wind interaction) (Conners and Naiman 1984). Wide and continuous riparian buffers (compared to narrow and fragmented) provide greater potential sources of lateral litter and detritus inputs. The significance of lateral litter inputs as well as a greater role of litter and detrital inputs in smaller streams suggests that wide and continuous riparian buffers along smaller floodplain channels, tributaries, headwaters, and valley-wall channels throughout the

Lower Snoqualmie River Valley may best support litter and detritus inputs and invertebrate communities.

While the role of localized litter and detritus inputs tends to be less significant in larger streams, these inputs still contribute to habitat diversity and food resources for benthic macroinvertebrates in large sand- and silt-bed watercourses (Parkyn 2004), such as the lower mainstem Snoqualmie River. Larger streams and rivers have a greater surface area for litter and detritus interceptions but the relative proportion of inputs to water area are significantly less than in small streams. Large rivers generally have the majority of litter inputs coming from vertical sources and upstream drift rather than lateral sources, which results in larger streams having a relatively smaller riparian litter-detritus source area (Bilby and Heffner 2016). The smaller source area of large streams may suggest a relatively smaller buffer width compared to smaller watercourses; however, when large streams have complex shorelines and intact floodplains, the aquatic-terrestrial interface is increased. For example, intact floodplains can contribute significant sources of litter and detritus when the rise and fall of flood waters acts as a lateral input (Junk et al. 1989, Benfield 1997, Naiman and Decamps 1997, Ward et al. 2002). Since much of the Lower Snoqualmie River Valley frequently floods, the contribution of seasonal lateral inputs likely provides significant pulses of litter and invertebrate resources to mainstem reaches. Additionally, since the mainstem Snoqualmie is a relatively low-gradient river, organic matter retention during summer months may be longer since low-flow and low-velocity summer conditions can minimize downstream transport. While the prioritization of smaller watercourses for wide riparian buffers may optimize terrestrial litter and invertebrate inputs, wide riparian buffers along mainstem reaches may also provide significant sources of lateral and upstream to downstream drift inputs.

4.0 CONCLUSIONS

This document is not intended to provide recommendations for riparian buffers on agricultural landscapes. Rather, the purpose is to summarize and discuss riparian buffer science pertinent to watercourses in the Snoqualmie Valley APD. The management or conservation goals of a given landscape as well as desired environmental conditions can greatly influence riparian buffer restoration and protection. This document aims to discuss how ecological functions vary across riparian buffer characteristics (e.g., width, length, composition, continuity) and how variation in ecological functions relate to salmonid aquatic habitat conditions across the Snoqualmie APD. It is the task of the King County Buffer Task Force to determine how these functions should be prioritized among watercourses across the Snoqualmie Valley landscape to benefit Chinook salmon, while also reducing impacts to agriculture in the Valley. Those priorities can inform site-specific recommendations for appropriately-sized riparian buffers.

To help inform the alignment of ecological functions, riparian buffer characteristics, and watercourses types, Table 1 summarizes the riparian buffer science and information relevant to the Snoqualmie APD. This information is organized to assist the Buffer Task Force in considering how ecological functions and related riparian buffer characteristics may vary across watercourses. Table 1 summarizes the riparian ecological functions discussed in this document and can be supplemented with Appendix I, which provides detailed information on related references. Specifically, Appendix I lists each reviewed reference and summarizes key pieces of information including riparian characteristics, landscape context, and key findings.

Table 1: Synthesis of riparian buffer information as well as potential Snoqualmie River landscape application.

				Potential Riparian Buffer Characteristics[Δ]			
Riparian Buffer Function	**Minimum Buffer Width***	**Minimum Buffer Length***	**Snoqualmie Watercourse Types**	**Relative Width**	**Length & Continuity**	**Composition & Density**	**Supportive Literature Information**
Water Quality - Nutrients, Sediment, Pesticides	10 ft-328 ft	984 ft-4,920 ft	**Mainstem, Large, Medium, and Small watercourses** (floodplain low-gradient watercourses including mainstem channels, floodplain channels, low-gradient tributaries)	Less-wide (relative to watercourse size-width)	Long-continuous	Trees and woody vegetation	• Low-gradients areas have higher removal efficacies of sediment, nutrients, and pesticides, compared to higher gradient areas • Soils with higher clay content have greater potential for nutrient and pesticide removal • Woody vegetation including shrubs and trees have higher removal efficacies of nutrients and pesticides compared to grasses • Long-continuous buffers have greater nutrient and pesticide uptake/processing compared to fragmented buffers; narrower buffer that are long-continuous are more effective than wide-fragmented buffers
			Maintained watercourses (dredged/ straightened)	Wide	Long-continuous	Trees and woody vegetation	• Straightened/channelized watercourses require wider, longer, and more continuous riparian buffers to compensate for lost capacity in aquatic in-stream microbial processing
Water Quality - Temperature & Riparian Shade	5 ft-225 ft	328 ft-8,202 ft	**Small and Medium watercourses** (east-west orientation)	Less-wide (relative to watercourse size-width)	Long-continuous	Dense vegetation	• Small and medium watercourses are most susceptible to temperature fluctuations and provide the greatest potential for shading benefits among watercourse sizes • Riparian vegetation height and density significantly influencing watercourse shading • Riparian buffer length accounts for a majority of temperature variation (the longer the buffer length, the greater the shading benefit) • Narrow-dense riparian buffers are most effective on east-west oriented watercourses • Wider-taller buffer width are needed for shading on north-south oriented watercourses • Agricultural-maintained channels may only require dense and overhanging buffers at relatively narrow widths to provide shade benefits
			Small and Medium watercourses (north-south orientation)	Wide	Long-continuous	Dense-tall vegetation	
			Small and Medium watercourses (agricultural watercourses)	Less-wide (relative to watercourse size-width)	Long-continuous	Dense vegetation	
			Mainstem and Large watercourses	Wide	Long-continuous	Dense-tall vegetation	• Larger waterways require tall, dense, and wide riparian buffers to shade waterbodies

* Range in minimum riparian buffer widths and lengths that support at least 50% and greater of a given function; reported values summarized from reviewed literature
[Δ] Information summarized from reviewed literature

				Potential Riparian Buffer Characteristics^Δ			
Riparian Buffer Function	**Minimum Buffer Width***	**Minimum Buffer Length***	**Snoqualmie Watercourse Types**	**Relative Width**	**Length & Continuity**	**Composition & Density**	**Supportive Literature Information**
Riparian Corridor Microclimate	50 ft-328 ft		**Mainstem, Large, Medium, and Small watercourses**	Wide (based on 1-2 conifer tree height)	Long-continuous		• Riparian buffer width, length, and continuity helps protect microclimate extent and presence from surrounding landscape climate conditions • Riparian areas closer to watercourses protect stream-center microclimate and riparian areas further from watercourses protect off-stream microclimate • The ability of microclimate conditions to buffer water temperatures decreases with increasing watercourse size-width
Large Wood (Recruitment and Retention)	13 ft-213 ft		**Mainstem and Large watercourses** (mainstem channels, large tributaries, alluvial reaches)	Wide (based on conifer tree height)		Mixed trees (conifer and deciduous)	• Primary wood input among mainstem and large watercourses comes from bank erosion • Areas of channel migration require wide buffers to provide continual wood sources • Large channels require relatively larger wood (i.e., tall and wide) to remain stable and influence channel and habitat forming processes • Coniferous trees provide long-term habitat benefits and deciduous provides short-term benefits
			Armored watercourses (reaches with armored banks)	Wide (based on conifer tree height)		Mixed trees (conifer and deciduous)	• Armoring shifts wood input drivers from erosion to windthrow and mortality • Large wood source distance from windthrow and mortality is based on max tree height (potential fall distance)
			Small and Medium watercourses (floodplain channels, small tributaries, maintained small channels)	Less-Wide		Mixed Trees (deciduous & woody vegetation)	• Size of habitat-forming wood is relatively smaller in small and medium watercourses • Small and medium watercourses receive a greater proportion of woody debris inputs from shorter source distances (closer to watercourses) • Hardwoods generally contributes more large wood in smaller channels
			High-gradient watercourses	Wide			• Primary wood inputs among high-gradient watercourses comes from debris flows, landslides, and windthrow (greater source distances than bank erosion) • High-gradient tributaries contribute to instream wood which is transported downstream

* Range in minimum riparian buffer widths and lengths that support at least 50% and greater of a given function; reported values summarized from reviewed literature
^Δ Information summarized from reviewed literature

				Potential Riparian Buffer Characteristics[Δ]			
Riparian Buffer Function	**Minimum Buffer Width***	**Minimum Buffer Length***	**Snoqualmie Watercourse Types**	**Relative Width**	**Length & Continuity**	**Composition & Density**	**Supportive Literature Information**
Erosion and Bank Stability	10 ft-164 ft		**Mainstem and Large watercourses** (mainstem channels, large tributaries)	Wide (based on 1/2 conifer tree height)		Mixed trees (conifer and deciduous)	• Woody riparian vegetation provides the greatest bank stabilization for large watercourses • Woody vegetation is more effective than shrubs/grasses on steep banks • Maximum root strength and depth can be achieve at around ½ site potential tree height
			Small and medium watercourses (floodplain channels, low-order tributaries)			Shrubs, grasses	• Grass/shrubs may be suitable for small and medium watercourses which have relatively less-steep banks
			Maintained watercourses (dredged/ straightened)			Trees, shrubs	• Dredging and channelization can increase bank steepness and instability • Dredged/channelized small and medium watercourses may require woody tree vegetation, rather than grass/shrubs (due to related bank steepness)
			Outside bends of watercourses	Wide (based on 1/2 conifer tree height)		Dense vegetation	• Bank erosion commonly occurs on the outside of river bends; outside bends with riparian vegetation can significantly decrease erosion during storm events • The denser vegetation is along outside bends, the more effective riparian vegetation is at reducing erosion impacts
Invertebrate Prey and Litter-Detritus Inputs	10 ft-246 ft	164 ft-1,969 ft	**Mainstem and Large watercourses** (mainstem channels, large tributaries)	Less-Wide	Long-continuous	Mixed trees (conifer and deciduous)	• Relative contribution and role of litter and detrital inputs tends to decrease from small streams to large streams • Riparian corridor length and continuity may be the primary drivers of macroinvertebrate structure and diversity • Percentage of tree coverage in a riparian corridor is positively related to stream invertebrate community structure and diversity • Deciduous trees provides seasonally pulses inputs and conifers trees provide year-around inputs
			Small and medium watercourses (floodplain channels, smaller tributaries, headwaters, valley-wall channels)	Wide	Long-continuous	Mixed trees (conifer and deciduous)	

* Range in minimum riparian buffer widths and lengths that support at least 50% and greater of a given function; reported values summarized from reviewed literature
Δ Information summarized from reviewed literature

5.0 REFERENCES

Abernethy, B., and I. Rutherfurd. 1998. Where Aong a River's Length Will Vegetation Most Effectively Stabilize Stream Banks?

Abernethy, B., and I. D. Rutherfurd. 2000. The effect of riparian tree roots on the mass-stability of riverbanks. Earth Surface Processes and Landforms **25**:921-937.

Aguiar, T. R., Jr., F. R. Bortolozo, F. A. Hansel, K. Rasera, and M. T. Ferreira. 2015. Riparian buffer zones as pesticide filters of no-till crops. Environ Sci Pollut Res Int **22**:10618-10626.

Allan, J. D. 1981. Determinants of Diet of Brook Trout (Salvelinus fontinalis) in a Mountain Stream. Canadian Journal of Fisheries and Aquatic Sciences **38**:184-192.

Allan, J. D. 2004. Landscapes and riverscapes: the influence of land use on stream ecosystems. Annual Review of Ecology, Evolution and Systematics **35**:257-284.

Allan, J. D., and A. Flecker. 1993. Biodiversity Conservation in Running Waters.

Allmendinger, N. E., J. E. Pizzuto, N. Potter, T. E. Johnson, and W. C. Hession. 2005. The influence of riparian vegetation on stream width, eastern Pennsylvania, USA. Geological Society of America Bulletin **117**:229-243.

Anderson, P. D., D. J. Larson, and S. S. Chan. 2007. Riparian buffer and density management influences on microclimate of young headwater forests of western Oregon. Forest Science **53**:254-269.

Andrus, C. W., B. A. Long, and H. A. Froehlich. 1988. Woody debris and its contribution to pool formation in a coastal stream 50 years after logging. Canadian Journal of Fisheries and Aquatic Sciences **45**:2080-2086.

ASCE Task Committee on Hydraul., B. M., and M. o. R. W. Adjust. 1998. River width adjustment. I: Processes and mechanisms. Journal of Hydraulic Engineering **124**:881-902.

Barling, R. D., and I. D. Moore. 1994. Role of buffer strips in management of waterway pollution: A review. Environmental Management **18**:543-558.

Barton, D. R., W. D. Taylor, and R. Biette. 1985. Dimensions of riparian buffer strips required to maintain trout habitat in southern Ontario streams. North American Journal of Fisheries Management **5**:364-378.

Baxter, C. V., K. D. Fausch, and W. Carl Saunders. 2005. Tangled webs: reciprocal flows of invertebrate prey link streams and riparian zones. Freshwater Biology **50**:201-220.

Bayley, P. B. 1995. Understanding large river-floodplain ecosystems. BioScience **45**:153-158.

Beamer, E., B. Hayman, and D. Smith. 2005. Linking freshwater rearing habitat to Skagit Chinook salmon recovery. Appendix C of the Skagit Chinook recovery plan.

Beamer, E. M., and R. Henderson. 1998. Juvenile salmonid use of natural and hydromodified stream bank habitat in the mainstem Skagit River, northwest Washington. Report by Skagit System Cooperative, LaConner, Wash., to US Army Corps of Engineers, Seattle, Wash.

Beechie, T., G. R. Pess, P. Kennard, R. E. Bilby, and S. Bolton. 2000. Modeling Recovery Rates and Pathways for Woody Debris Recruitment in Northwestern Washington Streams. North American Journal of Fisheries Management.

Beechie, T., and T. H. Sibley. 1997. Relationship between Channel Characteristics, Woody Debris and Fish Habitat in Northwestern Washington Streams. Transactions of the American Fisheries Society.

Beeson, C., and P. Doyle. 1995. Comparison of Bank Erosion at Vegetated and Non-vegetated Channel Bends 1 JAWRA Journal of the American Water Resources Association **31**:983-990.

Benda, L. E., P. Bigelow, and T. M. Worsley. 2002. Recruitment of wood to streams in old-growth and second-growth redwood forests, northern California, USA. Canadian Journal of Forest Research-Revue Canadienne De Recherche Forestiere **32**:1460-1477.

Benfield, E. F. 1997. Comparison of Litterfall Input to Streams. Journal of the North American Benthological Society **16**:104-108.

Benke, A. C., and J. B. Wallace. 1990. Wood dynamics in coastal plain blackwater streams. Canadian Journal of Fisheries and Aquatic Sciences **47**:92-99.

Bentrup, G. 2008. Conservation buffers: design guidelines for buffers, corridors, and greenways. US Department of Agriculture, Forest Service, Southern Research Station Asheville, NC.

Bereswill, R., B. Golla, M. Streloke, and R. Schulz. 2012. Entry and toxicity of organic pesticides and copper in vineyard streams: erosion rills jeopardise the efficiency of riparian buffer strips. Agriculture, Ecosystems & Environment **146**:81-92.

Beschta, R. L., R. E. Bilby, G. W. Brown, B. L. Holtby, and T. D. Hofstra. 1987. Stream Temperature and Aquatic Habitat: Fisheries and Forestry Interactions.

Bethel, J. 2004. An Overview of the Geology and Geomorphology of the Snoqualmie River Watershed. Page 94 *in* DNRP, editor. King County, Seattle, Washington.

Bigelow, P. E., L. E. Benda, D. J. Miller, and K. M. Burnett. 2007. On debris flows, river networks, and the spatial structure of channel morphology. Forest Science **53**:220-238.

Bilby, R. E. 1984. Characteristics and frequency of cool-water areas in a western Washington stream. Journal of Freshwater Ecology **2**:593-602.

Bilby, R. E., and P. A. Bisson. 1998. Function and distribution of large woody debris. Pages 324-346 *in* R. J. Naiman and R. E. Bilby, editors. River ecology and management: lessons from the Pacific coastal ecoregion. Springer-Verlag, New York.

Bilby, R. E., and J. T. Heffner. 2016. Factors influencing litter delivery to streams. Forest Ecology and Management **369**:29-37.

Bilby, R. E., and J. W. Ward. 1989. Changes in characteristics and function of woody debris with increasing size of streams in western Washington. Transactions of the American Fisheries Society **118**:368-378.

Bilby, R. E., and J. W. Ward. 1991. Characteristics and function of large woody debris in streams draining old-growth, clear-cut, and second-growth forests in southwestern Washington. Canadian Journal of Fisheries and Aquatic Sciences **48**:2499-2508.

Bilby, R. E., and L. J. Wasserman. 1989. Forest practices and riparian management in Washington State: data based regulation development. Practical approaches to riparian resource management:87-94.

Bisson, P. A. 1987. Large woody debris in forested streams in the pacific Northwest : Past, present, and future. Streamside management : Forestry and fishery interactions:143-190.

Bisson, P. A., and R. E. Bilby. 1998. Organic matter and trophic dynamics. Pages 373-398 *in* R. J. Naiman and R. E. Bilby, editors. River Ecology and Management: Lessons from the Pacific Coastal Ecoregion. Springer-Verlag, New York.

Bisson, P. A., C. C. Coutant, D. Goodman, R. Gramling, D. Lettenmaier, J. Lichatowich, W. Liss, E. Loudenslager, L. McDonald, and D. Philipp. 2002. Hatchery surpluses in the Pacific Northwest. Fisheries **27**:16-27.

Black, T. A., J.-M. Chen, X. Lee, and R. M. Sagar. 1991. Characteristics of shortwave and longwave irradiances under a Douglas-fir forest stand. Canadian Journal of Forest Research **21**:1020-1028.

Booth, D. B., and M. Fox. 2004. The role of large woody debris in lowland Puget Sound streams and rivers. University of Washington Center for Water and Watershed Studies.

Bottom, D. L., P. Howell, and J. Rogers. 1985. The effects of stream alterations on salmon and trout habitat in Oregon.

Brazier, J. R., and G. W. Brown. 1973. Buffer strips for stream temperature control.

Brett, M. T., S. E. Bunn, S. Chandra, A. W. Galloway, F. Guo, M. J. Kainz, P. Kankaala, D. C. Lau, T. P. Moulton, and M. E. Power. 2017. How important are terrestrial organic carbon inputs for secondary production in freshwater ecosystems? Freshwater Biology **62**:833-853.

Brosofske, K. D., J. Chen, R. J. Naiman, and J. F. Franklin. 1997. Harvesting effects on microclimatic gradients from small streams to uplands in western Washington. Ecological Applications **7**:1188-1200.

Budd, W. W., P. L. Cohen, P. R. Saunders, and F. R. Steiner. 1987. Stream corridor management in the Pacific Northwest: I. Determination of stream-corridor widths. Environmental Management **11**:587-597.

Buffler, S., C. Johnson, J. Nicholson, and N. Mesner. 2005. Synthesis of design guidelines and experimental data for water quality function in agricultural landscapes in the Intermountain West.

Bunzel, K., M. Liess, and M. Kattwinkel. 2014. Landscape parameters driving aquatic pesticide exposure and effects. Environ Pollut **186**:90-97.

Burckhardt, J. C., and B. L. Todd. 1998. Riparian Forest Effect on Lateral Stream Channel Migration in the Glacial Till Plains. JAWRA Journal of the American Water Resources Association **34**:179-184.

Cafferata, P. 1992. Soil compaction research. The contributions of Dr. Henry A. Froelich to forestry. Soc. Am. For., Bethesda, Md:8-22.

Campbell, I. C., K. R. James, B. T. Hart, and A. Devereaux. 1992. Allochthonous coarse particulate organic material in forest and pasture reaches of two south-eastern Australian streams: I. Litter accession. Freshwater Biology **27**:341-352.

Chen, J., J. F. Franklin, and T. A. Spies. 1993. An empirical model for predicting diurnal air-temperature gradients from edge into old-growth Douglas-fir forest. Ecological Modelling **67**:179-198.

Chen, J., J. F. Franklin, and T. A. Spies. 1995. Growing-Season Microclimatic Gradients from Clearcut Edges into Old-Growth Douglas-Fir Forests. Ecological Applications **5**:74-86.

Cole, E., and M. Newton. 2013. Influence of streamside buffers on stream temperature response following clear-cut harvesting in western Oregon. Canadian Journal of Forest Research **43**:993-1005.

Collier, K. J., R. J. Ilcock, and A. S. Meredith. 1998. Influence of substrate type and physico-chemical conditions on macroinvertebrate faunas and biotic indices of some lowland Waikato, New Zealand, streams. New Zealand Journal of Marine and Freshwater Research **32**:1-19.

Collins, B. D., and D. R. Montgomery. 2002. Forest development, wood jams, and restoration of floodplain rivers in the Puget Lowland, Washington. Restoration Ecology **10**:237-247.

Collins, B. D., and A. J. Sheikh. 2002. Mapping historical conditions in the Snoqualmie River valley (RM 0 ^{2} RM 40).

Conners, M. E., and R. J. Naiman. 1984. Particulate allochthonous inputs: relationships with stream size in an undisturbed watershed. Canadian Journal of Fisheries and Aquatic Sciences **41**:1473-1484.

Cristea, N., and J. Janisch. 2007. Modeling the effects of riparian buffer width on effective shade and stream temperature. Washington State Department of Ecology.

Cummins, K., M. Wilzbach, D. M. Gates, J. B. Perry, and W. Bruce Taliaferro. 1989. Shredders and Riparian Vegetation.

Davies-Colley, R. J., G. Payne, and M. Van Elswijk. 2000. Microclimate gradients across a forest edge. New Zealand Journal of Ecology:111-121.

Davies-Colley, R. J. 1997. Stream channels are narrower in pasture than in forest. New Zealand Journal of Marine and Freshwater Research **31**:599-608.

Davies, P., B. Cook, T. Walshe, and J. Rutherford. 2004. Managing high in-stream temperatures using riparian vegetation.

Davies, P., and M. Nelson. 1994. Relationships between riparian buffer widths and the effects of logging on stream habitat, invertebrate community composition and fish abundance. Marine and Freshwater Research **45**:1289-1305.

Death, R. G. 2010. Disturbance and riverine benthic communities: What has it contributed to general ecological theory? River Research and Applications **26**:15-25.

DeWalle, D. R. 2010. Modeling Stream Shade: Riparian Buffer Height and Density as Important as Buffer Width1. JAWRA Journal of the American Water Resources Association **46**:323-333.

Duehr, J. P., M. J. Siepker, C. L. Pierce, and T. M. Isenhart. 2006. Relation of riparian buffer strips to in-stream habitat, macroinvertebrates and fish in a small Iowa stream. Journal of the Iowa Academy of Science: JIAS **113**:101-107.

Edwards, J. S., and M. Andersen. 1984. The ecology of aquatic insects. . Prager, New York.

EPA. 2007. National Management Measures to Control Nonpoint Source Pollution from Hydromodification.*in* E. P. Agency, editor.

Erman, D. C., J. D. Newbold, and K. B. Roby. 1977. Evaluation of streamside bufferstrips for protecting aquatic organisms.

Everest, F. H., R. L. Beschta, J. C. Scrivener, K. Koski, J. R. Sedell, and C. Cederholm. 1987. Fine sediment and salmonid production: a paradox.

Everest, F. H., and D. Chapman. 1972. Habitat selection and spatial interaction by juvenile chinook salmon and steelhead trout in two Idaho streams. Journal of the Fisheries Board of Canada **29**:91-100.

Everett, R. A., and G. M. Ruiz. 1993. Coarse woody debris as a refuge from predation in aquatic communities. Oecologia **93**:475-486.

FEMAT. 1993. Forest ecosystem management: An ecological, economic, and social assessment. Report of the Forest Ecosystem Mananagement Team, Portland, OR.

Fetherston, K. L., R. J. Naiman, and R. E. Bilby. 1995. Large woody debris, physical process, and riparian forest development in montane river networks of the Pacific Northwest. Geomorphology **13**:133-144.

Fischer, R. A., and J. C. Fischenich. 2000. Design recommendations for riparian corridors and vegetated buffer strips. Army engineer waterways experiment station vicksburg ms engineer research and development center.

Fisher, S. G., and G. E. Likens. 1973. Energy flow in Bear Brook, New Hampshire: an integrative approach to stream ecosystem metabolism. Ecological Monographs **43**:421-439.

Florsheim, J. L., J. F. Mount, and A. Chin. 2008. Bank erosion as a desirable attribute of rivers. AIBS Bulletin **58**:519-529.

Foster, S., R. Hirata, D. Gomes, M. D'Elia, and M. Paris. 2002. Groundwater quality protection: a guide for water service companies, municipal authorities and environment agencies. The World Bank.

Fox, M. J. 2001. A new look at the quantities and volumes of instream wood in forested basins within Washington State. University of Washington.

Franklin, J. F., F. J. Swanson, and J. R. Sedell. 1982. Relationships within the valley floor ecosystems in western Olympic National Park: A summary. Pages 43-45 *in* Ecological Research in National Parks of the Pacific Northwest. Oregon Sate University, Forest Research Lab, San Francisco, California.

Gebhards, S. 1970. The vanishing stream. Idaho Wildl. Rev **22**:3-8.

Gersib, R., L. Wildrick, C. Freeland, S. Grigsby, K. Bauersfeld, S. Butkus, R. Coots, and J. Franklin. 1999. Process-based river basin characterization: a case study Snohomish Basin, Washington. Washington State Department of Ecology. Olympia, WA.

Gerth, W. J., J. Li, and G. R. Giannico. 2017. Agricultural land use and macroinvertebrate assemblages in lowland temporary streams of the Willamette Valley, Oregon, USA. Agriculture, Ecosystems & Environment **236**:154-165.

Gomi, T., R. D. Moore, and A. S. Dhakal. 2006. Headwater stream temperature response to clear-cut harvesting with different riparian treatments, coastal British Columbia, Canada. Water Resources Research **42**.

Gorrick, S., and J. Rodriguez. 2012. Sediment dynamics in a sand bed stream with riparian vegetation.

Goss, C. W., P. C. Goebel, and S. M. P. Sullivan. 2014. Shifts in attributes along agriculture-forest transitions of two streams in central Ohio, USA. Agriculture, Ecosystems & Environment **197**:106-117.

GRAF, W. L. 1978. Fluvial adjustments to the spread of tamarisk in the Colorado Plateau region. GSA Bulletin **89**:1491-1501.

Grant, G., and F. Swanson. 1995. Morphology and processes of valley floors in mountain streams, western Cascades, Oregon. Geophysical Monograph-American Geophysical Union **89**:83-83.

Gregory, S., G. Lamberti, D. Erman, K. Koski, M. Murphy, and J. Sedell. 1987. Influence of forest practices on aquatic production.

Griffin, E., J. Kean, K. Vincent, J. Smith, and J. Friedman. 2005. Modeling effects of bank friction and woody bank vegetation on channel flow and boundary shear stress in the Rio Puerco, New Mexico. Journal of Geophysical Research: Earth Surface **110**.

Groot, C., and L. Margolis. 1991. Pacific salmon life histories. UBC press.

Gurnell, A., H. Piegay, F. Swanson, and S. Gregory. 2002a. Large wood and fluvial processes. Freshwater Biology **47**:601-619.

Gurnell, A. M., K. J. Gregory, and G. E. Petts. 1995. The role of coarse woody debris in forest aquatic habitats - implications for management. Aquatic Conservation-Marine and Freshwater Ecosystems **5**:143-166.

Gurnell, A. M., and G. E. Petts. 2002. Island-dominated landscapes of large floodplain rivers, a European perspective. Freshwater Biol **47**:581-600.

Gurnell, A. M., G. E. Petts, D. M. Hannah, B. P. G. Smith, P. J. Edwards, J. KOLLMANN, J. V. Ward, and K. Tockner. 2001. Riparian vegetation and island formation along the gravel-bed Fiume Tagliamento, Italy. Earth Surface Processes and Landforms **26**:31-62.

Gurnell, A. M., H. Piegay, F. J. SWANSON, and S. V. GREGORY. 2002b. Large wood and fluvial processes. Freshwater Biol **47**:601-619.

Hairston-Strang, A. B., and P. W. Adams. 2000. Riparian management area condition for timber harvests conducted before and after the 1994 Oregon water protection rules. Western Journal of Applied Forestry **15**:147-153.

Hansen, B., P. Reich, P. S. Lake, and T. Cavagnaro. 2010. Minimum width requirements for riparian zones to protect flowing waters and to conserve biodiversity: a review and recommendations. Monash University, Melbourne.

Harding, J. S., K. Claassen, and N. Evers. 2006. Can forest fragments reset physical and water quality conditions in agricultural catchments and act as refugia for forest stream invertebrates? Hydrobiologia **568**:391-402.

Haring, D. 2002. Salmon Habitat Limiting Factors Analysis, Snohomish Watersehd, Water Resource Inventory Area 7.*in* W. S. C. Comission, editor., Olympia, WA.

Harmon, M. E., J. F. Franklin, F. J. Swanson, P. Sollins, S. Gregory, J. Lattin, N. Anderson, S. Cline, N. G. Aumen, and J. Sedell. 1986a. Ecology of coarse woody debris in temperate ecosystems. Pages 133-302 Advances in Ecological Research. Elsevier.

Harmon, M. E., J. F. Franklin, F. J. Swanson, P. Sollins, S. V. Gregory, J. D. Lattin, N. H. Anderson, S. P. Cline, N. G. Aumen, J. R. Sedell, G. W. Lienkaemper, K. Cromack Jr., and K. W. Cummins. 1986b. Ecology of coarse woody debris in temperate ecosystems. Advances in Ecological Research **15**:133-302.

Harris, K. A., N. Dangerfield, M. Woudneh, T. Brown, S. Verrin, and P. S. Ross. 2008. Partitioning of current-use and legacy pesticides in salmon habitat in British Columbia, Canada. Environmental Toxicology and Chemistry **27**:2253-2262.

Henry, R. L., D. M. Gillespie, and R. J. Hunter. 1985. Importance of Snag Habitat for Animal Production in Southeastern Streams AU - Benke, A. C. Fisheries **10**:8-13.

Hession, W., J. Pizzuto, T. Johnson, and R. Horwitz. 2003. Influence of bank vegetation on channel morphology in rural and urban watersheds. Geology **31**:147-150.

Hickin, E. J. 1984. Vegetation and river channel dynamics. Canadian Geographer/Le Géographe canadien **28**:111-126.

Hicks, M. 2000. Evaluating standards for protecting aquatic life in Washington's surface water quality standards: temperature criteria. Washington State Department of Ecology.

Higgins, K. 2016. Ecosystem Management Decision Support.

Hilborn, R., T. P. Quinn, D. E. Schindler, and D. E. Rogers. 2003. Biocomplexity and fisheries sustainability. Proceedings of the National Academy of Sciences **100**:6564-6568.

Hill, A. R. 2018. Landscape Hydrogeology and its Influence on Patterns of Groundwater Flux and Nitrate Removal Efficiency in Riparian Buffers. JAWRA Journal of the American Water Resources Association **54**:240-254.

Holtby, B. L., B. C. Andersen, and R. K. Kadowaki. 1990. Importance of smolt size and early ocean growth to interannual varibility in marine survival of coho salmon (*Oncorhynchus kisutch*). Canadian Journal of Fisheries and Aquatic Sciences **47**:2181-2194.

Hunt, R. L. 1969. Overwinter survival of wild fingerling brook trout in Lawrence Creek, Wisconsin. Journal of the Fisheries Board of Canada **26**:1473-1483.

Hupp, C. R. 1992. Riparian vegetation recovery patterns following stream channelization: a geomorphic perspective. Ecology **73**:1209-1226.

Hyatt, T. L., and R. J. Naiman. 2001. The residence time of large woody debris in the Queets River, Washington, USA. Ecological Applications **11**:191-202.

Ice, G. G. 1985. Catalog of landslide inventories for the northwest.*in* Proceedings of the... Society of American Foresters National Convention (USA).

Isaak, D., S. Wollrab, D. Horan, and G. Chandler. 2012. Climate change effects on stream and river temperatures across the northwest US from 1980–2009 and implications for salmonid fishes. Climatic Change **113**:499-524.

Isenhart, T., R. Schultz, and J. Colletti. 1997. Watershed restoration and agricultural practices in the Midwest: Bear Creek of Iowa.

Jackson, C. R., D. S. Leigh, S. L. Scarbrough, and J. F. Chamblee. 2015. Herbaceous Versus Forested Riparian Vegetation: Narrow and Simple Versus Wide, Woody and Diverse Stream Habitat. River Research and Applications **31**:847-857.

Jackson, C. R., and C. A. Sturm. 2002. Woody debris and channel morphology in first-and second-order forested channels in Washington's coast ranges. Water Resources Research **38**:16-11-16-14.

Jeffres, C. A., J. J. Opperman, and P. B. Moyle. 2008. Ephemeral floodplain habitats provide best growth conditions for juvenile Chinook salmon in a California river. Environmental Biology of Fishes **83**:449-458.

Johnson, D. H., J. O'Neal, J. Knutsen, B. Shrier, X. Augerot, P. Roger, and T. O'Neil. 2003. Protocols for counting salmonids, resident fish, and lamprey in the Pacific Northwest (project briefing paper). briefing paper, Washington Department of Fish and Wildlife, Olympia, WA.

Johnson, F. 1971. Stream temperatures in an alpine area. Journal of Hydrology **14**:322-336.

Johnson, L. B., G. Host, and C. Richards. 2015. Channel, Riparian and Catchment Features as Predictors of Wood Abundance in Low Gradient, Agricultural Streams.

Johnson, S. L. 2004. Factors influencing stream temperatures in small streams: substrate effects and a shading experiment. Canadian Journal of Fisheries and Aquatic Sciences **61**:913-923.

Johnston, N. T., S. A. Bird, D. L. Hogan, and E. A. MacIsaac. 2011. Mechanisms and source distances for the input of large woody debris to forested streams in British Columbia, Canada. Canadian Journal of Forest Research **41**:2231-2246.

Junk, W. J., P. B. Bayley, and R. E. Sparks. 1989. The flood pulse concept in river-floodplain systems. Canadian special publication of fisheries and aquatic sciences **106**:110-127.

Kaje, J. 2009. Snoqualmie Watershed Water Quality Synthesis Report. The Division.

Karr, J. R., and I. J. Schlosser. 1977. Impact of nearstream vegetation and stream morphology on water quality and stream biota. Environmental Protection Agency, Office of Research and Development ….

Keller, E. A., and F. J. Swanson. 1979. Effects of large organic material on channel form and fluvial processes. Earth surface processes **4**:361-380.

King County. 2011. Snoqualmie at Fall City Reach Restoration Assessment. Department of Natural Resources and Parks, Seattle, WA.

Knudsen, E. E., and S. J. Dilley. 1987. Effects of riprap bank reinforcement on juvenile salmonids in four western Washington streams. North American Journal of Fisheries Management **7**:351-356.

Knutson, K. L., and V. Naef. 1997. Management recommendations for Washington's priority habitats: riparian. Washington Department of Fish and Wildlife.

Kubo, J., K. Finley, K. Nelson, M. Sheldon, T. Chairman, D. Parker, C. James, M. Fryberg Jr, T. Sheldon, and G. Gobin. 2013. 2000-2012 Skykomish and Snoqualmie Rivers Chinook and Coho Salmon Out-migration Study.

Langendoen, E. J., R. Richard Lowrance, and A. Simon. 2009. Assessing the impact of riparian processes on streambank stability. Ecohydrology: Ecosystems, Land and Water Process Interactions, Ecohydrogeomorphology **2**:360-369.

Latterell, J. J., and R. J. Naiman. 2007. Sources and dynamics of large logs in a temperate floodplain river. Ecological Applications **17**:1127-1141.

Lenat, D. R. 1993. A Biotic Index for the Southeastern United States: Derivation and List of Tolerance Values, with Criteria for Assigning Water-Quality Ratings. Journal of the North American Benthological Society **12**:279-290.

Levin, P. S., and N. Tolimieri. 2001. Differences in the impacts of dams on the dynamics of salmon populations. Animal Conservation **4**:291-299.

Lewicki, M., J. E. Pizzuto, G. E. Moglen, and N. E. Allmendinger. 2007. A watershed scale numerical model of the impact of land use change on bed material transport in suburban Maryland, USA. Water Resources Research **43**.

Lichatowich, J. 1999. Salmon without rivers: a history of the Pacific salmon crisis. Island Press, Washington, DC.

Lienkaemper, G. W., and F. J. Swanson. 1987. Dynamics of large woody debris in streams in old-growth Douglas-fir forests. Canadian Journal of Forest Research **17**:150-156.

Loeb, S. L., and V. H. Resh. 1994. Biological Monitoring of Aquatic Systems. Lewis, Boca Raton.

Lyons, J., S. W. Thimble, and L. K. Paine. 2000a. Grass versus trees: managing riparian areas to benefit streams of central North America. Journal of the American Water Resources Association **36**:919-930.

Lyons, J., S. W. Thimble, and L. K. Paine. 2000b. GRASS VERSUS TREES: MANAGING RIPARIAN AREAS TO BENEFIT STREAMS OF CENTRAL NORTH AMERICA 1. JAWRA Journal of the American Water Resources Association **36**:919-930.

Macdonald, J. S., E. A. MacIsaac, and H. E. Herunter. 2003. The effect of variable-retention riparian buffer zones on water temperatures in small headwater streams in sub-boreal forest ecosystems of British Columbia. Canadian Journal of Forest Research **33**:1371-1382.

Magilligan, F. J., and P. F. McDowell. 1997. Stream Channel Adjustments Following Elimination of Cavfle Grazing1 JAWRA Journal of the American Water Resources Association **33**:867-878.

Malanson, G. P., and J. A. Kupfer. 1993. Simulated fate of leaf litter and large woody debris at a riparian cutbank. Canadian Journal of Forest Research **23**:582-590.

Maser, C., and J. R. Sedell. 1994. From the forest to the sea: the ecology of wood in streams, rivers, estuaries, and oceans.

Maser, C., R. F. Tarrant, J. M. Trappe, and J. F. Franklin, editors. 1988. From the forest to the sea: a story of fallen trees. [online] edition. U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station, Portland, OR. Gen. Tech. Rep. PNW-GTR-229.

Mayer, P. M., S. K. Reynolds, Jr., M. D. McCutchen, and T. J. Canfield. 2007. Meta-analysis of nitrogen removal in riparian buffers. J Environ Qual **36**:1172-1180.

McDade, M., F. Swanson, W. McKee, J. Franklin, and J. V. Sickle. 1990. Source distances for coarse woody debris entering small streams in western Oregon and Washington. Canadian Journal of Forest Research **20**:326-330.

McElhany, P., M. Ruckelshaus, M. Ford, T. Wainwright, and E. Bjorkstedt. 2000. Viable salmonid populations and the recovery of evolutionarily significant units U.S. Dept. Commer.

McMahon, T. E., and G. F. Hartman. 1989. Influence of cover complexity and current velocity on winter habitat use by juvenile coho salmon (Oncorhynchus kisutch). Canadian Journal of Fisheries and Aquatic Sciences **46**:1551-1557.

Meehan, R. I., F. J. S, and J. R. Sedel. 1977. Influences of Riparian Vegetation on Aquatic Ecosystems with Particular Reference to Salmonid Fishes and Their Food Supplyl.2.

Micheli, E. R., J. W. Kirchner, and E. W. Larsen. 2004. Quantifying the effect of riparian forest versus agricultural vegetation on river meander migration rates, central Sacramento River, California, USA. River Research and Applications **20**:537-548.

Montgomery, D. R. 2007. Soil erosion and agricultural sustainability.

Montgomery, D. R., S. Bolton, D. Booth, and L. Wall. 2003. Restoration of Puget Sound rivers. University of Washington Press, Seattle, WA.

Montgomery, D. R., and J. M. Buffington. 1997. Channel-reach morphology in mountain drainage basins. Geological Society of America Bulletin **109**:596-611.

Montgomery, D. R., J. M. Buffington, N. P. Peterson, D. Schuett-Hames, and T. P. Quinn. 1996. Stream-bed scour, egg burial depths, and the influence of salmonid spawning on bed surface mobility and embryo survival. Canadian Journal of Fisheries and Aquatic Sciences **53**:1061-1070.

Montgomery, D. R., J. M. Buffington, R. D. Smith, K. M. Schmidt, and G. Pess. 1995. Pool spacing in forest channels. Water Resources Research **31**:1097-1105.

Moore, R. D., D. Spittlehouse, and A. Story. 2005. Riparian Microclimate and Stream Temperature Response to Forest Harvesting: A Review. JAWRA Journal of the American Water Resources Association **41**:813-834.

Murphy, M. L., and K. V. Koski. 1989. Input and depletion of woody debris in Alaska streams and implications for streamside management. North American Journal of Fisheries Management **9**:427-436.

Murphy, M. L., J. F. Thedinga, K. V. Koski, and G. B. Grette. 1984. A Stream Ecosystem in an Old-growth Forest in Southeast Alaska, Part V. Seasonal Changes in Habitat Utilization by Juvenile Salmonids.*in* Fish and Wildlife Relationshipos in Old-Growth Forests, Juneau, AK.

Naiman, R. J., T. J. Beechie, L. E. Benda, D. R. Berg, P. A. Bisson, L. H. MacDonald, M. D. O'Connor, P. L. Olson, and E. A. Steel. 1992. Fundamental elements of ecologically healthy watersheds in the Pacific Northwest coastal ecoregion. Pages 127-188 *in* Watershed management. Springer.

Naiman, R. J., and H. Decamps. 1997. The ecology of interfaces: riparian zones. Annual Review of Ecology and Systematics **28**:621-658.

Naiman, R. J., and H. Décamps. 1997. The ecology of interfaces: riparian zones. Annual Review of Ecology and Systematics **28**:621-658.

Naiman, R. J., H. Decamps, and M. E. McClain. 2010. Riparia: ecology, conservation, and management of streamside communities. Elsevier.

Nakamura, F., and F. J. Swanson. 1993. Effects of coarse woody debris on morphology and sediment storage of a mountain stream system in western Oregon. Earth Surface Processes and Landforms **18**:43-61.

Nanson, G. C. 1981. New evidence of scroll-bar formation on the Beatton River. Sedimentology **28**:889-891.

Newbold, J., D. Erman, and K. Roby. 1980. Effects of logging on macroinvertebrates in streams with and without buffer strips. Canadian Journal of Fisheries and Aquatic Sciences **37**:1076-1085.

Newcombe, C. P., and J. O. Jensen. 1996. Channel suspended sediment and fisheries: a synthesis for quantitative assessment of risk and impact. North American Journal of Fisheries Management **16**:693-727.

Nguyen, M., G. Sheath, C. Smith, and A. Cooper. 1998. Impact of cattle treading on hill land: 2. Soil physical properties and contaminant runoff. New Zealand Journal of Agricultural Research **41**:279-290.

Nielsen, J. L., T. E. Lisle, and V. Ozaki. 1994. Thermally stratified pools and their use by steelhead in northern California streams. Transactions of the American Fisheries Society **123**:613-626.

NMFS. 1999. Endangered and threatened species: threatened status for three Chinook Salmon evolutionarily significant units (ESUs) in Washington and Oregon, and endangered status for one Chinook Salmon ESU in Washington. Federal Register **64**:14308-14328.

Norris, V. 1993. The use of buffer zones to protect water quality: A review. Water Resources Management **7**:257-272.

NRC. 2002. Riparian areas: functions and strategies for management. National Academies Press.

Oke, T. R. 2002. Boundary layer climates. Routledge.

Olson, D. H., P. D. Anderson, C. A. Frissell, H. H. Welsh, and D. F. Bradford. 2007. Biodiversity management approaches for stream–riparian areas: Perspectives for Pacific Northwest headwater forests, microclimates, and amphibians. Forest Ecology and Management **246**:81-107.

Oregon-Washington Interagency Wildlife, C. 1979. Managing riparian ecosystems (zones) for fish and wildlife in eastern Oregon and eastern Washington. Prepared by Riparian Habitat Subcomm. of the Oreg./Wash. Interagency Wildlife Comm. Portland, Oreg. 44pp.

Osborne, L. L., and D. A. Kovacic. 1993. Riparian vegetated buffer strips in water-quality restoration and stream management. Freshwater Biology **29**:243-258.

Parkyn, S. 2004. Review of riparian buffer zone effectiveness. Citeseer.

Piegay, H., and J. P. Bravard. 1997. Response of a mediterranean riparian forest to a 1 in 400 year flood, Ouveze River, Drome-Vaucluse, France. Earth Surface Processes and Landforms **22**:31-43.

Piégay, H., and A. Gurnell. 1997. Large woody debris and river geomorphological pattern: examples from SE France and S. England. Geomorphology **19**:99-116.

Plafkin, J. L., M. Barbour, K. D. Porter, S. K. Gross, and R. M. Hughes. 1989. Rapid Bioassessment Protocols for Use in Streams and Rivers: Benthic Macroinvertebrates and Fish.

Pollen-Bankhead, N., and A. Simon. 2010. Hydrologic and hydraulic effects of riparian root networks on streambank stability: Is mechanical root-reinforcement the whole story? Geomorphology **116**:353-362.

Pollen, N., and A. Simon. 2005. Estimating the mechanical effects of riparian vegetation on stream bank stability using a fiber bundle model. Water Resources Research **41**.

Pollock, M. M., M. Heim, and D. Werner. 2003. Hydrologic and geomorphic effects of beaver dams and their influence on fishes. Pages 213-233 *in* American Fisheries Society Symposium.

Polvi, L. E., E. Wohl, and D. M. Merritt. 2014. Modeling the functional influence of vegetation type on streambank cohesion. Earth Surface Processes and Landforms **39**:1245-1258.

Poole, G. C., and C. H. Berman. 2001. An Ecological Perspective on In-Stream Temperature: Natural Heat Dynamics and Mechanisms of Human-CausedThermal Degradation. Environmental Management **27**:787-802.

Prevention, P. 2005. National management measures to control nonpoint source pollution from urban areas. Environmental Protection Agency, Cincinnati.

Quigley, J., and D. Harper. 2004. Streambank protection with rip-rap: an evaluation of the effects on fish and fish habitat. Habitat and Enhancement Branch, Fisheries and Oceans Canada.

Quinn, J. M., and A. B. Cooper. 1997. Land-water interactions at Whatawhata, New Zealand: Introduction and synthesis. New Zealand Journal of Marine and Freshwater Research **31**:569-577.

Quinn, T. P. 2018a. The behavior and ecology of Pacific salmon and trout. University of Washington press.

Quinn, T. W., George; Kruegaer, Kirk;. 2018b. Riparian Ecosystems, Volume 1: Science synthesis and management implications. .*in* W. D. o. F. a. Wildlife, editor., Olympia, WA.

Reeves, G., J. Hall, and S. Gregory. 1997. The impact of land-management activities on coastal cutthroat trout and their freshwater habitats. American Fishereies Society, Oregon Chpater, Corvallus, Oregon (USA).138-145.
Reeves, G. H., D. B. Hohler, D. P. Larsen, D. E. Busch, and a. others]. 2003. Aquatic and riparian effectiveness monitoring plan for the Northwest Forest Plan. General Technical Report. PNW-GTR-577, USDA Forest Service, Pacific Northwest Research Station, Portland, OR.
Reeves, G. H., D. H. Olson, S. M. Wondzell, P. A. Bisson, S. Gordon, S. A. Miller, J. W. Long, and M. J. Furniss. 2018. The aquatic conservation strategy of the northwest forest plan—A review of the relevant science after 23 years. In: Spies, TA; Stine, PA; Gravenmier, R.; Long, JW; Reilly, MJ, tech. coords. 2018. Synthesis of science to inform land management within the Northwest Forest Plan area. Gen. Tech. Rep. PNW-GTR-966. Portland, OR: US Department of Agriculture, Forest Service, Pacific Northwest Research Station: 461-624. **966**:461-624.
Reeves, G. H., B. R. Pickard, and K. N. Johnson. 2016. An initial evaluation of potential options for managing riparian reserves of the Aquatic Conservation Strategy of the Northwest Forest Plan. United States Department of Agriculture, Forest Service, Pacific Northwest ….
Reid, D. J., P. S. Lake, G. P. Quinn, and P. Reich. 2008. Association of reduced riparian vegetation cover in agricultural landscapes with coarse detritus dynamics in lowland streams. Marine and Freshwater Research **59**.
Reifsnyder, W. E., and H. W. Lull. 1965. Radiant energy in relation to forests. US Department of Agriculture, Forest Service.
Reiser, D., and T. C. Bjornn. 1979. Influence of forest and rangeland management on anadromous fish habitat in Western North America: habitat requirements of anadromous salmonids. Gen. Tech. Rep. PNW-GTR-096. Portland, OR: US Department of Agriculture, Forest Service, Pacific Northwest Research Station: 1-54 **96**.
Rice, S., A. Roy, and B. Rhoads. 2008. River confluences, tributaries and the fluvial network. John Wiley & Sons.
Rinaldi, M., N. Casagli, S. Dapporto, and A. Gargini. 2004. Monitoring and modeling pore water pressure changes and riverbank stability during flow events.
Robison, E. G., and R. L. Beschta. 1990. Identifying trees in riparian areas that can provide coarse woody debris to streams. Forest Science **36**:790-801.
Rosenberg, D. M., and V. H. Resh. 1993. Freshwater Biomonitoring and Benthic Macroinvertebrates. Springer US.
Rosenfeld, J. S., and L. Huato. 2003. Relationship between large woody debris characteristics and pool formation in small coastal British Columbia Streams. North American Journal of Fisheries Management **23**:928-938.
Rot, B. W., R. J. Naiman, and R. E. Bilby. 2000. Stream channel configuration, landform, and riparian forest structure in the Cascade Mountains, Washington. Canadian Journal of Fisheries and Aquatic Sciences **57**:699-707.
Rutherford, J. C., N. A. Marsh, P. M. Davies, and S. E. Bunn. 2004. Effects of patchy shade on stream water temperature: how quickly do small streams heat and cool? Marine and Freshwater Research **55**:737-748.

Rykken, J. J., S. S. Chan, and A. R. Moldenke. 2007. Headwater riparian microclimate patterns under alternative forest management treatments. Forest Science **53**:270-280.

Scarsbrook, M. R., and J. Halliday. 1999. Transition from pasture to native forest land-use along stream continua: Effects on stream ecosystems and implications for restoration. New Zealand Journal of Marine and Freshwater Research **33**:293-310.

Scarsbrook, M. R., J. M. Quinn, J. Halliday, and R. Morse. 2001. Factors controlling litter input dynamics in streams draining pasture, pine, and native forest catchments. New Zealand Journal of Marine and Freshwater Research **35**:751-762.

Schindler, D. E., R. Hilborn, B. Chasco, C. P. Boatright, T. P. Quinn, L. A. Rogers, and M. S. Webster. 2010. Population diversity and the portfolio effect in an exploited species. Nature **465**:609.

Schmidt, J. C., and T. M. Allred. 1999. Channel narrowing by vertical accretion along the Green River near Green River, Utah. GSA Bulletin **111**:1757-1772.

Sedell, J. R., and J. L. Froggatt. 1984. Importance of streamside forests to large rivers: The isolation of the Willamette River, Oregon, USA, from its floodplain by snagging and streamside forest removal: With 2 figures and 1 table in the text. Internationale Vereinigung für theoretische und angewandte Limnologie: Verhandlungen **22**:1828-1834.

Sedell, J. R., and F. J. Swanson. 1982. Fish habitat and streamside management: Past and present. Pages 244-255 *in* Proceedings of the Society of American Foresters Annual Meeting. Society of American Foresters, Bethesda, Maryland.

Sickle, J. V., and S. V. Gregory. 1990. Modeling inputs of large woody debris to streams from falling trees. Canadian Journal of Forest Research **20**:1593-1601.

Simon, A., and A. J. C. Collison. 2002. Quantifying the mechanical and hydrologic effects of riparian vegetation on streambank stability. Earth Surface Processes and Landforms **27**:527-546.

Simon, A., A. Curini, S. E. Darby, and E. J. Langendoen. 2000. Bank and near-bank processes in an incised channel. Geomorphology **35**:193-217.

Simon, A., N. Pollen, and E. Langendoen. 2006. Influence of Two Woody Riparian Species on Critical Conditions for Streambank Stability: Upper Truckee River California 1 JAWRA Journal of the American Water Resources Association **42**:99-113.

Simpson, P. W., J. Newman, M. Keirn, R. Matter, and P. Guthrie. 1982. Manual of stream channelization impacts on fish and wildlife.

Snohomish Basin Salmon Recovery Forum. 2005. Snohomish River Basin Salmon Conservation Plan. Page 402 *in* S. W. M. D. Snohomish County Department of Public Works, editor., Everett, WA.

Snohomish Basin Salmonid Recovery Technical Committee. 2004. Snohomish River Basin Ecological Analysis for Salmonid Conservation. Snohomish County Surface Water Management, Everett, WA.

Snoqualmie Watershed Forum. 2016. Snoqualmie Watershed Forum Ten-Year Status Report. King County Water and Land Resources Division, Seattle, WA.

Sobota, D. J. 2003. Fall directions and breakage of riparian trees along streams in the Pacific Northwest.

Sommer, T. R., M. L. Nobriga, W. C. Harrell, W. Batham, and W. J. Kimmerer. 2001. Floodplain rearing of juvenile Chinook salmon: evidence of enhanced growth and survival. Canadian Journal of Fisheries and Aquatic Sciences **58**:325-333.

Spence, B. C., G. A. Lomnicky, R. M. Hughes, and R. P. Novitzki. 1996. An ecosystem approach to salmonid conservation. TR-4501-96-6057, ManTech Environmental Research Services Corp. (Available from the National Marine Fisheries Service, Portland, OR.), Corvallis OR.

Spies, T., M. Pollock, G. Reeves, and T. Beechie. 2013. Effects of riparian thinning on wood recruitment: a scientific synthesis. Science Review Team Wood Recruitment Subgroup, USDA Forest Service, PNW Research Station, Portland.

Stanford, J., and J. Ward. 1988. The hyporheic habitat of river ecosystems. Nature **335**:64.

Steinblums, I. J. 1977. Streamside buffer strips: survival, effectiveness, and design.

Stewart, J. S., L. Wang, J. Lyons, J. A. Horwatich, and R. Bannerman. 2001. Influcences of Watershed, Riparian-Corridor, and Reach-Scale Characteristics on Aquatic Biota in Agricultural Watersheds. JAWRA Journal of the American Water Resources Association **37**:1475-1487.

Stohr, A., K. James, and R. Svrjcek. 2011. Snoqualmie River Basin Temperature Total Maximum Daily Load Water Quality Improvement Report and Implementation Plan.

Sullivan, K., and T. N. Adams. 1991. The physics of stream heating: An analysis of temperature patterns in stream environments based on physical principles and field data.

Swales, S. 1982. Environmental effects of river channel works used in land drainage improvement. Journal of Envrionmental Management **14**:103-126.

Swanson, F. J., and G. W. Lienkaemper. 1978. Physical consequences of large organic debris in Pacific Northwest streams. Gen. Tech. Rep. PNW-GTR-069. Portland, OR: US Department of Agriculture, Forest Service, Pacific Northwest Research Station: 1-12 **69**.

Swanson, F. J., and G. W. Lienkaemper. 1982. Interactions among fluvial processes, forest vegetation, and aquatic ecosystems, South Fork Hoh River, Olympic National Park. Page 142 *in* E. E. Starkey, J. F. Franklin, and J. W. Matthews, editors. Ecological research in National Parks in the Pacific Northwest. Oregon State University Forest Research Laboratory, Corvallis, OR.

Sweeney, B. W. 1993. Effects of Streamside Vegetation on Macroinvertebrate Communities of White Clay Creek in Eastern North-America. Proceedings of the Academy of Natural Sciences of Philadelphia **144**:291-340.

Sweeney, B. W., T. L. Bott, J. K. Jackson, L. A. Kaplan, J. D. Newbold, L. J. Standley, W. C. Hession, and R. J. Horwitz. 2004. Riparian deforestation, stream narrowing, and loss of stream ecosystem services. Proceedings of the National Academy of Sciences **101**:14132-14137.

Sweeney, B. W., and J. D. Newbold. 2014. Streamside Forest Buffer Width Needed to Protect Stream Water Quality, Habitat, and Organisms: A Literature Review. JAWRA Journal of the American Water Resources Association **50**:560-584.

Theurer, F. D., I. Lines, and T. Nelson. 1985. Interation Between Riparian Vegetation, Water Temperature, and Salmonid Habitat in the Tucannon River 1. JAWRA Journal of the American Water Resources Association **21**:53-64.

Trimble, S., and A. C. Mendel. 1995. The Cow as a Geomorphic Agent – A Critical Review.

Trimble, S. W. 1997. Stream channel erosion and change resulting from riparian forests. Geology **25**.

Triska, F. J. 1984. Role of wood debris in modifying channel geomorphology and riparian areas of a large lowland river under pristine conditions: A historical case study: With 7 figures and 4 tables in the text. Internationale Vereinigung für theoretische und angewandte Limnologie: Verhandlungen **22**:1876-1892.

Urgenson, L. S., S. H. Reichard, and C. B. Halpern. 2009. Community and ecosystem consequences of giant knotweed (Polygonum sachalinense) invasion into riparian forests of western Washington, USA. Biological Conservation **142**:1536-1541.

Vannote, R. L., G. W. Minshall, K. W. Cummins, J. R. Sedell, and C. E. Cushing. 1980. The river continuum concept. Canadian Journal of Fisheries and Aquatic Sciences **37**:130-137.

Vezina, P., and G. Pech. 1964. Solar radiation beneath conifer canopies in relation to crown closure. Forest Science **10**:443-451.

Vidon, P., C. Allan, D. Burns, T. P. Duval, N. Gurwick, S. Inamdar, R. Lowrance, J. Okay, D. Scott, and S. Sebestyen. 2010. Hot spots and hot moments in riparian zones: potential for improved water quality management1. JAWRA Journal of the American Water Resources Association **46**:278-298.

Vidon, P. G., and A. R. Hill. 2006. A Landscape-based Approach to Estimate Riparian Hydrological and Nitrate Removal Functions 1. JAWRA Journal of the American Water Resources Association **42**:1099-1112.

Wallace, J., J. R. Webster, and J. L. Meyer. 1995. Influence of Log Additions on Physical and Biotic Characteristics of a Mountain Stream.

Wallace, J. B., S. L. Eggert, J. L. Meyer, and J. R. Webster. 1997. Multiple Trophic Levels of a Forest Stream Linked to Terrestrial Litter Inputs. Science **277**:102-104.

Wallace, J. B., and J. R. Webster. 1996. The role of macroinvertebrates in stream ecosystem function. Annual Review of Entomology **41**:115-139.

Ward, J. V., K. Tockner, D. B. Arscott, and C. Claret. 2002. Riverine landscape diversity. Freshwater Biol **47**:517-539.

Watson, C. C., S. R. Abt, and D. Derrick. 1997. Willow Posts Bank Stabilization 1 JAWRA Journal of the American Water Resources Association **33**:293-300.

Weigel, B. M., J. Lyons, L. K. Paine, S. I. Dodson, and D. J. Undersander. 2000. Using Stream Macroinvertebrates to Compare Riparian Land Use Practices on Cattle Farms in Southwestern Wisconsin. Journal of Freshwater Ecology **15**:93-106.

Welty, J. J., T. Beechie, K. Sullivan, D. M. Hyink, R. E. Bilby, C. Andrus, and G. Pess. 2002a. Riparian aquatic interaction simulator (RAIS): a model of riparian forest dynamics for the generation of large woody debris and shade. Forest Ecology and Management **162**:299-318.

Welty, J. J., T. Beechie, K. Sullivan, D. M. Hyink, R. E. Bilby, C. Andrus, and G. Pess. 2002b. Riparian aquatic interaction simulator (RAIS): a model of riparian forest dynamics for the generation of large woody debris and shade. Forest Ecology and Management **162**:299-318.

Whitney, A. N., and J. E. Bailey. 1959. Detrimental effects of highway construction on a Montana stream. Transactions of the American Fisheries Society **88**:72-73.

Wipfli, M. S. 1997. Terrestrial invertebrates as salmonid prey and nitrogen sources in streams: contrasting old-growth and young-growth riparian forests in southeastern Alaska. Canadian Journal of Fisheries and Aquatic Sciences **54**:1259-1269.

Wohl, E., N. Kramer, V. Ruiz-Villanueva, D. N. Scott, F. Comiti, A. M. Gurnell, H. Piegay, K. B. Lininger, K. L. Jaeger, D. M. Walters, and K. D. Fausch. 2019. The Natural Wood Regime in Rivers. BioScience **69**:259-273.

Wood, P. J., and P. D. Armitage. 1997. Biological effects of fine sediment in the lotic environment. Environmental Management **21**:203-217.

Wooster, D. E., and S. J. DeBano. 2006. Effect of woody riparian patches in croplands on stream macroinvertebrates. Archiv Fur Hydrobiologie **165**:241-268.

Yuan, Y., R. L. Bingner, and M. A. Locke. 2009. A Review of effectiveness of vegetative buffers on sediment trapping in agricultural areas. Ecohydrology **2**:321-336.

Zhang, X., X. Liu, M. Zhang, R. A. Dahlgren, and M. Eitzel. 2010. A review of vegetated buffers and a meta-analysis of their mitigation efficacy in reducing nonpoint source pollution. J Environ Qual **39**:76-84.

ZumBerge, J. R., J. A. Perry, and K. E. Lee. 2003. Influence of local riparian cover and watershed runoff potential on invertebrate communities in agricultural streams in the Minnesota River Basin. US Department of the Interior, US Geological Survey.

6.0 APPENDIX I

Function: Water Quality – Nutrients, Sediment, Pesticides

Riparian Buffer Width (25ft, 50ft, 75ft, 100ft, 150ft, 200ft, >250ft)

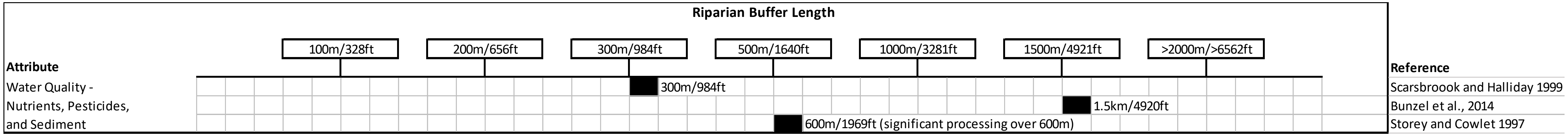
Attribute: Water Quality - Nutrients, Pesticides, and Sediment

Attribute	Buffer width values	Reference
N (% reduction)	49% @ 5m/16ft; 71% @ 10m/33ft; 91% @ 20m/66ft; 98% @ 30m/98ft	Zhang et al. 2010
N (% reduction)	63% @ 5m/16ft; 85% @ 10m/33ft; 100% @ 20m/66ft	Zhang et al. 2010
N (% reduction)	54% @ 16ft; 73% @ 9m/30ft	Dillaha et al. 1989
N (% reduction)	50% @ 17m/56ft; 75% 51m/167ft; 90% @ 84m/276ft	Mayer et al. 2007
N (% reduction)	50% @ 3m/10ft; 75% @ 18m/59ft; 90% @ 44m/144ft	Mayer et al. 2007
N (% reduction)	15m/50ft; 30m/100ft	Wenger and Fowler 2000
N (% reduction)	79-98% @ 30-50m/98-164ft	Peterjohn and Correll 1984
N (% reduction)	48% @ 30m/98ft; 90% @ 100m/328ft	Sweeny and Newbold 2014
N (% reduction)	90% @ 15m/50ft; 90% @ 25m/82ft	Vidon and Hill 2006
P (% reduction)	51% @ 5m/16ft; 69% @ 10m/33ft; 97% @ 20m/66ft; 100% @ 30m/98ft	Zhang et al. 2010
P (% reduction)	80% @ 5m/16ft; 95% @ 10m/33ft; 100% @ 20m/66ft	Zhang et al. 2010
P (% reduction)	61% @ 16ft; 79% @ 9m/30ft	Dillaha et al. 1989
P (% reduction)	27% @ 16ft; 46% @ 9.2m/30ft	Magette et al. 1989
P (% reduction)	83% @ ~25m/82ft (21-27m)	Young et al. 1980
P (% reduction)	50-85% @ 16-50m/52-164ft	Peterjohn and Correll 1984
Pest. (% red.)	62% @ 5m/15ft; 83% @ 10m/33ft; 92% @ 20m/66ft; 93% @ 30m/98ft	Zhang et al. 2010
Pest. (% red.)	15m/50ft	Wenger and Fowler 2000
Pest. (% red.)	10m/33ft; 15m/50ft	Rasmussen et al 2011
Pest. (% red.)	5m/16ft	Bunzel et al. 2014
Pest. (% red.)	40% @ 12m/40ft; 60% @ 24m/79ft; 70% @ 36m/118ft; 100% @ 60m/197ft	Aguiar Jr. et al. 2015
Sediment (% reduction)	67% @ 5m/15ft; 76% @ 10m/33ft; 78% @ 20m/66ft	Zhang et al. 2010
Sediment (% reduction)	82% @ 5m/16ft; 91% @ 10m/33ft; 93% @ 20m/66ft	Zhang et al. 2010
Sediment (% reduction)	90% @ 10m/33ft	Liu et al. 2008
Sediment (% reduction)	65% @ 10m; 78% @ 20m/66ft; 84% @ 30m/98ft	Sweeny and Newbold 2014
Sediment (% reduction)	80% @ 5m/16ft	Yuan et al. 2009
Sediment (% reduction)	5m/16ft; 9m/30ft; 30m/100ft	Wenger and Fowler 2000
Sediment (% reduction)	74% @ 16ft; 87% @ 9m/30ft	Dillaha et al. 1989
Sediment (% reduction)	82% @ 14ft; 90% @ 8.5m/28ft	Mendez et al. 1999
Sediment (% reduction)	100% @ 30m/98ft	Lynch et al. 1985
Sediment (% reduction)	66% @ 4.6m/15ft; 9.2m/30ft	Magette et al. 1989

Reference	Riparian Cover Type	Stream order, Width, or Catchment Size	Gradient or Slope	Landscape	Comments	Cited in	Citation Title
Zhang et al. 2010	Mixed grass and trees/grass only			Agricultural Lands	Meta-Analysis of different types of buffers in agricultural landscapes		A Review of Vegetated Buffers and a Meta-analysis of Their Mitigation Efficacy in Reducing Nonpoint Source Pollution
Zhang et al. 2010	Trees			Agricultural Lands	Meta-Analysis of different types of buffers in agricultural landscapes		A Review of Vegetated Buffers and a Meta-analysis of Their Mitigation Efficacy in Reducing Nonpoint Source Pollution
Dillaha et al. 1989	Grass		Buffer Slope: 5, 11, and 16%	Virginia Agricultural Lands	A rainfall simulator was used on experimental plots with set amounts of fertilizers added	Osborne and Kovacic 1993; Castelle et al., 1993	Vegetative filter strips for agricultural nonpoint source pollution control
Mayer et al. 2007	Herbaceous				Meta-analysis of nitrogen removal in riparian buffers; surface and groundwater		Meta-Analysis of Nitrogen Removal in Riparian Buffers
Mayer et al. 2007	Herbaceous/Forest				Meta-analysis of nitrogen removal in riparian buffers; surface and groundwater		Meta-Analysis of Nitrogen Removal in Riparian Buffers
Wenger and Fowler 2000					Literature review aimed at providing buffer requirement guidance for the state of GA; recommends a minimum of 15m/50ft to remove contaminants in many cases, but 30m/98ft is best in most cases.		Protecting Streams and River Corridors
Peterjohn and Correll 1984					The study focused on surface water nutrient removal and found that most of the removal occurred within the first 19m of the riparian zone. Widths and percentages taken from Osborne and Kovacic (1993).		Nutrient Dynamics in an Agricultural Watershed - Observations on the Role of a Riparian Forest
Sweeny and Newbold 2014					Meta-Analysis with updated studies; Created a model that incorporated a variety of studies. Because of the wide variation in study sites incorporated in their model, their suggested interpretation is a minimum 30m buffer and as the width increases so does the likelihood of high removal efficiencies.		Streamside Forest Buffer Width Needed to Protect Stream Water Quality, Habitat, and organisms
Vidon and Hill 2006				Southern Ontario	Conceptual model created from data collected in Southern Ontario and validated using data from North America and Europe. Found that as soils become more coarse and/or soil permeability get deeper, wider buffers are needed to remove N. 15m coincides with silt/loam soils, and 25m coincides with sand soils both at 90% removal efficacy		A landscape based approach to estimate riparian hydrological and nitrate removal functions
Zhang et al. 2010	Mixed Grass & Forest			Agricultural Lands	Meta-Analysis of different types of buffers in agricultural landscapes		A Review of Vegetated Buffers and a Meta-analysis of Their Mitigation Efficacy in Reducing Nonpoint Source Pollution

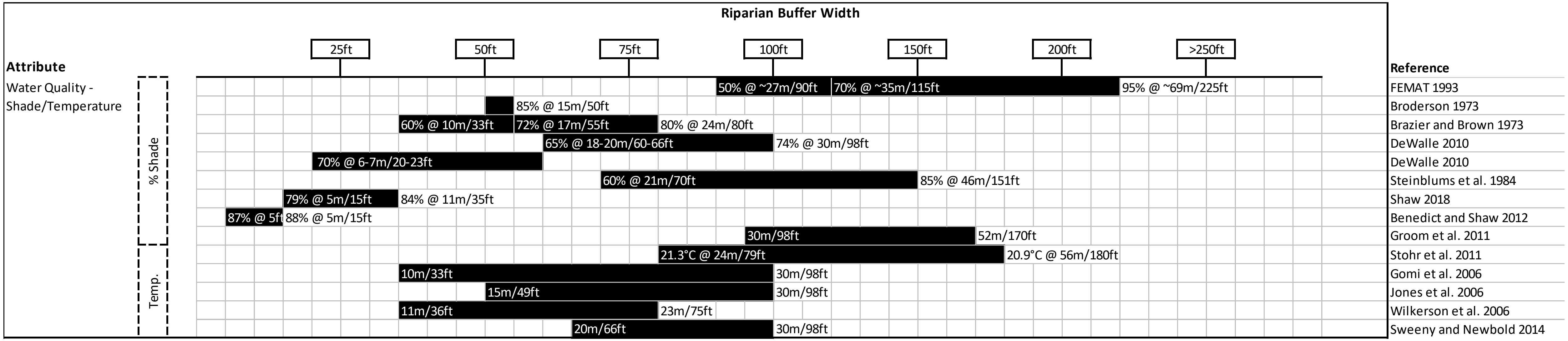
Zhang et al. 2010	Forest			Agricultural Lands	Meta-Analysis of different types of buffers in agricultural landscapes		A Review of Vegetated Buffers and a Meta-analysis of Their Mitigation Efficacy in Reducing Nonpoint Source Pollution
Dillaha et al. 1989	Grass		Buffer Slope: 5, 11, and 16%	Agricultural Lands	A rainfall simulator was used on experimental plots with set amounts of fertilizers added		Vegetative filter strips for agricultural nonpoint source pollution control
Magette et al. 1989	Grass		Buffer Slope: 2-4%	Maryland Experiment al Plots	Utilized simulated rainfall to assess the effectiveness of vegetated filter strips on removing nutrients from agricultural runoff	Dosskey 2001	Nutrient and Sediment Removal by Vegetated Filter Strips
Young et al. 1980	Grass		Buffer slope: 4%	Virginia Agricultural Lands	Rain simulator was used to assess the effectiveness of grass buffers in filtering feedlot runoff		Effectiveness of Vegetated Buffer Strips in Controlling Pollution from Feedlot Runoff
Peterjohn and Correll 1984	Forest, deciduous		2.65%	Maryland Agricultural Lands, sandy loam soils	The study focused on surface water nutrient removal and found that most of the removal occurred within the first 19m of the riparian zone. Widths and percentages taken from Osborne and Kovacic (1993).	Osborne and Kovacic 1993	Nutrient Dynamics in an Agricultural Watershed - Observations on the Role of a Riparian Forest
Zhang et al. 2010				Agricultural Lands	Meta-Analysis of different types of buffers in agricultural landscapes		A Review of Vegetated Buffers and a Meta-analysis of Their Mitigation Efficacy in Reducing Nonpoint Source Pollution
Wenger and Fowler 2000					Literature review aimed at providing buffer requirement guidance for the state of GA, buffers should be a minimum of 15m/50ft to remove pesticides		Protecting Streams and River Corridors
Rasmussen et al 2011	Forest	1st and 2nd order		Agricultural landscape in Denmark	Percent removal not given. 15m buffers seemed to be where peak removal took place, not much more removal from 15-25m. 10m seems to be about 90% as effective as 15m (Figure 2 in paper).		Buffer strip width and agricultural pesticide contamination in Danish lowland streams: Implications for stream and riparian management
Bunzel et al. 2014	Forest			Agricultural landscape in Germany	Used a macroinvertebrate index called SPEAR to measure the effects of pesticides on instream biotic communities. Buffers were 5m wide. Buffers of 5m must extent at least 1.5km upstream of the sample site to be fully effective in protecting the biotic community.		Landscape Parameters Driving Aquatic Pesticide Exposure and Effects
Aguiar Jr. et al. 2015	Forest		Slope: 8-9%	Agricultural landscape of southern Brazil	Examined the effectiveness of woody (forest), shrub, and grass buffers. Woody buffers always filtered out more pesticides. At 12m wood buffers over 60% of all pesticides measured were removed except for Atrazine which had a removal efficacy of 40%. Shrub and grass buffers at 60m did not remove as much pesticide as woody buffers at 12m.		Riparian Buffer Zones as Pesticide Filters of No-Till Crops
Zhang et al. 2010	Mixed Grass & Forest		Buffer Slope: 5%		Meta-Analysis		A Review of Vegetated Buffers and a Meta-analysis of Their Mitigation Efficacy in Reducing Nonpoint Source Pollution

Zhang et al. 2010	Grass or Forest		Buffer Slope: 5%		Meta-Analysis		A Review of Vegetated Buffers and a Meta-analysis of Their Mitigation Efficacy in Reducing Nonpoint Source Pollution
Liu et al. 2008	Mainly Grass				Meta-Analysis		Major factors influencing the efficacy of vegetated buffers on sediment trapping - A review and analysis
Sweeny and Newbold 2014					Meta-Analysis with updated studies		Streamside Forest Buffer Width Needed to Protect Stream Water Quality, Habitat, and organisms
Yuan et al. 2009	Grass & Forest			Agricultural Lands	Litt. Review		A Review of effectiveness of vegetative buffers on sediment trapping in agricultural areas
Wenger and Fowler 2000					Litt. Review		Protecting Streams and River Corridors
Dillaha et al. 1989	Grass VFS		Buffer Slope: 11-16%	Virginia Agricultural Lands	Experimental Plots	Dosskey 2001	Vegetative filter strips for agricultural nonpoint source pollution control
Mendez et al. 1999							Sediment and Nitrogen Transport in Grass Filter Strips
Lynch et al. 1985				Forest Lands	Logging activity stormwater		Best management practices for controlling nonpoint-source pollution on forested watersheds
Magette et al. 1989	Grass		Buffer Slope: 2-4%	Maryland Experimental Plots		Dosskey 2001	Nutrient and Sediment Removal by Vegetated Filter Strips



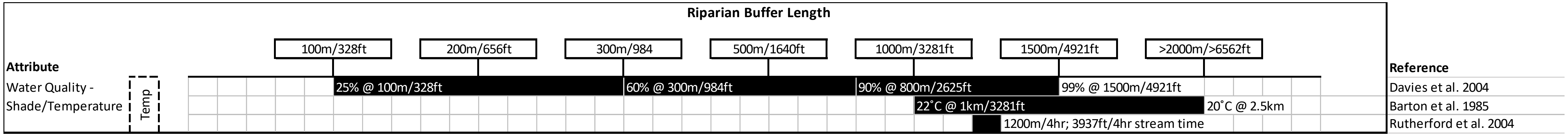
Reference	Riparian Cover Type	Stream order, Width, or Catchment Size	Landscape	Comments	Citation Title
Scarsbroook and Halliday 1999	Pasture and forested streams in New Zealand	1st-2nd order		Studied the changes of a stream that was previously unbuffered in an agricultural landscape as it entered and moved through a forested area. After 300 m into the forested area, the water chemistry (including nutrients) was still significantly different from that of the native forest stream condition.	Transition from pasture to native forest land-use along stream continua: effects on stream ecosystems and implications for restoration
Bunzel et al., 2014	Forest		Agricultural landscape in Germany	Used a macroinvertebrate index called SPEAR to measure the effects of pesticides on instream biotic communities. Buffers were 5-m wide. Buffers of 5 m must extent at least 1.5 km upstream of the sample site to be fully effective in protecting the biotic community.	
Storey and Cowlet 1997					Recovery of three New Zealand Rural Streams as They Pass Through Native Forest Remnants

Function: Water Temperature/Riparian Shade



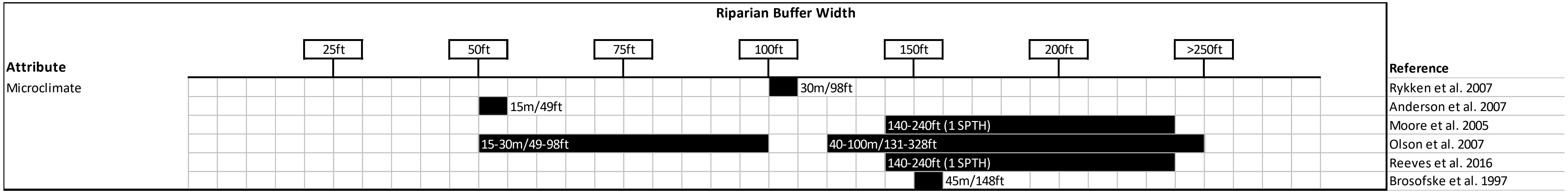
Reference	Riparian Cover Type	Stream order, Width, or Catchment Size	Gradient or Slope	Landscape	Comments	Cited in	Citation Title
FEMAT 1993						Reeves et al. 2018	Forest ecosystem management: an ecological, economic, and social assessment
Broderson 1973		Small streams with flows <5 cfs		Western Oregon and Washington	Created an equation from the literature that estimated shade based on riparian width. Found 85% of shade for "small streams" produced from a width of 50 ft.		Sizing Buffer Strips to Maintain Water Quality
Brazier and Brown 1973		"small streams"		Umpqua National Forest; Southern Cascade Mountains; Forestry	80% needed for water temp control and equivalent to full forest conditions; maximum shade at 80 ft and 90% of max at 55 ft	Beschta et al. 1987, Sweeny and Newbold 2014, Osborne and Kovacic 1993,	Buffer Strips for Stream Temperature Control
DeWalle 2010	Forest	fixed stream width = 3 m (N-S orientation)			Modeled stream shade at different buffer widths, also kept in mind stream orientation. This line is specific to N-S oriented streams, shade was maximized at widths ~30 m		Modeling Stream Shade: Riparian Buffer Height and Density as Important as Buffer Width
DeWalle 2010	Forest	fixed stream width = 3 m (E-W orientation)			Modeled stream shade at different buffer widths, also kept in mind stream orientation. This line is specific to E-W oriented streams, shade was maximized at widths ~7 m		Modeling Stream Shade: Riparian Buffer Height and Density as Important as Buffer Width
Steinblums et al. 1984	Conifers			Cascade Mountains	Widths and percentages taken from the regression line fitted to their data (Fig. 2)	Beschta et al. 1987, Sweeny and Newbold 2014	Designing Stable Buffer Strips for Stream Protection

Shaw 2018	Mixed - Roses, willow, dogwood, Douglas fir			Agricultural Watercourses in Whatcom County, WA	Percentages were the average of the mean % effective shade for both study years (2014 and 2015)		The Effectiveness of Forested and Hedgerow Riparian Buffers
Benedict and Shaw 2012		4-13 ft		Agricultural Watercourses in Whatcom County, WA	Measured air temperature over the stream, found that all buffers significantly lower temperature over streams but there was no significant difference between any of the buffer widths in temperature control.		Agricultural Waterway Buffer Study
Groom et al. 2011	Mixed	Avg. 2 m	Avg. 6%	Oregon Coastal Range, Forestry study	Data taken from Sweeney and Newbold; 31 m buffer provides 92% of the shade that a 52 m buffer does. 52 m buffer = no temp. increase compared to fully forested while 31 m avg. ~0.7° C increase.	Sweeney and Newbold 2014	Response of western Oregon stream temperature to contemporary forest management
Stohr et al. 2011	Mature Riparian Vegetation	Middle fork and Mainstem Snoqualmie River		Snoqualmie River, WA	Temperature indicated 7-DADMax at critical flow and meteorological conditions during July/August in mainstem Snoqualmie River. There is assumed to be no microclimate effect with the narrower buffer. Mature 180ft buffer corridor could decrease water temp by 1.9°C (2.8°C including tributaries and microclimate) compared to current conditions. Compared to a 180ft buffer, a 79ft buffer would result in be a 5% reduction in effective shade and a 0.4°C increase in temperature.		Snoqualmie River Basin Temperature Total Maximum Daily Load Water Quality Improvement Report and Implementation Plan
Gomi et al. 2006	Mixed	0.5-4.0; all streams (N-S orientation)	0.02-0.11	University of British Columbia Malcolm Knapp Research Forest	Forestry study examining buffers effects on mitigating stream warming. Found 10 m buffers to be sufficient enough to not cause significant warming in relation to non-buffered sites and 30 m buffered sites were more "subdued," controlling all stream temps within 2°C of fully forested sites.		Headwater stream temperature response to clear-cut harvesting with different riparian treatments, coastal British Columbia
Jones et al. 2006	Forest	2nd-5th order streams		Northeastern corner of GA in the Appalachian Mountains	Study assessing 15 and 30 m buffers' likelihood of protecting brook trout stream temperatures in GA. 15 m buffers keep temperatures from rising more than 2.3°C. 30 m buffers = no temperature increase	Sweeney and Newbold 2014	The Identification and Management of Significant Fish and Wildlife Resources in Southern Coastal Maine
Wilkerson et al. 2006	Forest	1.9-4.2 m - width	5-18%	Western Maine	36 ft buffer <1.5°C and 75 ft buffer = not temperature increase as compared to before harvest conditions		The effectiveness of different buffer widths for protecting headwater stream temperature in Maine
Sweeny and Newbold 2014					Litt. Review making recommendations off of all the information compiled - not a meta-analysis; >20 m to keep temp within 2˚C of full-forested; >30 m for full temp protection		Streamside Forest Buffer Width Needed to Protect Stream Water Quality, Habitat, and organisms



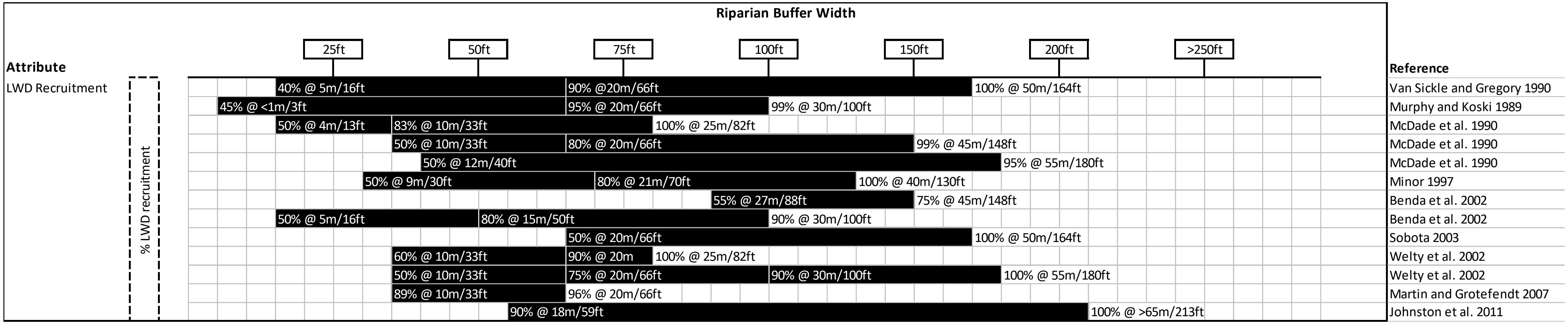
Reference	Riparian Cover Type	Stream order, Width, or Catchment Size	Landscape	Comments	Citation Title
Davies et al. 2004					Managing high in-stream temperatures using riparian vegetation
Barton et al. 1985			Southern Ontario trout streams	Forest upstream needs to be at least 80% forested/buffered to maintain these temperatures	Dimensions of Riparian Buffer Strips Required to Maintain Trout Habitat in Southern Ontario Streams
Rutherford et al. 2004	Forest	2nd order streams; width 1-2 m; depth 5-15 cm	New Zealand	Modeled based on their research into how long it would take for the stream to reach it's original equilibrium with a continuous buffer. In other words, how long will it take a non-buffered stream to recover once it is within a fully buffered area.	Effects of Patchy Shade on Stream Water Temperature: How Quickly do Small Streams Heat and Cool?

Function: Riparian Corridor Microclimate



Reference	Riparian Cover Type	Stream order, Width, or Catchment Size	Gradient or Slope	Landscape	Comments	Cited in	Citation Title
Rykken et al. 2007	Forest			Old Growth Forest	Protects "stream-center" microclimate	Sweeny and Newbold 2014	Headwater Riparian Microclimate Patterns under Alternative Forest Management Treatments
Anderson et al. 2007	Forest			Second growth forest, western Oregon	Max daily air temp inc. <1°C above stream center, daily minimum relative humidity <5% lower		Riparian Buffer and Density Management Influences on Microclimate of Young Headwater Forests of Western Oregon
Moore et al. 2005	Forest				a review; SPTH = site potential tree height;		Riparian Microclimate and Stream Temperature Response to Forest Harvesting: A Review
Olson et al. 2007	Forest				A review, 49-98 ft for some water quality and aquatic habitat and 131-328 ft for aquatic/riparian-dependent species		Biodiversity Management Approaches for Stream-Riparian Areas: Perspectives for Pacific Northwest Headwater Forests, Microclimates, and Amphibians
Reeves et al. 2016	Forest				A review; SPTH = site potential tree height; 1 SPTH is the most protective	Reeves et al. 2018	An Initial Evaluation of Potential Options for Managing Riparian Reserved for the Aquatic Conservation Strategy of the Northwest Forest Plan
Brosofske et al. 1997	Conifers	width 2-4 m	steep slopes, western slope of Cascades		Goal of protecting entirety of microclimate in riparian area (minimum 30-m [air and soil temp] up to 62-m [surface temp and humidity] into riparian area from stream)	Hansen 2010; Parkyn 2000	Harvesting Effects on Microclimatic Gradients from Small Streams to Uplands in Western Washington

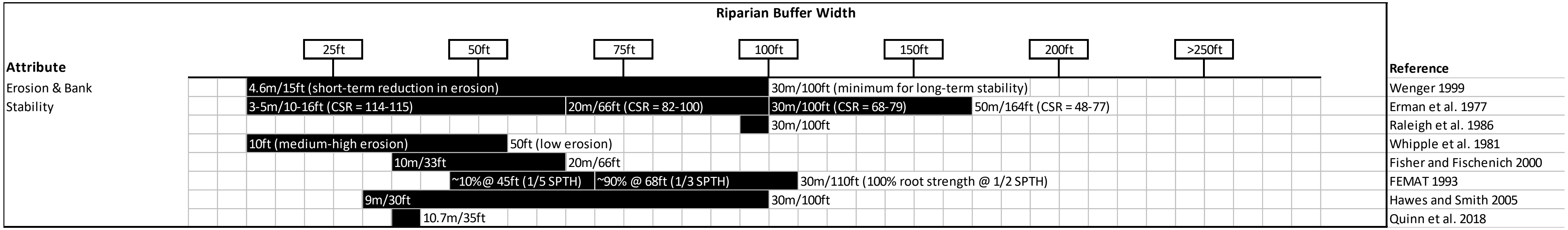
Function: Large Wood (Recruitment and Retention)



Reference	Riparian Cover Type	Stream order, Width, or Catchment Size	Gradient or Slope	Landscape	Comments	Cited in	Citation Title
Van Sickle and Gregory 1990	Mixed (hardwoods and conifers)	3rd order (12-m)	13%	Mack Creek Andrews Experimental Forest (Western Oregon Cascade Mountains)	Model applied to Mack Creek	Reeves et al. 2018, Spies et al. 2013, Gregory et al. 2003, Welty et al. 2002	Modeling inputs of large woody debris to streams from falling trees.
Murphy and Koski 1989	Coniferous	2nd to 5th order (8.2 - 31.4-m)	0.4% - 2.9%	Southeast Alaska	32 stream reaches	Spies et al. 2013, Gregory et al. 2003	Input and Depletion of Woody Debris in Alaska Streams and Implications for Streamside Management
McDade et al. 1990	Hardwood	1st - 3rd order		Central-western Cascades and Coastal Oregon	Empirical and modelled	Reeves et al. 2018, Spies et al. 2013, Gregory et al. 2003	Source distances for coarse woody debris entering small streams in western Oregon and Washington
McDade et al. 1990	Conifers	1st - 3rd order		Central-western Cascades and Coastal Oregon	Empirical and modelled	Reeves et al. 2018, Spies et al. 2013, Gregory et al. 2003	Source distances for coarse woody debris entering small streams in western Oregon and Washington
McDade et al. 1990	Old-Growth	1st - 3rd order		Central-western Cascades and Coastal Oregon	Empirical and modelled	Reeves et al. 2018, Spies et al. 2013, Gregory et al. 2003	Source distances for coarse woody debris entering small streams in western Oregon and Washington
Minor 1997	Conifers		Hill Slope: 0%		Modelled for a test Douglas Fir riparian polygon; Only 0% hillslope reported here	Gregory et al. 2003	Estimating large woody debris recruitment from adjacent riparian areas

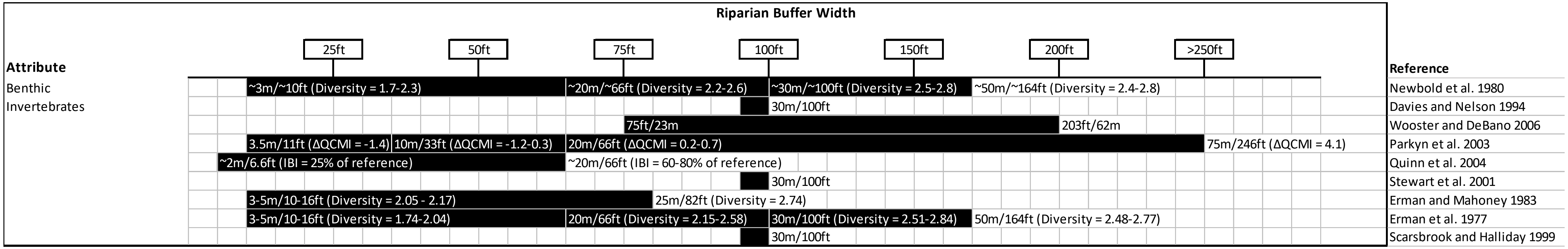
Benda et al. 2002	Conifers	17-m	1%	Little Lost Man Creek Northern California	Old growth; primarily bank erosion		Recruitment of wood to streams in old-growth and second-growth redwood forests, northern California, U.S.A.
Benda et al. 2002	Conifers	14-m	4%	Prairie Creek Northern California	Old growth; primarily land sliding and then bank erosion		Recruitment of wood to streams in old-growth and second-growth redwood forests, northern California, U.S.A.
Sobota 2003	Conifers	2nd to 4th order (avg. 8.7-m)	1-13% (avg. 7%)	Cascade Mountain Crest and Interior Columbia Basin	21 sites; empirical and modelled		Fall directions and breakage of riparian trees along streams in the Pacific Northwest
Welty et al. 2002	Hardwood	5-25-m	<6%	Pacific Northwest	Model simulation specific to PNW (uses McDade et al. 1990 function for distance)	Spies et al. 2013, Gregory et al. 2003	Riparian aquatic interaction simulator (RAIS): a model of riparian forest dynamics for the generation of large woody debris and shade
Welty et al. 2002	Conifers	5-25-m	<6%	Pacific Northwest	Model simulation specific to PNW (uses McDade et al. 1990 function for distance)	Spies et al. 2013, Gregory et al. 2003	Riparian aquatic interaction simulator (RAIS): a model of riparian forest dynamics for the generation of large woody debris and shade
Martin and Grotefendt 2007	Conifers	5-30-m	<2% to >6%	Southeast Alaska	Logged compared to Reference		Stand mortality in buffer strips and the supply of woody debris to streams in Southeast Alaska
Johnston et al. 2011	Conifers	1-17-m	1-20%	Forest Lands southern British Columbia	51 stream reaches in undisturbed mature or old-growth forests		Mechanisms and source distances for the input of large woody debris to forested streams in British Columbia, Canada

Function: Erosion and Bank Stability



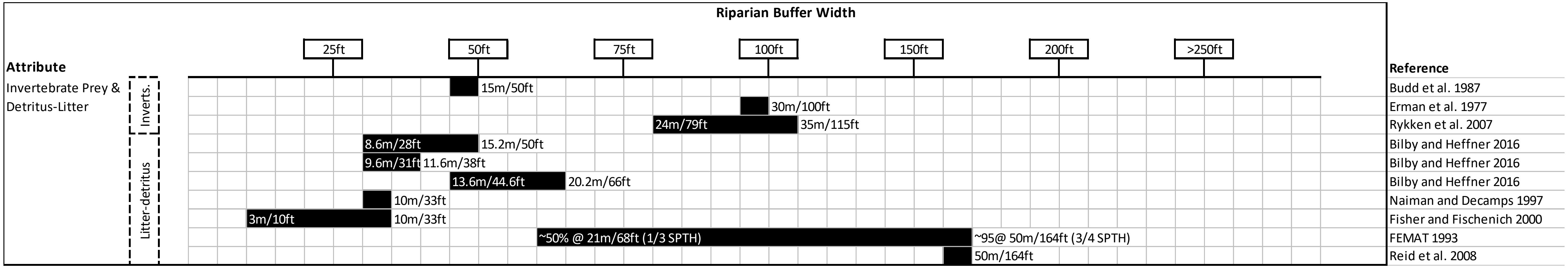
Reference	Riparian Cover Type	Stream order, Width, or Catchment Size	Landscape	Comments	Cited in	Citation Title
Wenger 1999				Review article; short-term reduction in erosion (4.6 m) & minimum for long-term bank stability (30-m); Buffer width should be wide enough to permit channel migration		A Review of the Scientific Literature on Riparian Buffer Width, Extent and Vegetation
Erman et al. 1977	Mixed Forest		Forested Streams Northern California	CSR = Channel stability rating (higher = more instable); Channel Stability Rating for narrow (3 m, 5 m, 20 m) and wide buffers (30 m, 50 m) reported (Table 2)		Evaluation of Streamside Bufferstrips for Protecting Aquatic Organisms
Raleigh et al. 1986				"30 m on each side of the stream, 80% of which is either well vegetated or has stable rocky streambanks, provides adequate erosion control and maintains undercut stream banks"; based on percent fines in spawning gravels; To protect cutthroat, rainbow and chinook		Habitat Suitability Index Models: Chinook Salmon
Whipple et al. 1981		0.12-9.40 mi^2	Piedmont areas of New Jersey	Urbanized areas; erosion rarely occurred when buffers were >50 ft; good buffers >50 ft, poor buffers <10 ft, moderate >10 ft & <50 ft		Erosion Potential of Streams in Urbanizing Areas
Fisher and Fischenich 2000	Woody Vegetation			Review article; stream bank stabilization btw 10-20 m; highlights importance of width, vegetation assemblage, layout, and length	Hansen 2010; Parkyn 2000	Design Recommendations for Riparian Corridors and Vegetated Buffer Strips
FEMAT 1993				Cite Burroughs and Thomas 1977, Wu et al. 1986 for root strength determination; SPTH = site potential tree height; Site potential tree height for Douglas Fir in the Snoqualmie is ~225 ft; half tree crown diameter is extent to where roots affects soil stability		Forest ecosystem management: an ecological, economic, and social assessment
Hawes and Smith 2005				Review article; width to prevent most erosion		Riparian Buffer Zones: Functions and Recommended Widths
Quinn et al. 2018			Literature Review	Review article: based on root radius of Douglas Fir (citing Roeringe t al. 2003); in undisturbed old-growth riparian forest, full contribution of root strength to streambank		Riparian Ecosystems, Volume 1: Science Synthesis and Management Implications

Function: Invertebrate Prey and Litter-Detritus Inputs



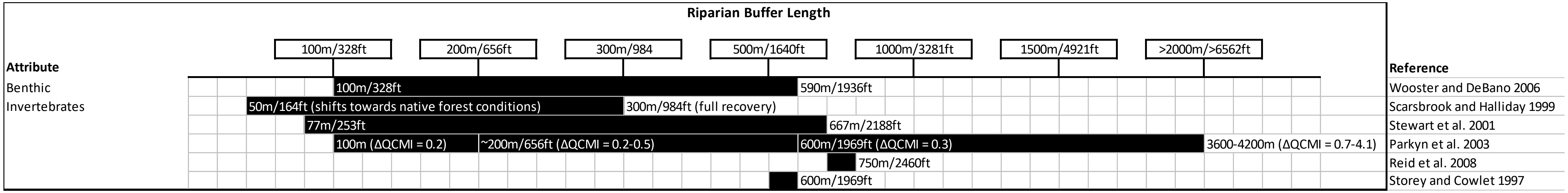
Reference	Riparian Cover Type	Stream order, Width, or Catchment Size	Gradient or Slope	Landscape	Comments	Cited in	Citation Title
Newbold et al. 1980	Mixed (conifer dominant)	1st - 3rd order (0.28 - 45k-m^2)		Northern California Forested Streams	Shannon Diversity reported; Increase in benthic invertebrate diversity with an increase in buffer width; 57 stations in 50 streams	Sweeny and Newbold 2014, Gregory et al. 1987	Effects of Logging on Macroinvertebrates in Streams With and Without Buffer Strips
Davies and Nelson 1994	Eucalyptus Forests	2.5 - 40.7 km^2		Forest streams Tasmania Australia	84 sites across 34 streams; <30m = 80% decrease in macroinvertebrate abundance	Sweeny and Newbold 2014	Relationships between Riparian Buffer Widths and the Effects of Logging on Stream Habitat, Invertebrate Community Composition and Fish Abundance
Wooster and DeBano 2006	Tree patches	2nd to 3rd order	1.1-3.2%	Small Streams in Northeastern Oregon Croplands	12 sites; only observed differences in taxa richness and emphasizes importance of buffer length		Effects of Woody Riparian Patches on Croplands on Stream Macroinvertebrates
Parkyn et al. 2003	Tree patches	1.4-8.1 m	0.11-3.27%	Agricultural Landscapes New Zealand	9 buffer sites; QCMI = quantitative macroinvertebrate community index; ΔQCMI = change between buffer and control; changes in invertebrate communities related to buffer width, length, substrate, and daily mean temperature	Parkyn et al. 2004	Planted Riparian Buffer Zones in New Zealand: do they live up to expectations?
Quinn et al. 2004	Pine Trees	0.2-2.4 km^2	0.6-5.8°	Coastal Catchments in New Zealand	28 stream sites; IBI (Index of Biological Integrity); supported stream invertebrate communities similar to native or mature plantation forest	Parkyn et al. 2004	Riparian buffers mitigate effects of pine plantation logging on New Zealand streams
Stewart et al. 2001		9-71 km^2	Low Gradient	Agricultural Watersheds in Eastern Wisconsin	38 streams; loamy to clayey ground moraine; percent EPT species increased with percent forest cover		Influences of Watershed, Riparian-Corridor, and Reach-Scale Characteristics on Aquatic Biota in Agricultural Watersheds

Erman and Mahoney 1983	Mixed Forest	0.33-1.24 km^2		Forested Streams Northern California	Shannon Diversity reported; increase in benthic invertebrate diversity with an increase in buffer width; invertebrate diversity across narrow buffers (<30-m) lower than controls (>30-m)		Recovery After Logging In Streams With and Without Buffer Strips in Northern California
Erman et al. 1977	Mixed Forest			Forested Streams Northern California	Shannon Diversity reported for narrow (3-m, 5-m, 20-m, 22-m) and wide buffers (30-m, 50-m, 60-m) (Table 2 & 5); Increase in benthic invertebrate diversity with an increase in buffer width	Erman and Mahoney 1983, Gregory et al. 1987	Evaluation of Streamside Bufferstrips for Protecting Aquatic Organisms
Scarsbrook and Halliday 1999	Deciduous	1st and 2nd order	1.01-13.94	Pasture Streams in New Zealand	Highlighting the importance of length over width		Transition from pasture to native forest land-use along stream continua: effects on stream ecosystems and implications for restoration



Reference	Riparian Cover Type	Stream order, Width, or Catchment Size	Gradient or Slope	Landscape	Comments	Cited in	Citation Title
Budd et al. 1987	Mixed Forest		15-40% & >40%	Bear Creek watershed, King County	Invertebrate prey...primarily through sediment control, stream structure, temp		Stream Corridor Management in the Pacific Northwest: I. Determination of Stream-Corridor Widths
Erman et al. 1977	Mixed Forest			Forested Streams Northern California	Shannon Diversity reported; Increase in benthic invertebrate diversity with an increase in buffer width	Erman and Mahoney 1983, Gregory et al. 1987	Evaluation of Streamside Bufferstrips for Protecting Aquatic Organisms
Rykken et al. 2007	Conifers	1st and 2nd order		Willamette National Forest in Oregon	15 stream sites; Microclimate needed to support aquatic insect adult stages		Headwater Riparian Microclimate Patterns under Alternative Forest Management Treatments
Bilby and Heffner 2016	Young & Mature Conifer			Cascade Mountain Western Washington	Buffer width (28-50 ft) to capture 95% of litter (canopy radius + delivery area)		Factors Influencing Litter Delivery to Streams
Bilby and Heffner 2016	Deciduous			Cascade Mountain Western Washington	Buffer width (28-50 ft) to capture 95% of litter (canopy radius + delivery area)		Factors Influencing Litter Delivery to Streams
Bilby and Heffner 2016	Mixed			Cascade Mountain Western Washington	Buffer width accounting for input from forest floor		Factors Influencing Litter Delivery to Streams
Naiman and Decamps 1997					Review article; riparian structure appears to be the main factor influencing litter entering streams either directly or transported laterally from the forest floor	Hansen 2010; Parkyn 2000	The Ecology of Interfaces: Riparian Zones
Fisher and Fischenich 2000					Review article; reported numbers specific to litter (leaves, twigs, branches) ; highlights importance of width, vegetation assemblage, layout, and length	Hansen 2010; Parkyn 2000	Design Recommendations for Riparian Corridors and Vegetated Buffer Strips

FEMAT 1993					SPTH = site potential tree height; Site potential tree height for Douglas Fir in the Snoqualmie is ~225 ft; percent function based on best professional judgement		Forest Ecosystem Management: an Ecological, Economic, and Social Assessment
Reid et al. 2008	Trees	3rd and 4th order		Pasture Lands in Victoria, Australia	Reserve reaches had at least 50 m of riparian buffer; reserve reaches had generally had higher allochthonous inputs than farmed reaches; percent canopy cover was positively related to CPOM as well as benthic leaf material and benthic woody material		Association of Reduced Riparian Vegetation Cover in Agricultural Landscapes with Coarse Detritus Dynamics in Lowland Streams



Reference	Riparian Cover Type	Stream order, Width, or Catchment Size	Gradient or Slope	Landscape	Comments	Cited in	Citation Title
Wooster and DeBano 2006	Tree patches	2nd to 3rd order	1.1-3.2%	Small Streams in Northeastern Oregon Croplands	12 sites; positive relationship between macroinvertebrate abundance, and diversity and riparian buffer length		Effects of Woody Riparian Patches on Croplands on Stream Macroinvertebrates
Scarsbrook and Halliday 1999	Deciduous	1st and 2nd order	1.01-13.94	Pasture Streams in New Zealand	Highlighting the importance of length over width		Transition from pasture to native forest land-use along stream continua: effects on stream ecosystems and implications for restoration
Stewart et al. 2001		9-71 km^2	Low Gradient	Agricultural Watersheds in Eastern Wisconsin	38 streams; loamy to clayey ground moraine; Insect diversity (Hilsenhoff Biotic Index) increased with percent forested stream length		Influences of Watershed, Riparian-Corridor, and Reach-Scale Characteristics on Aquatic Biota in Agricultural Watersheds
Parkyn et al. 2003	Tree patches	1.4-8.1 m	0.11-3.27%	Agricultural Landscapes New Zealand	9 buffer sites; QCMI = quantitative macroinvertebrate community index; QCMI compared to buffer length/stream width; ΔQCMI = change between buffer and control; changes in invertebrate communities related to buffer width, length, substrate, and daily mean temperature	Parkyn et al. 2004	Planted Riparian Buffer Zones in New Zealand: Do They Live up to Expectations?
Reid et al. 2008	Trees	3rd and 4th order		Pasture Lands in Victoria, Australia	Reserve reaches had at least 50 m of riparian buffer; reserve reaches had generally had higher allochthonous inputs than farmed reaches; percent canopy cover was positively related to CPOM as well as benthic leaf material and benthic woody material		Association of Reduced Riparian Vegetation Cover in Agricultural Landscapes with Coarse Detritus Dynamics in Lowland Streams
Storey and Cowlet 1997							Recovery of Three New Zealand Rural Streams as They Pass Through Native Forest Remnants