

Stream-Riparian Ecosystems
In the Puget Sound Lowland Eco-Region

A Review of Best Available Science



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*“How like fish we are; ready, nay eager, to seize upon whatever new thing some
wind of circumstance shakes down upon the river of time. And, how we rue our
haste, finding the gilded morsel to contain a hook!”*

Aldo Leopold

Introduction

The purpose of this report is to present a summary of the current level of scientific knowledge on the management of riparian ecosystems and the use of riparian buffers to protect aquatic resources, including sensitive biota and critical instream habitat. This report will also make recommendations as to how riparian zone management guidelines should be modified to make them more ecologically sound and scientifically defensible.

The National Research Council recently completed an excellent review of riparian areas (NRC, 2002) that includes a review of riparian functions and management strategies from a national perspective. The NRC reached several overarching conclusions and recommendations with regard to riparian ecosystem conservation and management. These include the following:

- Conservation of riparian functions along America's waterbodies should be a national goal. Riparian areas are part of an integrated watershed ecosystem and must not be thought of in isolation from their stream channels and shorelines. In addition, riparian areas are not immune from poor management of associated uplands.
- Riparian zones, in proportion to their area within a watershed, perform more biologically productive and critical functions than do upland areas. Because they are located at the convergence of terrestrial and aquatic ecosystems, riparian zones are often biological diversity “hot-spots” and/or highly productive areas.
- Riparian areas have adapted to natural hydrologic disturbance regime. Historical and current land-use practices have a significant impact on hydrologic, geomorphic, and biological structure and function of riparian ecosystems.
- Protection should be the goal for riparian areas in the best ecological condition, while restoration is needed for degraded riparian areas. Degraded riparian areas should be prioritized for restoration based on their potential ecological value.
- Patience and persistence in riparian management is needed. The overall restoration and protection program should be a long-term, comprehensive effort.

The objective of this report is to provide sufficient information, such that natural resource managers can properly identify the boundaries of the stream-riparian ecosystem and make sound decisions on the appropriate configuration of the riparian management zone and associated buffers. Buffer criteria, sensitive area ordinances, and land-use regulations designed to protect aquatic resources should be based on *best-available science*. Best available science (BAS) is defined by Washington State as research conducted by qualified individuals using documented methodologies that leads to verifiable results and conclusions. The goal of including best available science is to ensure that scientific information is considered by decision-makers that develop

policies and regulations that impact natural resources. The underlying goal of this report is the conservation of our valuable aquatic resources, including native biota (e.g. salmonids). In addition, the information presented here should provide a foundation for enhancement, rehabilitation, and restoration efforts within the stream-riparian ecosystem.

Background

The term “riparian” is derived from the Latin word “riparius” meaning “of or belonging to the bank of a river” (Naiman and Decamps 1997). Riparian area refers to the land and vegetation adjacent to streams, rivers, wetlands, and lakes that are influenced by perennial or intermittent water (Naiman and Bilby, 1998). Riparian areas are dynamic biological and physical systems that act as the interface between terrestrial and aquatic ecosystems (Likens and bormann, 1974;Gregory et al. 1991; Naiman and Decamps 1997; Naiman and Bilby, 1998; Naiman et al., 2000). The NRC (2002) defines riparian areas as follows:

Riparian areas are transitional zones between terrestrial and aquatic ecosystems and are distinguished by gradients in biophysical conditions, ecological processes, and biota. They are areas through which surface and subsurface hydrology connect waterbodies with their adjacent uplands. They include those portions of terrestrial ecosystems that significantly influence exchanges of energy and matter with aquatic ecosystems. Riparian areas are found adjacent to perennial, intermittent, and ephemeral streams, lakes, estuaries, and marine shorelines.

Because of the ecological functions they provide, riparian areas can be considered as “zones of influence” between terrestrial and aquatic ecosystems (NRC, 2002). Another way of characterizing riparian areas is to compare and contrast them with adjacent aquatic (i.e. streams, wetlands, etc.) and terrestrial (upland) areas. Riparian areas can include portions of the adjacent upland or aquatic environments. For example, many river riparian corridors include off-channel wetlands and forest terraces, as well as floodplain areas. This is also true in an estuarine or nearshore setting where a riparian zone may include extensive salt marshes as well as forested bluffs. Because of the close ecological relationship that exists between the aquatic ecosystem and the riparian zone, the combined system is often referred to as the *stream-riparian ecosystem* (see Figures 1, 2, 3, & 4).

The term “riparian buffer” is often used in a general sense to describe the vegetated area alongside a river, stream, lake, or wetland. This area, in a natural setting, might better be called the riparian zone, riparian forest, or streamside forest. The term “buffer” is typically used in a management connotation and should only be used to denote an area set aside and managed to protect a natural area from the effects of surrounding land-use or human activities. Buffers can be forested areas, landscaped areas, or even grassy swales or vegetated “filter-strips” (VFS) designed for water quality treatment. In this respect, buffers are often designed to perform a specific function or set of functions, such a filtering pollutants from surface runoff or providing

shade for a water body. For example, a VFS composed of grass can be designed to filter pollutants from parking lot runoff prior to discharging this water into a nearby forested-wetland, stream corridor, or nearshore area. It is a generally accepted principle that riparian buffers should be designed based on the resource to be protected and in proportion to the potential threat of the surrounding human activities or land-use. Based on this concept, the more sensitive or valuable the natural resource being “buffered”, the more protective the buffer should be. By the same token, the more intense the surrounding land-use or the more potential for damage to the resource, the more protection the buffer should provide. Buffers should not be confused with the natural riparian zone, which is an integral part of the natural ecosystem. The term “riparian management zone” (RMZ) may be used to describe the combination of the stream-riparian ecosystem and the buffer zone.

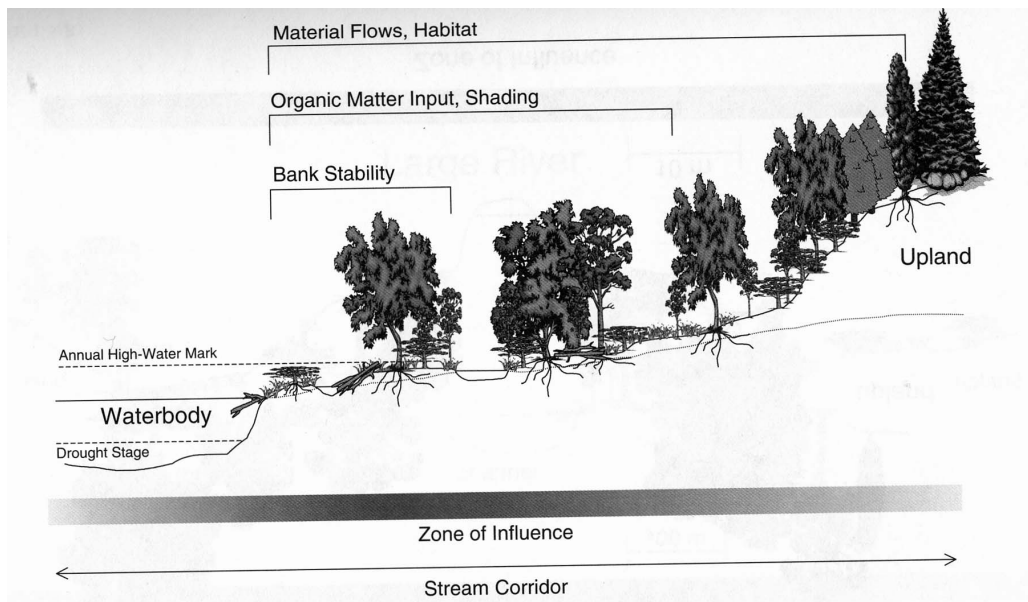


Figure 1: Generic schematic view of a stream-riparian ecosystem (NRC, 2002).

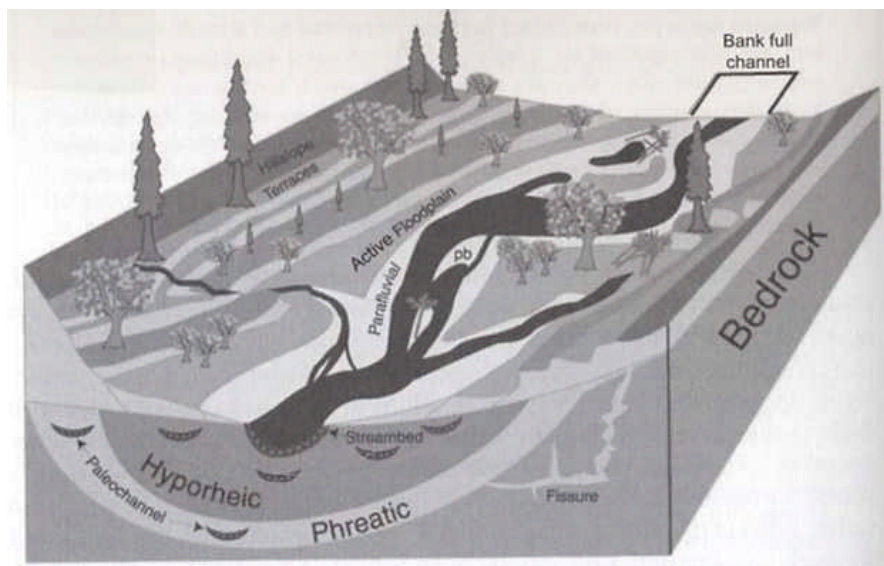


Figure 2: Idealized view of a stream corridor showing the longitudinal, lateral, and vertical dimensions of the stream-riparian ecosystem (Stanford and Ward, 1993).

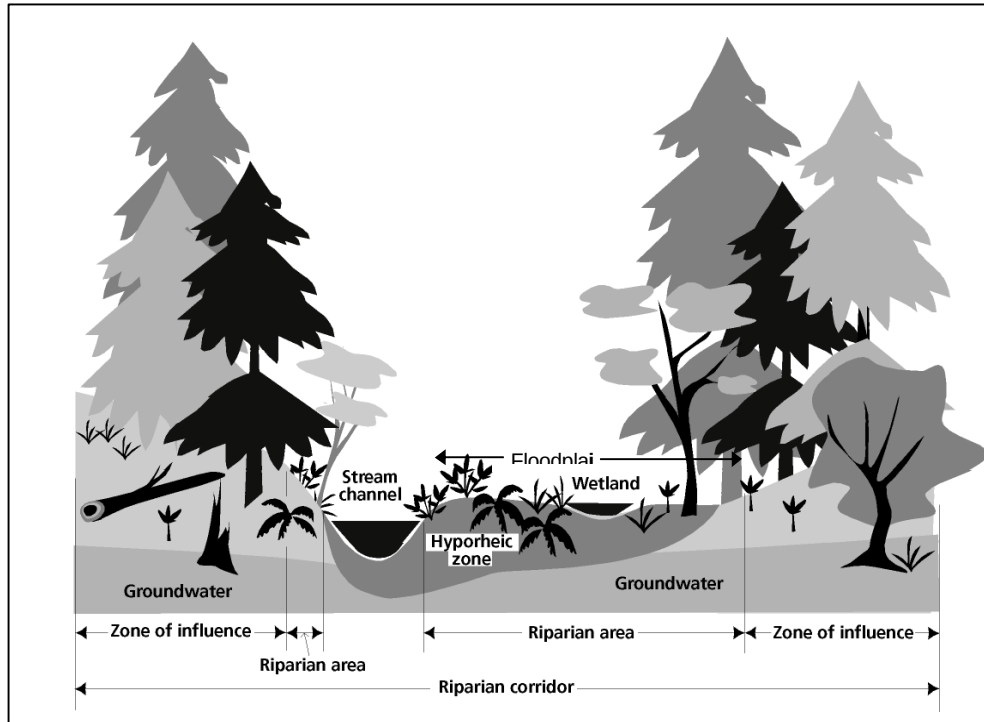
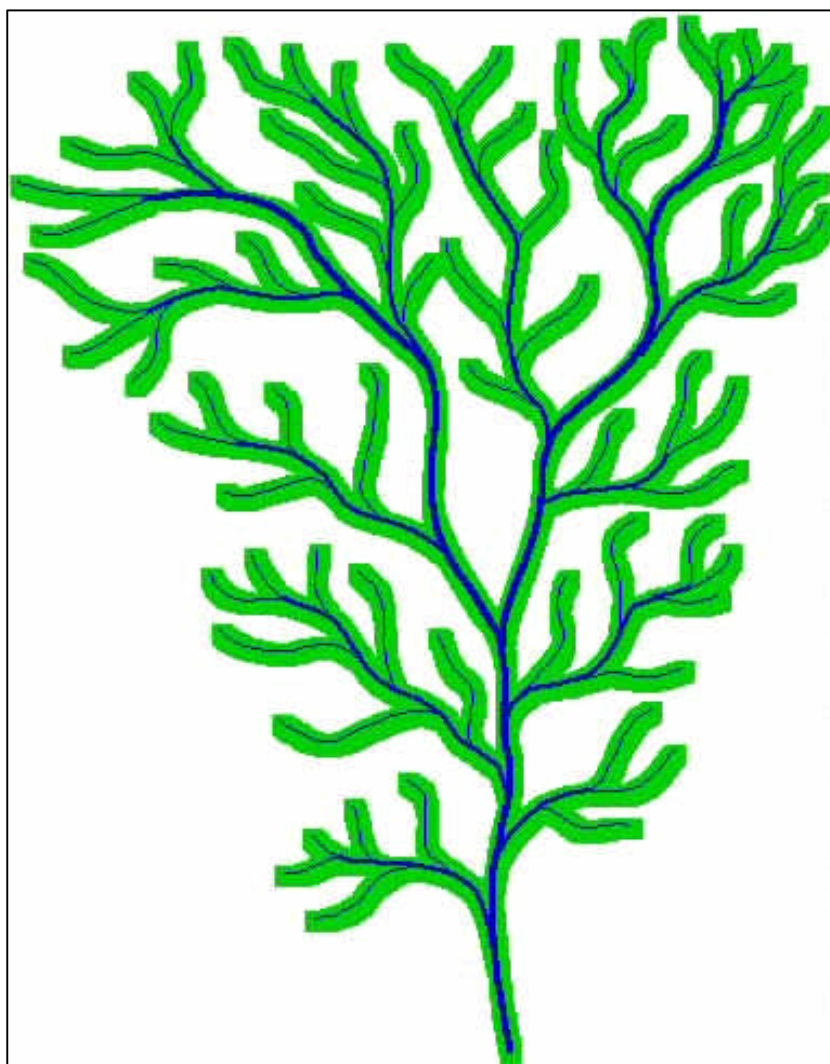


Figure 3: Typical Stream-Riparian Ecosystem in the PNW.



Figure 4: Typical Riparian Zone in the Puget Sound Lowland Eco-Region**Stream-Riparian Ecosystem Structure**

Due to natural landscape features and the complexity of stream-riparian ecosystems, the spatial extent or width of the riparian zone is often difficult to delineate. Naiman and others (1993) describe the riparian area as encompassing “the stream channel between the low and high water marks and that portion of the terrestrial landscape from the high water mark toward the upland where vegetation may be influenced by elevated water tables or flooding and the ability of the soils to hold water.” Gregory et al., (1991) further describes riparian areas as “three-dimensional zones of direct interaction between terrestrial and aquatic ecosystems,” the boundaries of which “extend outward to the limits of flooding and upward into the canopy of streamside vegetation” (see Figures 1, 2, & 3). The transition zone between the purely aquatic ecosystem and upland, terrestrial habitat is commonly referred to as the *riparian ecotone* (Naiman et al., 1993). The term ecotone implies a zone of transition from one type of ecosystem (terrestrial) ecosystem to another (aquatic). It also implies that this zone is ecologically



important to both “linked” ecosystems (Gregory et al., 1991; Naiman et al. 1993; Naiman and Bilby, 1998). In the PNW, the riparian corridor typically refers to the nearly continuous vegetated area that surrounds the stream channel network (Naiman and Bilby, 1998). See Figure 5 for an illustration of the riparian corridor concept.

The riparian corridor may contain stream-associated or *riparian wetlands*. Wetlands may occur adjacent to stream channels and within the *floodplain* of the stream-riparian corridor (see Figure 6). They are defined by hydrology, *hydric soils*, and vegetation that depend on frequent and recurrent shallow inundation or saturation at, or near, the soil surface. Plant communities in wetlands are dominated by species

Figure 5: Illustration of Riparian Corridor Concept.

adapted to survive and grow under periods of inundation and anaerobic soil conditions. Because wetlands may occur within riparian areas, the scientific literature often treats wetlands and riparian areas as synonymous to simplify discussion. This is a generalization that may not apply to every riparian zone, depending on the eco-region under consideration.

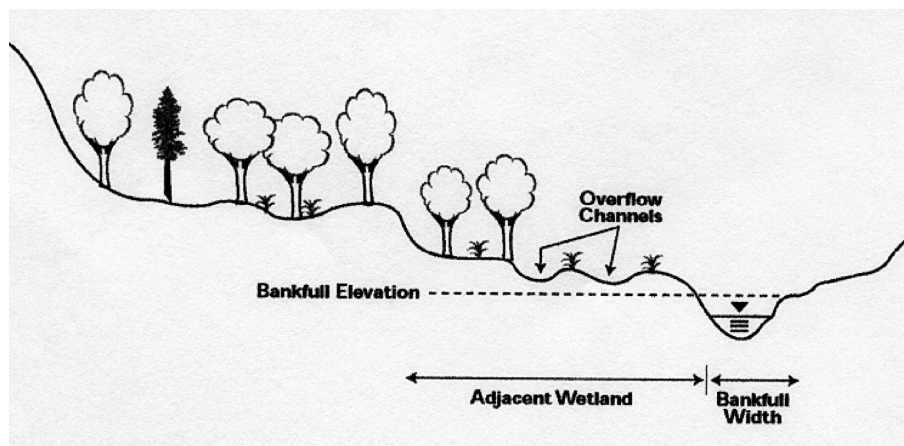


Figure 6: Typical Off-Channel Wetlands and Floodplain Area.

There are many types of wetlands that could be found within or adjacent to riparian areas, from those dominated by open water, to forested wetlands in which standing water is rarely present for an extended period of time. Common wetland types include marshes, bogs, fens, wet meadows, shrub swamps, wooded swamps, and beaver ponds.

Wetlands perform a number of diverse and often critical ecological functions that also benefit the human-dominated environment. These functions include floodwater storage and retention, groundwater recharge, and water filtration. In addition to those functions that directly benefit humans, wetlands also maintain stream baseflow during dry periods, enhance natural water quality, and provide habitat for a myriad of fish, amphibians, birds, and wildlife (Richter and Azous, 2000). Wetlands, especially riparian wetlands, also provide a broad range of recreational and aesthetic opportunities for surrounding communities. The specific functions that wetlands provide are dependent on their natural characteristics, their position in the watershed (i.e. headwater, off-channel, floodplain, etc.), and their proximity to human activities or land-uses that have the potential to degrade their functional capacity. The cumulative impacts of urbanization have been shown to be especially damaging to wetland hydrology and water quality, which then impacts habitat value and other functions (Azous and Horner, 2000). As is the case with streams, riparian buffers are often used to protect wetlands. It is generally understood that the more sensitive or critical the wetland area is, the wider the buffer needed to protect it (Castelle et al., 1994). In addition, the more potentially damaging the surrounding land-use, the larger the buffer should be (Castelle et al., 1994). Unfortunately, this scientific principle is often ignored in favor of the "one-size-fits-all" solution to wetland buffers, which is generally not effective (Castelle et al., 1994; McMillan, 2000; Thom et al., 2001).

In many rivers and larger streams, the *floodplain* is an integral part of the stream-riparian ecosystem (see Figures 6 & 7). The floodplain is generally a relatively flat, low-lying area adjacent to the main channel of a river or stream. Floods are part of the natural hydrologic regime and result in over-bank flows that temporarily inundate the low-lying areas adjacent to the stream or river. Flooding can also result in streambank erosion and channel migration. The flood-induced processes of erosion and subsequent deposition are essential to the creation and maintenance of many riparian areas, especially those in the lower reaches of large streams and rivers. Flooding also results in so-called “flood hazard zones” where flooding events can threaten private property or human life. These flood hazard zones are usually regulated to protect people and property. However, in some cases structural measures are used to facilitate human activities within the floodplain or flood hazard zone. Dikes and levees are the most common of these measures. In most cases, these measures are only partially effective in preventing flooding and the best method of protection is to avoid human activity within the floodplain (Poff et al., 1997; Naiman and Bilby, 1998; Bolton and Shellberg, 2001). Minimizing floodplain modification and development within the flood hazard zone, is generally the best management strategy to both ensure human safety and support ecological function. Based on this understanding, the floodplain should be considered a part of the stream-riparian corridor.

The typical RMZ should include the entire extent of the floodplain, an integral part of the riparian corridor in low-gradient streams and rivers. As was defined earlier, a *floodplain* is defined as the low gradient area adjacent to the stream or river channel that becomes inundated with over-bank flows during storm events (see Figure 7). This area begins at the edge of the bankfull channel and typically receives over-bank flows during larger storm events. The frequency of inundation depends on the size of the stormflow event and the topography of the floodplain. The so-called “100-year flood” is often used as the defining flood-flow for purposes of delineating the nominal extent of the floodplain (Dunne and Leopold, 1977). According to Bayley (1995), the floodplain is “that part of the river floodplain ecosystem that is regularly flooded and dried, and it represents a type of wetland.” Well-developed, complex floodplains are characteristic in large river systems where there are long periods of seasonal flooding, oxbow lakes, wetlands, a diverse forest community and moist soils (Gregory et al., 1991; Naiman et al., 1992; Poff et al., 1997; Naiman and Bilby, 1998). Flood events of different size and frequency play a vital role in maintaining a diversity of riparian plant species and aquatic habitat (Junk et al. 1989; Poff et al., 1997; Swanson et al. 1998). Biological productivity is often enhanced in floodplains because sediment and nutrients are deposited during the advance and retreat of floodwaters (Bayley, 1995). Small floods transport fine sediments and organic matter downstream and laterally, and help create and maintain the stream-riparian ecosystem. Intermediate and large floods create opportunities for larger organic material input and allow for the nourishment and establishment of pioneer plant species (Gregory et al., 1991; Naiman et al., 1992; Poff et al., 1997; Naiman and Bilby, 1998; Naiman et al., 2000). Although floodplain area does not necessarily delineate the CMZ, they often do overlap and can be useful in defining the limits of channel migration for most streams.

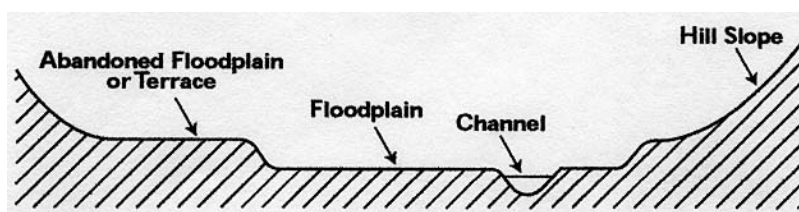


Figure 7: Typical Floodplain Area.

Because of the dynamic equilibrium of stream systems, in addition to a floodplain area, many streams may also have a characteristic *channel migration zone* (CMZ). Channel migration is the process of a river or stream channel moving laterally across or within its floodplain. During this process, the stream erodes one bank while depositing sediment along the other, resulting in a net lateral movement of the channel. These processes typically occur gradually, often resulting in significant channel movement over a long period of time. Ongoing lateral channel migration typically results in the development of meander bends, which themselves often migrate downstream over time. Channel migration can also occur abruptly in a process called *avulsion*, which is more common in large rivers than small streams (Dunne and Leopold, 1977).

Due to natural topography and geomorphology, some streams are constrained to narrow valleys or ravines. These streams typically have a smaller (or non-existent) floodplain and a constrained CMZ. For the purposes of designating riparian buffers, streams prone to channel migration and streams with a well-defined floodplain need to be identified. The floodplain or CMZ can then be used as the starting point for RMZ delineation. Streams within narrow valleys or ravines may not move laterally and thus do not have a CMZ. These streams should be delineated by their bankfull width (BFW). In these streams the edge of the bankfull channel typically corresponds to the start of the active floodplain, but may not. The floodplain itself may also be relatively narrow, depending on valley form and topographic constraints. Identification of the BFW can be made using bank shape or slope breaks, sediment deposition and scour patterns, or based on streambank vegetation. The bankfull flow is that streamflow (approximated by the flow of the 2-year flood recurrence interval) which has the capability of moving a significant amount of sediment or bedload (Dunne and Leopold, 1977). Therefore, streams within ravines or those with no CMZ or floodplain should have their riparian buffers measured from the edge of the bankfull channel. In most cases, the typical RMZ for ravine streams will encompass the ravine area up to and including the steep slopes that form the ravine. Often the driving force behind establishing buffers for steep slopes is to prevent geo-hazards such as landslides.

As was discussed, many streams have a *channel migration zone* (CMZ) in reaches where the channel is not constrained by narrow valleys or ravines (see Figure 8). Over time, streams move back and forth across the valley floor in a process called lateral migration. The CMZ is the lateral extent of likely channel movement over the past 100-year period or where aquatic or wetland habitat could possibly exist at some time in the future (Pollock and Kennard, 1998; WA DNR, 1999; Naiman et al., 2000; Bolton and

Shellberg, 2001). The CMZ usually includes the lower terraces and the toe of hill slopes adjacent to the floodplain where the stream is likely to meander (Pollock and Kennard, 1998). The CMZ delineates the area over which the channel may occupy

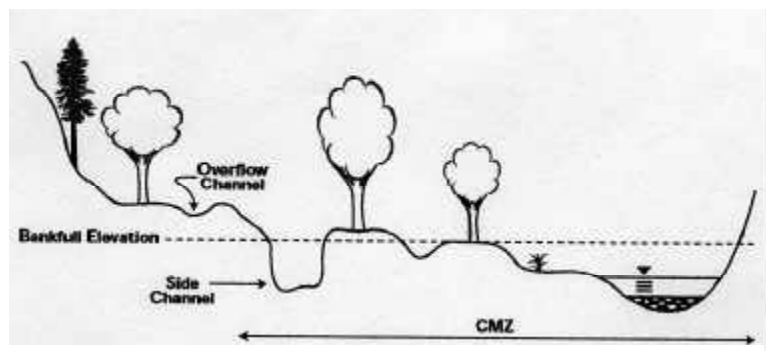


Figure 8: Typical Channel Migration Zone (CMZ).

based on its dynamic equilibrium characteristics. The CMZ can be identified using historic records, aerial photos, or field verification of paleo-channels or channel features such as braided channels, over-flow channels, progressive meandering, meander cutoffs, oxbows, side channels, or channel avulsions (Dunne and Leopold, 1977).

Consideration should also be given to the natural or historic levels of LWD found in the stream channel. Streams with abundant LWD and/or beaver activity, such as natural PNW lowland streams, often have a more active CMZ (Pollock and Kennard, 1998). Often, the 100-year floodplain delineation is used to delineate both the floodplain area and CMZ for a river or stream (Bolton and Shellberg, 2001).

The *hyporheic zone* is another critical component of the stream-riparian ecosystem. The hyporheic zone is the saturated substrata beneath a stream or river channel and under the riparian zone where groundwater and surface water mix (see Figure 9). Properties of both groundwater and surface water are blended in the hyporheic zone, significantly changing the water's chemical composition and often stimulating unique biological activity (Naiman et al. 2000). The complex mix of cobble, gravel, and sediment provide a wide range of microhabitats that vary in nutrient and oxygen content. A myriad of specialized insects and microorganisms take advantage of this habitat, some never emerging for their entire life cycle. Important biological activities (such as denitrification or the removal of excess nitrogen) take place in the hyporheic zone, mediated by specialist biota. In addition, the hyporheic zone plays an important role in aquatic food webs by storing particulate organic

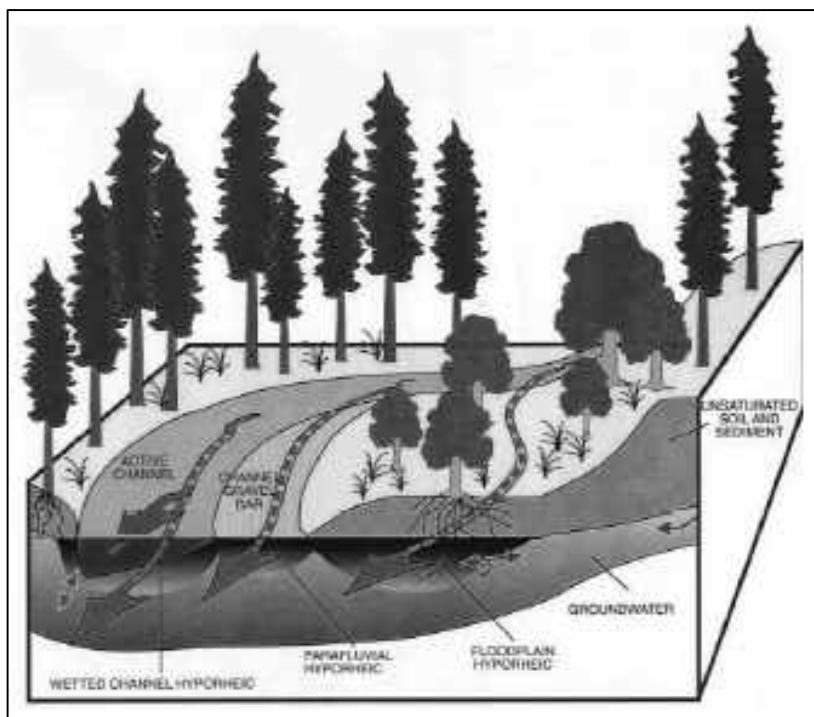


Figure 9: Hyporheic Zones in a Typical Riparian Corridor (NRC, 2002).

matter, for processing by benthic invertebrates and other instream biota.

Stream-Riparian Ecosystem Processes

Diverse stream and floodplain characteristics, as well as native plant communities are created in the riparian ecotone by the interaction of the natural hydrologic regime, geomorphic processes, and inputs of organic and inorganic material from upland areas and hillslopes within a watershed (Gregory et al., 1991; Naiman et al., 1992; Naiman et al., 2000; Rot et al., 2000).

The *hydrologic regime* refers specifically to the type of seasonal precipitation patterns, storm characteristics (rainfall intensity, storm size, etc.), rainfall-runoff relationships, water storage capacity, and surface water-groundwater interactions. Local and regional streamflow reflects the variability of the watershed hydrologic regime (Naiman et al., 1992; Poff et al., 1997; Naiman et al., 2000). Precipitation (rain or snow) is the ultimate source of all streamflow, although some precipitation may take a significant amount of time, and travel a substantial distance, before contributing to streamflow. The intensity, timing and duration of a storm event influences, in part, how quickly water reaches the stream. In addition, wetland and depressional storage, as well as groundwater pathways can influence the interaction of precipitation and instream flow. The variability of climate and land use and their influence on vegetation, soil cover and condition also affect how quickly precipitation reaches streams (Poff et al., 1997).

Streamflow quantity and timing are critical components of water supply, water quality, and the ecological integrity of river systems (Dunne and Leopold, 1977; Poff and Ward, 1989; Poff et al., 1997). Indeed streamflow, which is strongly correlated with many critical physiochemical characteristics of rivers, such as water temperature, channel geomorphology, and habitat diversity, can be considered critical to the structure and function of the stream-riparian ecosystem (Naiman et al., 2000). Streamflow typically has two basic components: stormflow and baseflow (Dunne and Leopold, 1977). Based on the timing and balance of stormflow and baseflow, three categories of streams are generally recognized: perennial, intermittent and ephemeral streams (Dunne and Leopold, 1977). Perennial streams flow year round, even during periods of no rainfall. Groundwater is a source of much of the water in the channel. Intermittent streams flow only during certain times of the year, usually during the “wet” season. Ephemeral streams flow only during or immediately after periods of rainfall, usually for only a short period of time.

The size and shape of a channel is determined by three main variables (Dunne and Leopold, 1977): discharge, the volume of water moving down a channel per unit of time; gradient, the slope of the channel; and sediment load, the amount and size of sediment being transported. When one factor changes, the others must adjust. Adjustment is reflected in seasonal changes in the slope of the water surface, the degree of sinuosity (curvature) of a stream, discharge fluctuations, and sediment load. A wide range of flow characteristics is key in the formation and maintenance of a variety of geomorphologic and instream habitat features (Dunne and Leopold, 1977).

The primary geomorphic processes that operate throughout a watershed are upland erosion, sediment transport, and sediment deposition (Naiman et al. 1992; Poff et al., 1997; Naiman et al., 2000). The hydrologic pattern within a watershed drives these geomorphic processes. The type of precipitation or disturbance, timing, frequency and magnitude of the event; runoff processes (surface and subsurface flow); gravity; wind; ice; chemical reactions; and vegetation influence the yield and rate of sediment delivery to streams. Stream channels are formed, sustained, and changed by the water, sediment and organic material they carry (see Figure 10).

Erosion and sedimentation occur naturally in a watershed and provide the sources and surfaces necessary for habitat formation for aquatic and terrestrial wildlife species (Naiman et al., 1992). A disturbance, be it natural or human-induced, is any significant change in the supply or routing of water, sediment, or woody debris that causes a measurable difference in channel structure and biological community. Natural disturbances such as floods, fire, landslides, plant diseases and insect outbreaks are an integral part of watershed dynamics (see Figure 8). These events often result in significant structural changes to the stream channel and biological communities, both in the near term and over time. A natural disturbance, such as a landslide, may destroy aquatic and terrestrial organisms. However, such an event often revitalizes an area by depositing organic material, uncovering buried organic debris, and increasing sunlight by opening forest canopies. These areas often evolve into biologically productive sites over time (Gregory et al., 1991; Naiman et al., 1992; Naiman and Bilby, 1998; Naiman et al., 2000).

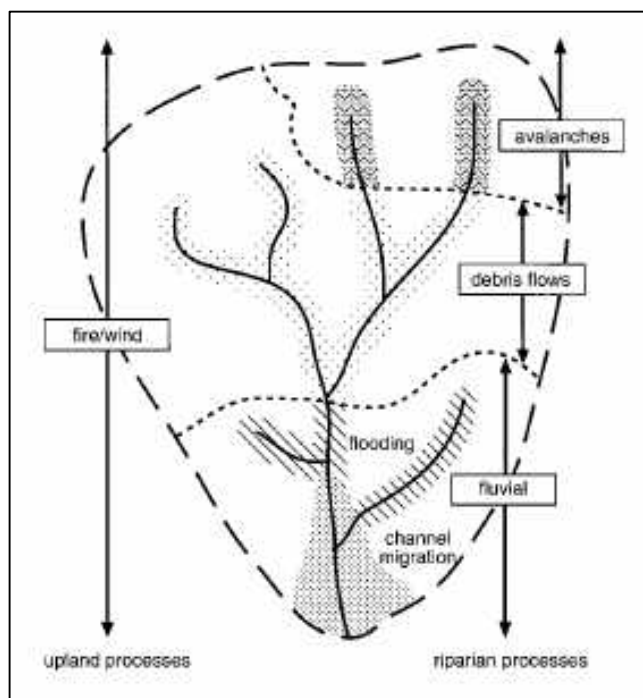


Figure 10: Typical Processes found within the Stream-Riparian Ecosystem of the PNW (Naiman et al., 2000).

Although some erosion occurs naturally, watersheds where human land-use activities dominate tend to experience a higher rate of soil erosion than that of undisturbed landscapes. Human disturbance, such as land-use practices associated with urbanization, agriculture, livestock grazing and timber harvest, contribute to this higher rate of soil erosion by altering the natural drainage basin. Many of these alterations have resulted in significant degradation and destruction of aquatic habitat. Erosion produces sediment that moves in suspension from its site of origin by air, water, or gravity. Eroded particles, regardless of size, are subject to being transported and deposited downstream. Sediment particles can range in size from fine clay to boulders. Small particles are transported more easily and may be suspended in the water column. Often only high flow events can move larger particles downstream. Sediments

are deposited within the stream channel when streamflow slows, losing the power (i.e., slope and discharge) to move sediment particles. The deposition of fine sediment can be especially damaging to aquatic ecosystems in general and salmonid spawning habitat in particular (Chapman, 1988).

As sediment, large woody debris (LWD) and other organic and inorganic materials are transported and deposited throughout a stream system, channel geo-morphologic characteristics and aquatic habitat features are formed. LWD is important because it influences the routing of water and sediment, as well as the development of channel bottom topography, including the formation and distribution of pools (Booth et al., 1996; May et al., 1997; Naiman et al., 2000). Large woody debris is also an important source of aquatic cover and acts as a surface for biological activity by aquatic organisms (Gregory et al. 1991; Naiman et al., 1992; May et al., 1997). In addition, LWD helps dissipate energy generated from streamflow, slowing erosion and sediment transport rate and retaining organic debris, making it available to organisms living there (Naiman et al., 1992). The coarse particulate organic matter (CPOM) that enters the stream along with LWD (e.g. leaves, twigs, etc.) also provide food for the base of the food-web within the stream-riparian ecosystem.

One of the most influential physical characteristics of the stream is the flow (discharge) regime. The disturbance regime in PNW streams is primarily discharge-driven. Salmonids are especially sensitive to changes in streamflow and tend to key their life cycle related movements to local discharge regimes (Stouder et al., 1997). Although a natural hydrologic regime is a necessary component of a functional stream-riparian ecosystem, it does not guarantee a healthy ecosystem if the water quality is degraded. Watershed land-use can significantly alter the hydrologic regime due to increases in impervious surface area, loss of natural forest infiltration capacity, and modification of the stream drainage network (Booth, 1990; Booth and Reinelt, 1993; Booth and Jackson, 1997; Horner and May, 1999; Horner and May, 2001; Booth et al., 2002). The resultant increase in peak discharge magnitude and frequency can have serious negative impacts on salmonids and instream habitat (May et al., 1997).

Physio-chemical water quality is a fundamental component of watersheds with high ecological integrity (Naiman and Bilby, 1998). Sediment load (suspended sediment in water) temperature, and chemical composition of water play important roles in water quality and thus the characteristics of aquatic and terrestrial communities. As was discussed in the previous section, the transport and deposition of sediment throughout a watershed are key channel and habitat forming processes. However, changes in sediment load and particle size resulting from human activities such as timber harvest, road construction, row-crop agriculture, grazing, or construction site runoff can have negative impacts on water quality and aquatic habitat. Water quality is reduced when excessive amounts of fine sediment such as silt and clay particles enter the stream and become suspended in the water column, causing water to become cloudy, or turbid. In addition, nutrients, metals, and toxic organic chemicals may attach to soil particles on land and enter the water where the pollutants either settle with the sediment or become soluble in water (Naiman and Bilby, 1998).

Physio-chemical water quality is generally taken to include temperature, dissolved oxygen (DO), suspended sediment (turbidity), nutrient levels, toxic compounds, and other pollutants. Water temperature is an important indicator of watershed health because of its controlling influence on the metabolism, development, and activity of aquatic organisms (Naiman and Bilby, 1998). Cold, well-oxygenated water is needed by many aquatic species. Shifting temperatures may have profound effects on aquatic species that can tolerate only a limited range of temperatures. Water temperature is influenced by many factors including groundwater and surface water flow, riparian vegetation (shading based on height and canopy density), incoming solar radiation, elevation, climate, stream size, water velocity and depth and turbidity.

Dissolved oxygen (DO) is a basic requirement for most aquatic species. Some species require high concentrations of DO (cold water species), while others can survive at lower levels (warm-water species). Oxygen gas readily dissolves in water, which absorbs it directly from the atmosphere. In addition, aquatic plants release oxygen to the water as a byproduct of photosynthesis. Increased temperatures reduce the amount of DO the water can hold. Natural streams generally contain an abundant supply of DO. The DO level in a water body depends in part on the internal mixing and turbulence of water and instream flow characteristics. Oxygen depletion occurs when oxygen-demanding waste (e.g., sewage, industrial waste, etc.) enters the stream. Oxygen-demanding waste loads are described by a parameter known as biochemical oxygen demand (BOD), a measure of the amount of oxygen required to breakdown organic matter. In general, the more organic matter there is in a stream, the higher the BOD. Intra-gravel DO (IGDO) is also an important variable for the survival of benthic organisms as well as salmonid eggs, embryos, and alevins (Naiman and Bilby, 1998). IGDO is the portion of the DO found within a stream that is transferred to the hyporheic zone by the flow of water through the streambed gravels. Excessive fine sediment deposition can significantly reduce IGDO levels and result in increased mortality to developing salmonids and other benthic organisms (Chapman, 1988; May et al., 1997; Naiman and Bilby, 1998).

Carbon, nitrogen and phosphorus are chemicals that play key roles in aquatic food webs (Meyer et al. 1988; Stanford and Ward 1993; Naiman and Bilby, 1998). Plants and animals need carbon because carbon forms the backbone of living molecules. Plants obtain and store carbon from carbon dioxide in the air. Animals obtain carbon from organic matter. Carbon becomes available to insects, fish and other aquatic biota as plants die, drop leaves, lose branches, or leach nutrients into a water body. Such materials are generally referred to as "organic matter" (Allan, 1995). As the primary carbon source, riparian vegetation strongly influences carbon inputs to the stream. Coarse particulate organic matter (CPOM) is converted into fine particulate organic matter (FPOM) or "seston" by physical, chemical, and biological processes in the stream (Naiman and Bilby, 1998).

When organic matter from the land enters water, it may be consumed or decomposed by insects and microorganisms, physically broken into smaller particles through abrasion, or leached and released into the water. These processes vary among vegetation types. For example, hardwood forests have a more seasonal component to

nutrient inputs and leaves decompose relatively quickly, whereas coniferous inputs are more constant with relatively slow decomposition rates due to the waxy leaf surface (Gregory et al., 1991). Seasonal patterns of organic inputs help determine biological community composition. Aquatic insects and microorganisms also convert nutrients and organic matter into forms useable by other organisms.

Nutrient cycling describes the passage of an atom or element from a phase where it exists as dissolved available nutrient, through its incorporation into living tissue and passage through perhaps several links in the food chain, to its eventual release by excretion and decomposition and re-entry into the pool of dissolved available nutrients (Allan 1995). Nitrogen and phosphorus are vital plant nutrients, although excessive inputs to the stream can lead to uncontrolled plant and algae growth (Allan 1995). Natural sources of nitrogen and phosphorus include plant decomposition and rock erosion. Nitrogen-fixing plants may also obtain atmospheric nitrogen. Nitrogen is readily water soluble, while phosphorus is typically carried to the stream attached to soil particles. These differences in transport to the stream, combined with local geology (mineral leaching and erosion) and riparian vegetation, influence the amounts of nitrogen and phosphorus entering aquatic ecosystems. Excessive aquatic plant (algal and periphyton) growth, due to an overload of nutrients (nitrogen and phosphorus) can also lead to oxygen depletion. This process is known as *eutrophication*.

Instream Salmonid Habitat

Salmonids, like most stream fishes, utilize specific instream habitat types during different life-stages (see Figure 11). Within salmonid populations, competition and territoriality plays an important role in stream habitat selection and utilization. This is particularly true of the juvenile life-stage. When food is limited, such “density-dependent” interactions result in habitat partitioning of sympatric populations and intra-species age-classes (Stouder et al., 1997). In general, juvenile coho salmon prefer deep, slow-water pools formed by LWD (logs and root-wads), whereas juvenile steelhead prefer riffles and lateral scour pools with faster water and cover provided by LWD, overhanging vegetation, or undercut banks (Stouder et al., 1997). Cutthroat trout are often competitively displaced and are opportunistic in their choice of habitat types, able to survive in pools, riffles, or glides provided cover (LWD) is present (Stouder et al., 1997). Juvenile salmonids move within their stream system to take advantage of seasonal environmental changes (Stouder et al., 1997). Juvenile coho often seek refuge from high stormflows and over-winter in off-channel (floodplain) ponds or wetlands (Stouder et al., 1997).

Adequate pool area and residual depth, along with sufficient cover are the keys to successful salmonid rearing. Studies have consistently indicated that the optimum pool-riffle ratio for coho production and over-winter survival is approximately 1:1 (Stouder et al., 1997). Coho often shift habitat preferences as the seasons change, due primarily to changes in flow and usable stream area. In winter, coho prefer off-channel, backwater or wetland pools and in summer they show a preference for main-channel pools formed by LWD (Stouder et al., 1997). Most studies have concluded

that winter habitat is the most limiting factor in streams impacted by human activities within the watershed (Stouder et al., 1997). This is mainly due to the lack of instream habitat complexity normally provided by the abundant LWD found in natural streams. With adequate LWD and complex habitat features less fish are lost due to flooding washout and there tends to be greater overall fish diversity (Stouder et al., 1997). Timber harvest, road-building, agriculture, and land development are all activities that tend to reduce LWD and instream pool habitat (Stouder et al., 1997).

High-quality rearing habitat is critical for the survival of juvenile salmonids from emergence to smolt migration. Adequate total pool area and residual depth along with sufficient cover are necessary for successful juvenile salmonid rearing (Stouder et al., 1997). Juvenile chinook, for example, utilize high-quality pools (good cover and relatively deep) when they are in transition from emergence to mortification (Stouder et al., 1997). Salmonids often shift their habitat preferences seasonally, primarily due to changes in flow and usable stream area. For example, juvenile coho prefer off-channel, backwater, or wetland/ beaver ponds during the winter, and show a preference for main-channel pools formed by large woody debris in the summer months. In addition, adult chinook require deep staging pools for their upstream migration (Stouder et al., 1997).

Large woody debris (LWD) performs numerous instream functions contributing to the formation of high quality aquatic rearing habitat. LWD is a key component for maintaining a high degree of habitat complexity or spatial heterogeneity in streams (Stouder et al., 1997). LWD maintains the hydraulic stability of critical instream habitat features, especially pools (Stouder et al., 1997). LWD dissipates hydraulic energy during peak flows, providing high-flow refuge for salmonids (Stouder et al., 1997). In addition, LWD stabilizes streambeds by minimizing scour and provides excellent cover and habitat diversity (Stouder et al., 1997) for salmonids. With the loss of LWD in the channel, stream morphology shifts away from the characteristic pool-riffle habitat to a more simplified, glide-dominant channel form, with a subsequent decrease in available rearing (pool) habitat. Large woody debris (LWD) is an integral and ubiquitous component of streams in forested watersheds of the PNW. Instream woody debris influences the physical, chemical, and biological processes occurring within the stream. LWD traps allochthonous organic matter, which represents a substantial portion of the energy base of the stream (Maser et al. 1988). LWD also influences the transport and storage of sediment within the channel (Maser et al. 1988). The morphological significance of large organic matter has been discussed. In the PNW, variations in channel sinuosity, gradient, and width are often regulated by LWD (Stouder et al., 1997). LWD can have a significant local influence on channel form, including formation of mid-channel bars, meander cutoffs, and the pool-riffle sequence (Maser et al. 1988). Riparian forests play a key role in the control of stream channel morphologic features. These “biophysical” interactions are particularly important to the stream ecosystems of the PNW (Rot, 1995). Riparian forests also stabilize the active floodplain and are the primary source of LWD. In turn, LWD plays a key role in the formation of riparian forests. LWD deposited in the active channel provides sites for vegetative colonization on forested islands and in floodplain areas (Fetherston et al, 1995).

In the streams of the PSL, organic debris enters the stream channel as a result of bank erosion, hillslope mass-wasting events, and blow-downs. The zone from which LWD is supplied to the channel varies as a function of riparian forest composition, valley landform, and stream characteristics (Maser et al. 1988). Much of the woody debris entering small, unconstrained channels, such as those common to the PSL, is introduced as a result of undercutting of trees located on streambanks (Maser et al. 1988). It has been found that 70-90% of riparian zone input of LWD originates from within 30 m of the stream channel, but as the forest becomes more mature and conifer-dominated, the proportion of input from beyond 30 m increases (Maser et al. 1988).

In general, smaller stream channels (low-order) contain the largest quantity (numbers of pieces) of LWD and have the highest LWD frequency (pieces/length of stream). In larger (higher order) channels, woody debris is more easily transported (Bisson et al, 1987). Larger stream channels tend to have larger sized LWD and also a greater frequency of debris jams and accumulations of LWD (Bilby and Ward, 1991). The quantity and distribution of LWD is also influenced by the riparian forest composition and age. Streams flowing through mature stands of cedar, hemlock, and fir in the PNW, tend to contain a larger quantity of woody debris with larger average-size pieces than streams within young and/or deciduous riparian zones (Bilby and Ward, 1991). LWD derived from conifers, especially Western Red Cedar, not only tends to be larger than deciduous species (predominantly Alder and Maple), thus reducing the chance of being washed downstream, but also have significantly greater resistance to decay, resulting in increased longevity as instream structural components (Maser et al. 1988).

Human activities within the riparian zone have been shown to have adverse impacts on LWD abundance, distribution, and function (Maser et al. 1988; Bilby and Ward, 1991; Stouder et al., 1997). Even if instream debris is left undisturbed during clearing of riparian forests, the quantity and quality of LWD declines over time because second-growth forests or urbanized riparian zones are unable to provide sufficient debris to replace that which is washed downstream or naturally decays (Maser et al. 1988; Bilby and Ward, 1991; Stouder et al., 1997). Under natural conditions, the quantity, size distribution, and species composition of organic debris varies considerably depending on stream size and riparian forest structure (Bilby and Ward, 1989). Depletion rates are inversely proportional to LWD diameter, showing the importance of mature riparian trees to the maintenance of instream structure (Maser et al. 1988; Bilby and Ward, 1991; Stouder et al., 1997). Recovery of LWD recruitment potential to natural levels (i.e. pre-logging or urban clearing) can take more than 100 years (Maser et al. 1988; Bisson et al, 1987; Bilby and Ward, 1989). In general, natural streams tend to have an abundance of LWD, while impacted channels tend to contain less LWD, smaller pieces, and have more LWD concentrated in debris jams.

There is no other structural component as important to salmonid habitat, in PNW streams, as LWD. LWD provides structure to the stream ecosystem and critical habitat for salmonids (Bisson et al, 1987; Maser et al. 1988; Stouder et al., 1997). LWD performs many critical functions in forested, lowland streams. This includes maintaining the hydraulic stability of key habitat features, especially pools (Bilby and Ward, 1991). LWD also dissipates flow energy during peak flow events providing high-

flow refuge, protecting streambanks from erosion and thus reducing sediment generation (Bisson et al, 1987), helps stabilize streambeds to minimize scour, and provides cover and habitat diversity (Maser et al. 1988). Human activities, such as timber harvesting and agriculture within the riparian forests of PNW streams have an adverse impact on LWD, instream habitat quality, and juvenile salmonid diversity (Bisson et al, 1987; Maser et al. 1988; Spence et al., 1996; Stouder et al., 1997). Urbanization has similar impacts, but may be even more long lasting, especially from a hydrological standpoint. In addition to the loss of hydraulic roughness (flow energy buffer) and channel stabilizing capacity, the reduction of in-channel LWD has a major effect on instream habitat complexity and diversity (May et al., 1997). With the loss of inchannel structure, there is a morphological shift away from the characteristic pool-riffle habitat to a glide-dominant channel form. There is a decrease in rearing (pool) habitat both from a quantitative and qualitative perspective. Coho in small streams have a very strong preference for structurally complex cover and low-flow microhabitats associated with organic debris (Stouder et al., 1997). Communities of aquatic biota in general, and salmonids in particular, depend on instream habitat complexity provided by LWD (Stouder et al., 1997). There is no question that the complexity of LWD accumulations in small lowland streams are important to salmonid populations.

The sand, gravel, and cobble that makes up the substrata of PNW streams, also plays a vital role in determining how the ecosystem of the stream will function. Substrata size distribution and spatial arrangement influences (physical) channel hydraulics. The substrata provides benthic habitat for macroinvertebrates and bottom-dwelling fish (sculpins). Periphyton and macrophytes also depend on the substrata composition. With respect to salmonids, the streambed substrata is critical to the level of spawning success, incubation, and survival to emergence. Each species of salmonids has specific preferences for gravel size and composition for spawning (Stouder et al., 1997), but all salmonids require spawning gravels that are highly permeable and relatively free of fine sediment (Chapman, 1988; Crisp and Carling, 1989; Stouder et al., 1997). In the process of building their redds, salmonids actually 'winnow' the fine sediment from the streambed gravels thus improving the interstitial flow of water to the incubating eggs within the redd (Kondolf et al, 1993). Survival to alevin emergence is generally strongly correlated to the percentage of fine sediment ("fines") in the substratum (Chapman, 1988). Elevated levels of fine sediment in spawning gravels have been associated with timber-harvest activities, mining, grazing, and other human activities (Stouder et al., 1997).

Anthropogenic activities in the watershed can also have detrimental effects on salmonid spawning habitat (Stouder et al., 1997). Some studies indicate that the optimum, natural pool to riffle ratio for salmonid production and over-winter survival is one that is relatively balanced (Stouder et al., 1997). In addition, streambed substrate is also critical to spawning success, incubation, and survival to emergence for salmonids. Each salmonid species has a specific preference for spawning habitat conditions (Stouder et al., 1997), but all salmonids require spawning gravels that are highly permeable and relatively free of fine sediment (Stouder et al., 1997). The substrate also provides benthic habitat for macroinvertebrates, freshwater mussels, and bottom-dwelling fish such as sculpin. Increased over-land flow (including runoff)—and

stream bank erosion caused by anthropogenic activities in the watershed—contribute to sediment deposition in the interstitial spaces of spawning gravels. This sediment suffocates biota reliant on well-oxygenated intra-gravel flow (Chapman, 1988) The % fines in PSL streams is also strongly correlated with the level of urbanization in the upstream basin (May et al., 1997).

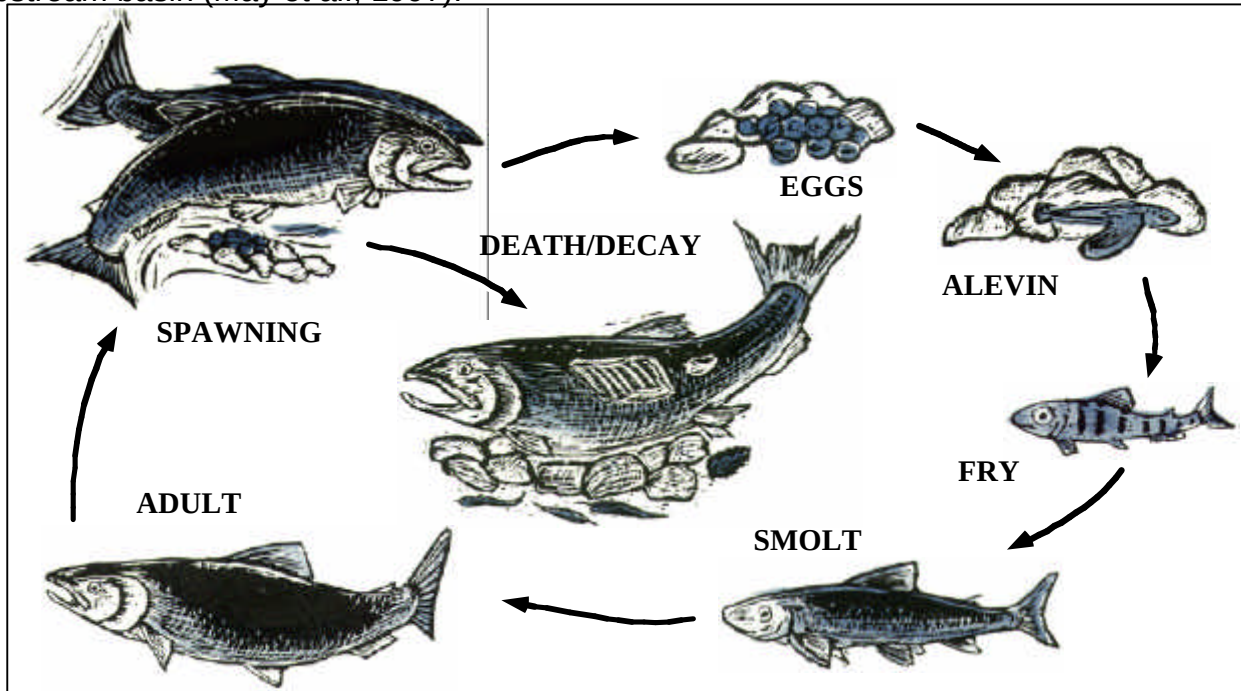


Figure 11: Typical Life Cycle of Pacific Salmon.

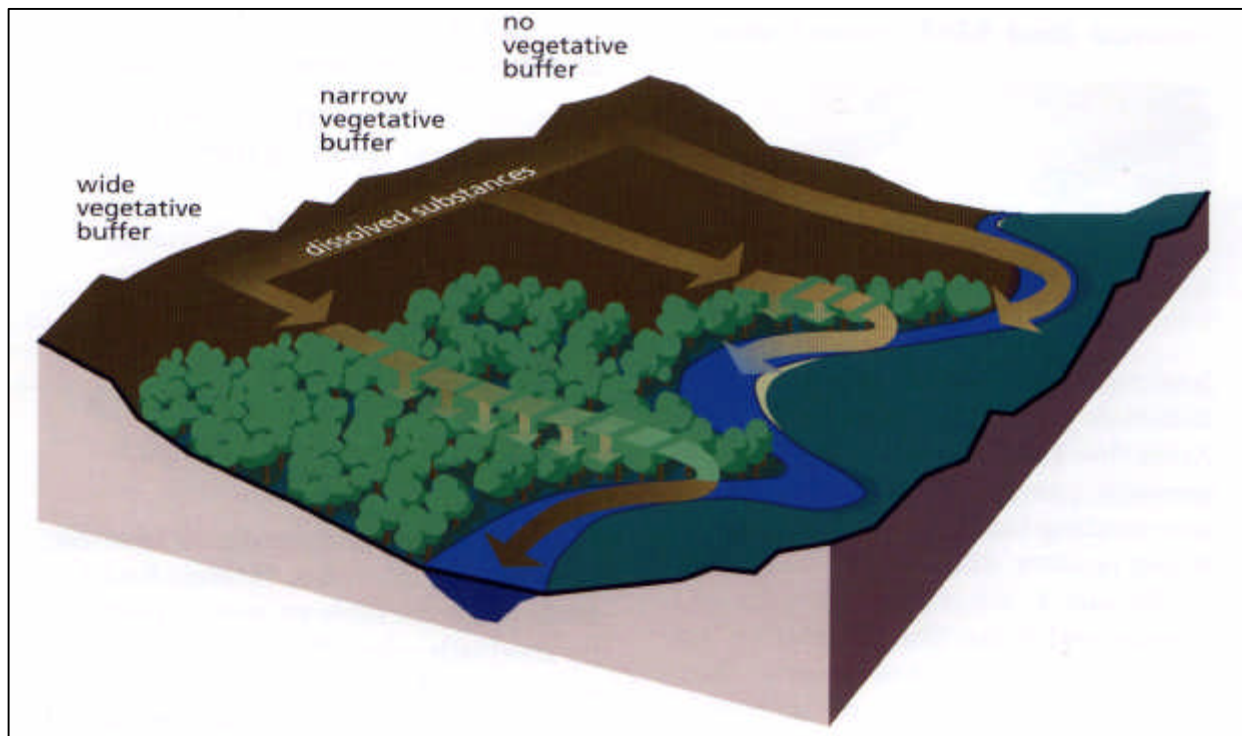


Figure 12: Functional Extent of Riparian Buffer Vegetation.

Riparian Vegetation

Native vegetation, in general, and native forest cover in particular, plays a critical role in healthy watersheds (Booth et al., 2002). Riparian vegetation, in particular, plays a critical role in aquatic ecosystem health (Naiman et al., 2000). Plant communities are dynamic. Soils, nutrients, and woody debris move from one area to another through precipitation and erosion, leaching, wind, natural and human disturbances, and a variety of other means. Plant communities in riparian areas help determine what, how much, and when materials from upland areas enter the stream ecosystem. For example, a wide, mature riparian forest will capture many soils and sediments, nutrients, and woody debris, adding richness and complexity to soil and plant communities near the water and protecting water from excessive nutrient or soil inputs (see Figure 12). A fine balance exists between having enough and having too much of these inputs to the stream. Riparian areas, and consequently the structure, functions and processes occurring within and around the stream, are fundamentally altered when upland and riparian vegetation is removed.

Vegetative communities in the riparian zone are dynamic, reflecting a dynamic landscape. Heterogeneity in landform, microclimate gradient, site productivity, and disturbance regime all play important roles in influencing forest structure, species richness, and colonization by exotic plants (Gregory et al., 1991; Naiman et al., 2000; Shafroth et al., 2002). Riparian vegetation refers specifically to plant communities occurring within the riparian area that are adapted to wet conditions and are distinct from upland communities (Gregory et al., 1991). Riparian areas are composed of a mixture of herbs and grasses, shrubs, deciduous trees, and coniferous stands of various ages. Younger vegetation occurs immediately adjacent to the stream channel and commonly consists of deciduous shrubs and trees. Generally, older plant communities in floodplains farther from the channel (Gregory et al., 1991; Naiman and Decamps, 1997; Naiman et al., 2000). The distribution, structure and composition of riparian plant communities are largely determined by climate, light and water availability, topographic features, chemical and physical properties of the soil (including moisture and nutrient content), the existence of tributary and groundwater flows, and natural disturbance regimes.

The integrity of the aquatic and terrestrial ecosystems is greatly influenced by the quantity, composition, and structure of riparian plant communities. Plant communities that cover large areas and that have an array of vertical (e.g., trees vs. shrubs) and horizontal (e.g., young stands vs. old growth) structural characteristics can support numerous animal species. In addition, riparian vegetation, through its root system and input of woody debris, influences stream channel characteristics. Riparian vegetation also directly affects aquatic organisms by providing organic materials to the aquatic food web (Gregory et al., 1991).

Riparian plant communities typically change from the headwaters to the mouth because of differences in gradient, hydrology, geomorphology and disturbance regimes (Naiman et al., 2000). For example, steeper slopes in headwater zones often restrict the extent of the riparian vegetation, which may closely resemble that of upland areas. Mid-section zones tend to have a band of riparian vegetation that is influenced by channel

dynamics such as flooding and channel migration (meandering). Riparian vegetation in large, low-gradient rivers is generally composed of specialized and disturbance-adapted species that flourish in floodplains where periodic inundation occurs (Naiman et al., 1992). For example, common riparian plant species such as willows and cottonwoods depend on flooding for regeneration (Rot et al., 2000).

Community characteristics of riparian vegetation determine the age and species of wood entering the fluvial system, and the variability in wood size and species has important ecological implications in terms of the persistence of LWD in the channel and subsequent successional processes associated with riparian forests. In most PNW rivers and streams, hardwood species are better represented among the riparian forests than among instream LWD. Conversely, are better represented among instream LWD than in the adjacent riparian forest (Naiman et al., 2000). These findings suggest that hardwoods are depleted from the channel faster than conifers. In general, the depletion rate for a population of LWD pieces follows an exponential decay curve. Various processes are responsible for LWD depletion. Some of the LWD decomposes in situ while other pieces either are deposited on the terrestrial portion of the floodplain during large flood events, exported to the ocean, or buried by sediments until being exhumed by scour at a later date (Naiman et al., 2000).

The persistence of LWD is of fundamental ecological importance because of its influence on channel dynamics and the subsequent succession of riparian vegetation (Fetherston et al., 1995, Abbe and Montgomery, 1996; Rot et al., 2000). LWD debris-jams often control local channel hydraulics and provide refugia for salmonids against flood scour. The deposition of very large or “key” pieces of LWD, usually with intact root wads, often initiates the formation of stable LWD debris-jams that alter the local hydraulics and thereby control the spatial pattern of scour and deposition, as well as creating sites for riparian vegetation initiation (see Figure 12). Even though LWD accumulations may appear to form at random, there are often distinctive structural patterns (Naiman et al., 2000). Individual jams may be remarkably stable over the long term, allowing mature riparian forest patches to form and persist within an environment that is characterized by rapid channel migration and frequent disturbance.

The longitudinal changes from the headwaters to the mouth of river ecosystems have been generalized in a conceptual model (Van Note et al., 1980) known as the River Continuum Concept (RCC). Connections between the watershed, floodplain, and stream systems are identified in the RCC, as well as how biological communities develop and change from the headwaters to the mouth. In general, the structure and form of the channel changes as it moves from the headwaters to the mid-section and low-gradient zones. The RCC generalizes the changes that occur in vegetation from the headwaters to the mouth (see Figure 13). In headwater streams, where forest canopy overhangs and shades the narrow channel, little sunlight is available to plants and algae within the stream, and most nutrients enter the stream from terrestrial sources. Such externally derived nutrients are termed “allochthonous”, and consist primarily of LWD, leaf litter, and other CPOM. The mid-section riparian zone is more open to sunlight and organisms rely more heavily on internally derived nutrients or “autochthonous” sources, such as instream algae and plants. However, small particles

of pre-processed nutrients from upstream are also available; therefore, mid-reach streams tend to balance inputs from both external and internal sources. Lower stream sections are generally wider and receive abundant sunlight, and acquire nutrients from upstream sources, with some primary production (Van Note et al., 1980).

Aquatic insects and microorganisms convert nutrients and organic matter into forms useable by other organisms. As described above, the importance of plants as instream nutrient sources changes between headwater, mid-section, and low-gradient zones. Aquatic insect communities are arranged accordingly, as theorized by the RCC (Van Note et al., 1980). For example, the dominant headwater insects or “shredders” specialize in breaking down coarse organic matter. In mid-section zones, benthic macroinvertebrates tend to collect organic matter (“collectors”) or graze on plants and diatoms (“scrappers”). In low-gradient zones, CPOM is relatively rare but FPOM is available from plants, decomposing insects, and sediments. Insects and fish in these reaches tend to be bottom or filter feeders. In each zone, predatory macroinvertebrates comprise a relatively small, but important, component of aquatic insect communities. Throughout this downstream continuum, insects play an important role in converting and supplying nutrients to other instream organisms. Many fish also species rely on aquatic insects as a primary food source (see Figure 13).

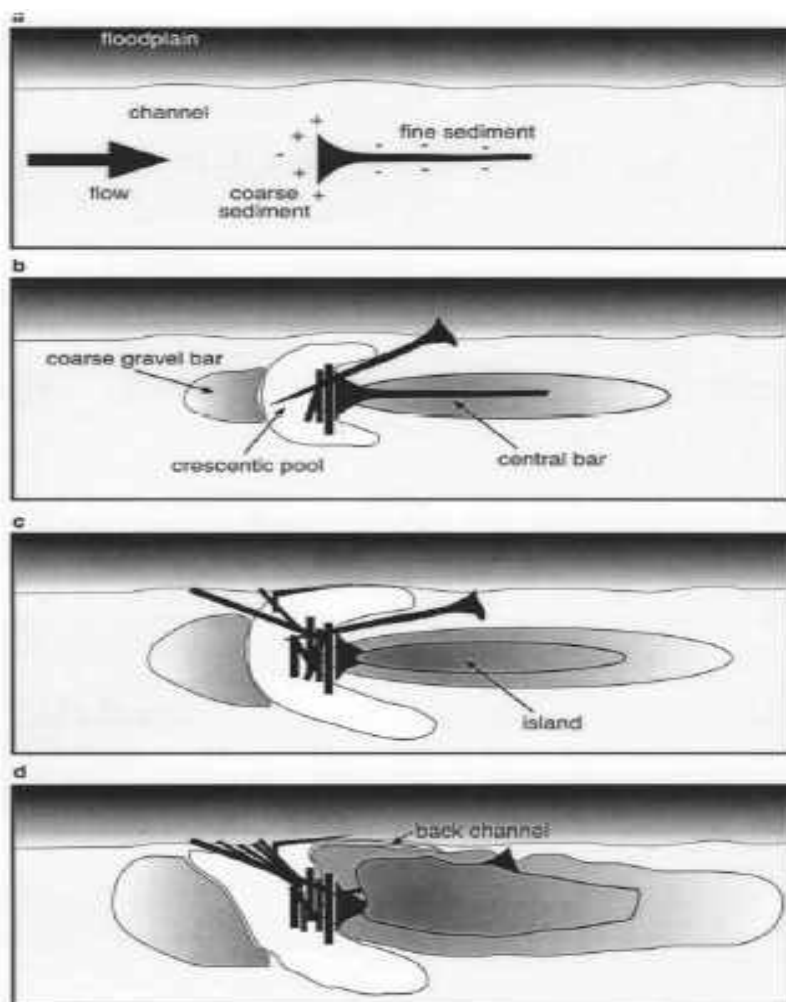


Figure 12: Morphological stages in alluvial topography associated with construction of a LWD debris-jam. (a) Deposition of an especially large tree with the root wad intact. (b) Formation of a coarse gravel bar upstream, a crescent-shaped pool immediately upstream of the root wad, and a downstream central bar of finer sediments along the axis of the tree. (c) Riparian island development along the central bar. (d) Integration into the broader floodplain. (Modified from Abbe and Montgomery, 1996).

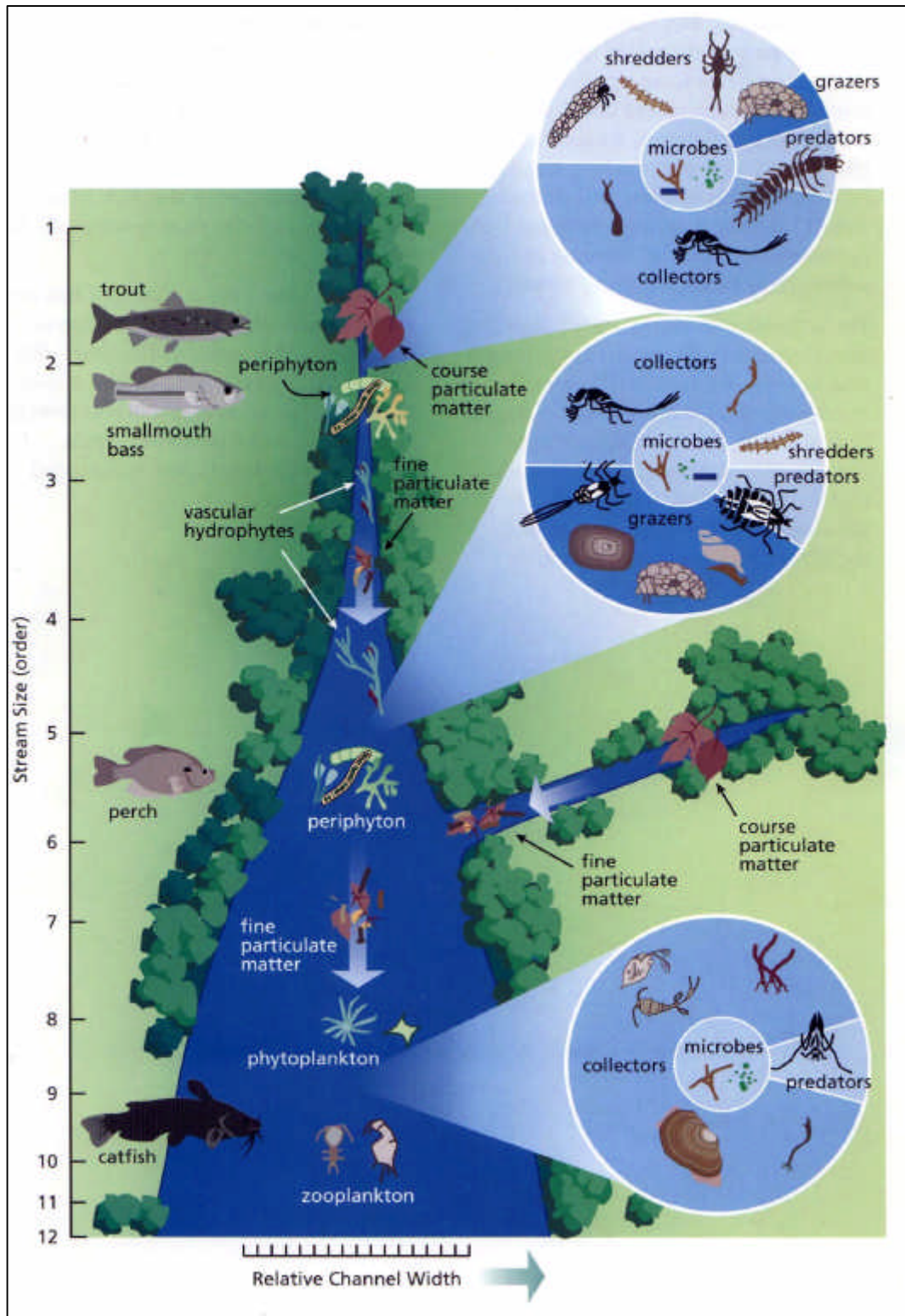


Figure 13: River Continuum Concept (Van Note et al., 1980)

Summary of Riparian Research

Numerous studies have been conducted in an attempt to quantify the effectiveness of riparian areas in protecting aquatic resources. In spite of this extensive research, there remains much we don't understand about the stream-riparian ecosystem and the utility of riparian "buffers" in protecting its ecological integrity. This should not be surprising based on the natural variability of aquatic and terrestrial ecosystems and the variety of stressors affecting them. There have been a few good reviews of scientific literature which do a good job of summarizing the current "best available science" (Johnson and Ryba, 1992; Castelle, 1994; Knutson and Naef, 1997; Wenger, 1999).

The Washington Department of Fish and Wildlife (WDFW) report done by Knutson and Naef (1997) is an excellent review with respect to the Pacific Northwest (PNW). The University of Georgia, Institute of Ecology report (Wenger, 1999) focuses on the southeast, although there are many parallels to other regions. It is current, very thorough, and utilizes much of the same literature as the WDFW report. Two earlier research summaries also focused on the PNW region, but included scientific data from throughout the country. These reviews are a bit dated and do not include some important functions of riparian areas (see Johnson and Ryba, 1992 and Castelle, 1994). A recent paper by Pollock and Kennard (1998) also provides excellent guidance on riparian management strategy in the PNW region, with applicability to other parts of the country as well. For each riparian function listed below, a summary table of current research is provided.

One of the most significant difficulties in trying to develop a recommendation for establishing an appropriate RMZ, using the most current research available, is that most studies only examine a few selected buffer widths, under specific environmental conditions, and typically for only one external stressor. Most of these studies tend to draw conclusions on "effective" buffer widths as a byproduct of their sampling design rather than deriving it experimentally (Fennesy and Cronk, 1997). Based on this caveat, the recommended buffer widths presented in the following tables should be used with caution and only when they meet the conditions applicable to the site in question.

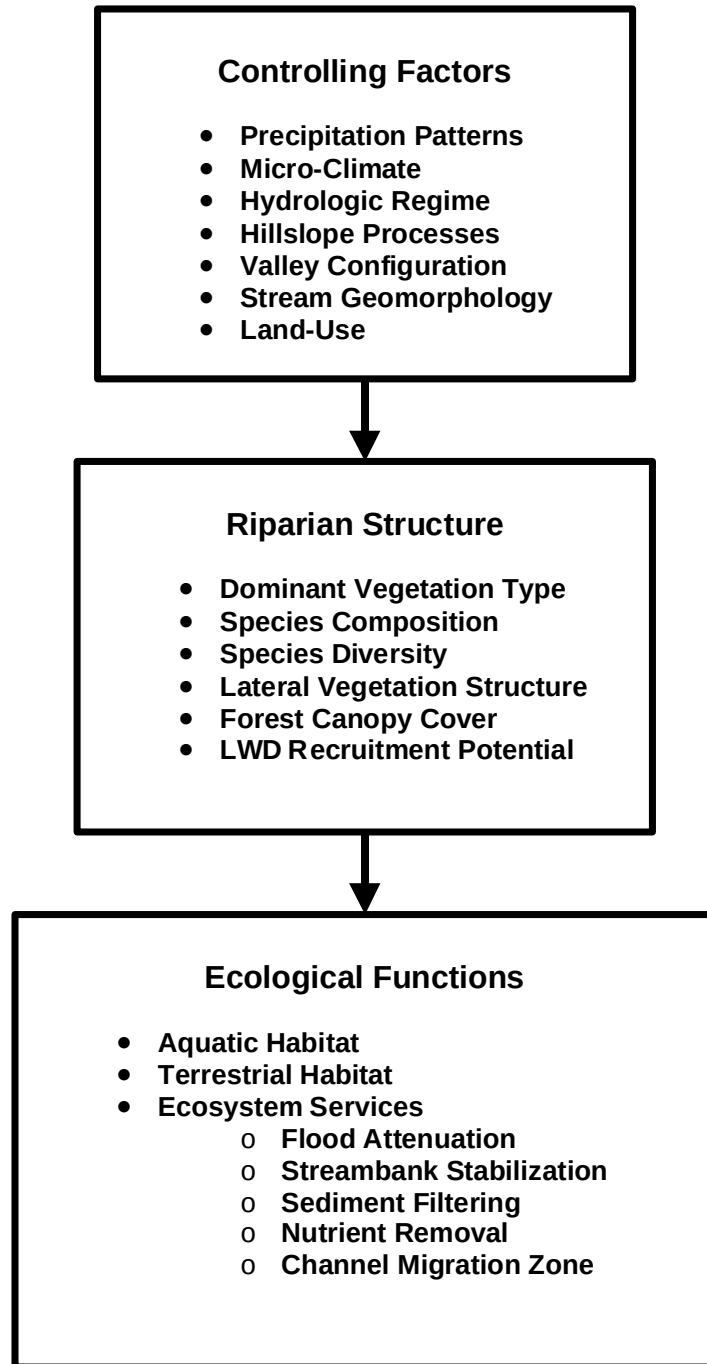
The most commonly recognized ecological functions of the riparian corridor include:

- Providing canopy-cover shade necessary to maintain cool stream temperatures. This is a critical function for cold-water stream habitats.
- Regulation of microclimate in the stream-riparian corridor.
- Reducing fine sediment input into the stream system through floodplain retention, filtering, and streambank protection.
- Stabilizing streambanks, minimizing streambank erosion, and reducing the occurrence of landslides within the riparian zone.
- Filtering and vegetative uptake of nutrients and potential anthropogenic pollutants from groundwater and surface runoff.
- Providing a source of coarse particulate organic matter and large woody debris (LWD) into the stream channel. LWD is an important instream structural element, which functions as a hydraulic roughness element to

moderate streamflows. CPOM also provides organic carbon for the base of the aquatic food web.

- Providing critical wildlife habitat including migration corridors, feeding and watering habitat, and refuge areas during upland disturbance events.

These functional relationships are illustrated in the conceptual models shown in



Figures 14 and 15.

Figure 14: Stream-Riparian Ecosystem Conceptual Model.

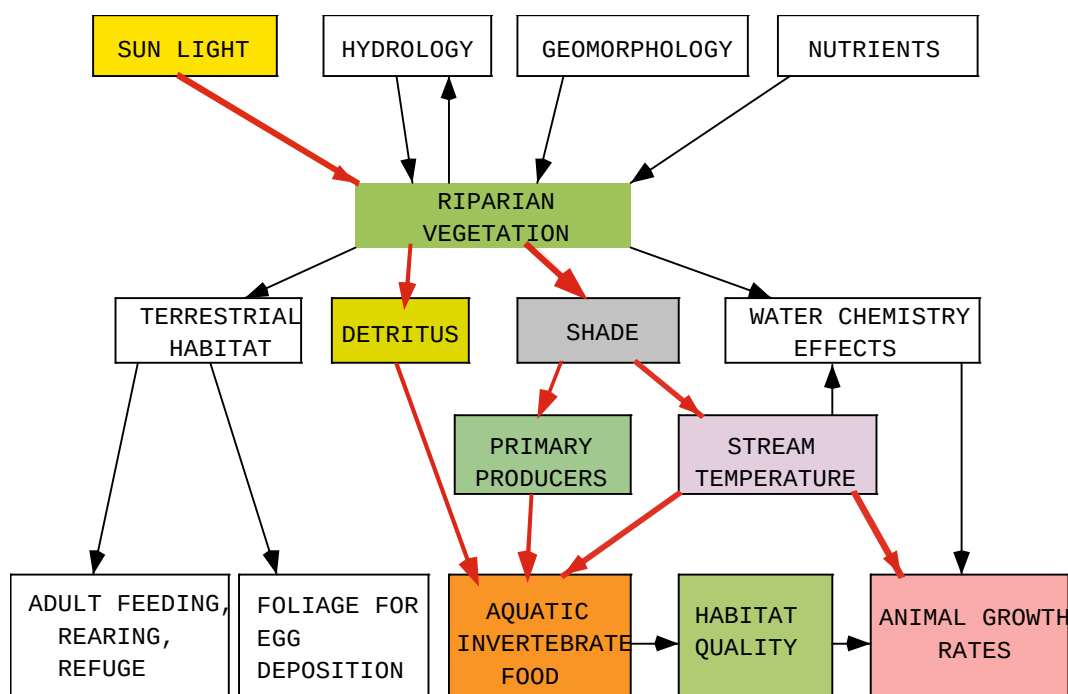


Figure 15: Functional Relationships between the Riparian Forest and Aquatic Biota.

Stream Temperature Control

Shade is an important function of riparian vegetation in that it strongly influences the regulation of instream water temperature. Water temperature is one of the most crucial environmental factors influencing fish and other aquatic species (Allen, 1992). Essentially all biological processes in the life cycle of aquatic organisms are affected by water temperature (Allen, 1992). Daily and seasonal water temperature are influenced by elevation, shade, water sources, streamflow, stream velocity, surface area, depth, undercut embankments, organic debris and the inflow of surface water and groundwater (Allen, 1992). Riparian vegetation moderates the amount of light reaching the stream channel by blocking or filtering solar radiation. The resulting shade helps to maintain cooler water temperature. The effectiveness of riparian vegetation in producing shade depends on the composition, height, and density of riparian vegetation, and the width of the stream channel and its orientation relative to solar angle (Gregory et al., 1991; Naiman et al., 1992; FEMAT, 1993; Spence et al., 1996; Palone and Todd, 1998; Kauffman et al., 2001). Riparian vegetation is less effective in providing shade and moderating stream temperature as streams increase in size. It has the greatest impact on headwater streams where it helps maintain temperature of surface water as well as shallow groundwater that feeds the stream. Although shading on larger rivers may have little or no influence on water temperature, overhanging riparian vegetation along the banks creates cooler micro-habitat for fish and aquatic organisms (Palone and Todd, 1997).

Based on current research in the PNW, the minimum forested corridor that on each side of the stream channel will generally provide adequate shade to maintain stream water temperature supportive of cold-water aquatic biota is approximately 30 m. A buffer width of 30 m also is commonly recognized as the minimum riparian width for natural stream temperature regulation as found in old-growth forests of the PNW (Beschta et al., 1987). This brings up an important point. Whenever we discuss buffer widths, we must qualify our width recommendations based on the type of vegetation present and the maturity (tree height) of the trees. For example, 30 m of mature forest may provide a natural level of shade, but the same width of deciduous trees (willow, alder, etc.) or shrubs may not. With respect to shade and temperature control, a buffer composed of grasses, shrubs, and/or small trees is not equivalent to a natural riparian forest of mixed, mature coniferous and deciduous trees. Buffer quality is as important as “buffer quantity”. This points out the need for active management of riparian buffers in areas where the forest has been impacted by timber harvest, agriculture, or any land-use activity that has disturbed the native vegetation. In fact, buffer width for temperature control may need to be different depending on the riparian vegetation type, maturity, and quality, as well as the valley configuration. Table 1 provides a summary of research on riparian areas in relation to temperature-control.

Microclimate Control

Riparian vegetation exerts strong control on the stream microclimate by protecting it against climatic changes caused by land use activities outside the riparian corridor (Naiman et al. 1992; Chen et al., 1995; Pollock and Kennard 1998; Naiman et al., 2000; Kauffman et al. 2001). The microclimate of riparian corridors is uniquely different from upland areas because of its proximity to water, which influences soil moisture, temperature, and relative humidity (Thomas et al. 1979; Swanson et al 1982; Naiman et al. 1992; Pollock and Kennard 1998; Kauffman et al. 2001). The microclimate of riparian areas is generally more moist and mild (cooler in summer and warmer in winter) than the surrounding area (Knutson and Naef 1997). This creates diverse habitat characteristics that are desirable to many species, particularly for amphibians year-round and for ungulates and other large mammals during hot, dry summers and severe winters (Knutson and Naef 1997).

The position of riparian areas along streams ensures adequate soil moisture available to riparian-associated plants throughout most of the year. For example, in Oregon headwater streams Olson et al. (2000) found cooler temperatures and increased relative humidity near the stream compared to upslope. Because of these factors, riparian vegetation is buffered from the stress of evapo-transpiration during the summer (Swanson et al., 1982; Naiman et al., 2000; Kauffman et al., 2001). During winter months, riparian areas can be warmer than upland areas because they are not exposed to the winds more common in higher elevations (Swanson et al., 1982). Microclimate also influences water quality by helping regulate water temperature (Pollock and Kennard 1998). Based on current research, the riparian forest is critical to the maintenance of local climate (temperature, humidity, wind, etc.) within the stream-riparian ecosystem. Figure 16 and Table 2 provide a summary of microclimate related research on riparian areas.

Width	Citation	Notes
11-38 m	Brazier & Brown, 1973	60-80% shade
20-30 m	Corbett & Lynch, 1985	60-80% shade
15-30 m	Hewlett & Fortson, 1982	60-80% shade
15.2 m	Broderon, 1973	Buffer widths decrease as tree heights increase
17-46 m	Steinblums et al., 1984	Maximum angular canopy density used
18 m	Moring, 1975	50-60% shade
23-28 m	Steinblums et al., 1984	60-80% shade
30 m	Beschta et al., 1987	Minimum shade to level of old growth forest
30 m	Lynch et al., 1985	Mature forest equivalent
30-43 m	Jones et al., 1988	80% shade
30 m	Spence et al., 1996	Natural temperature and shading
30 m	FEMAT, 1993	Mature forest equivalent
80 m	Brosofske et al. 1997	Natural temperature regulation

Table 1: Buffer Research on Temperature Control.

Width	Citation	Notes
20-30 m	Pollock and Kennard, 1998	Reduce wind-throw effects
61-122 m	Chen et al., 1995	Riparian forest ecosystem
160 m	Harris, 1984	Riparian forest ecosystem
160 m	Franklin and Forman, 1987	Riparian forest ecosystem
45-110 m	Spence et al., 1996	Forests of PNW
50-100 m	Brosofske et al., 1997	Natural riparian microclimate
~150 m	FEMAT, 1993	3 Site Potential Tree Heights (SPTH) to maintain natural riparian micro-climate

Table 2: Riparian Research on Microclimate Regulation

Fine Sediment Removal and Streambank Erosion Control

Riparian vegetation provides for natural streambank stabilization, as well as erosion and sediment control (ESC). Sediment delivered to streams and rivers can originate from streambank erosion, from within the channel, from upland land-use activities (logging, construction sites, roads, etc.), and from natural disturbances (e.g., debris flows and landslides). Sediment occurs naturally in any stream, but changes in the total sediment load and particle size that exceed natural levels, due to human activities, can have negative impacts on fish and other aquatic habitat (Beauchamp et al., 1983; Chapman, 1988; May et al., 1997; Naiman et al., 2000).

Stable, well-vegetated streambanks provide resistance to erosion (Simon and Collison, 2002). The root network of riparian vegetation increases resistance to erosion by anchoring soil and stabilizing the bank. Woody riparian species typically have a dense root network that is effective in protecting streambanks (Naiman et al., 2000).

During periods of high water flow, streambanks are especially vulnerable

to the erosive forces of water. The physical structure provided by riparian vegetation slows water, mechanically filters and stores fine sediment, and holds materials in place (Swanson et al., 1982; Gregory et al., 1991; Knutson and Naef, 1997; Naiman and Decamps, 1997; May et al., 1997; Naiman et al., 2000). This process may also facilitate streambank building as sediment is deposited on the streambank and floodplain, allowing the channel to change in morphology (Fetherston et al., 1995; Abbe and Montgomery, 1996; Rot et al., 2000).

Streams of all sizes benefit from the regulating influence that riparian vegetation has on the amount of sediment entering aquatic habitats. Riparian vegetation is especially important in headwater zones where many natural disturbances occur and where the cumulative effect of uninhibited sediment entry from many small streams can significantly impact larger downstream reaches (Knutson and Naef, 1997; May et al., 1997; Naiman et al., 2000). Natural floodplains are also important as sites for sediment deposition and retention (Kauffman et al., 2001).

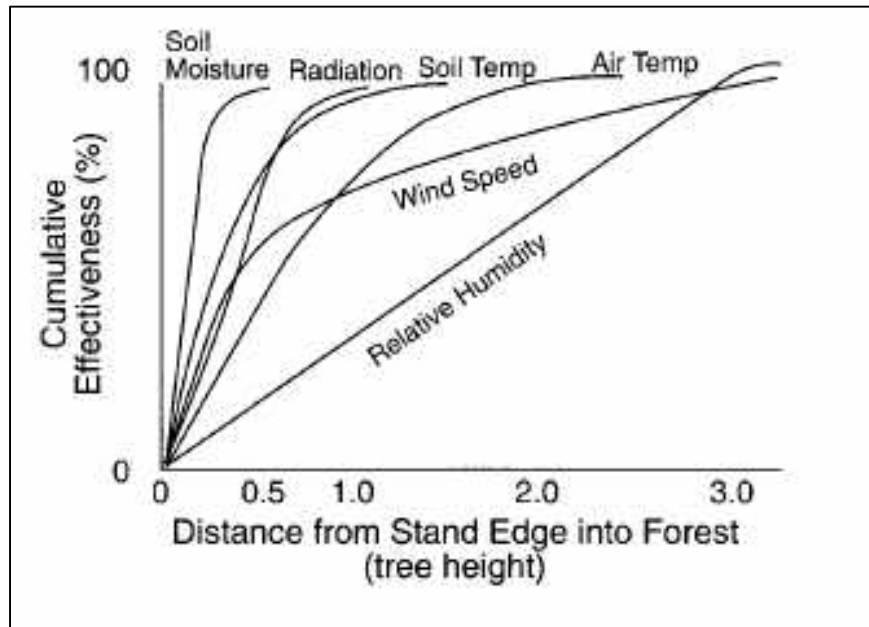


Figure 16: Cumulative Effectiveness for Microclimate Factors relative to the Edge of the Stream Channel (FEMAT, 1993).

Fine sediment is a primary pollutant of interest in watersheds with land uses ranging from agriculture, to forestry, to urbanization. The impacts of excessive fine sediment deposition in the streambed gravel can be significant (Chapman, 1988). Fine sediment can originate from within the stream channel, from streambank erosion and mass-wasting events caused by excessive stormflows (Trimble, 1997). Fine sediment can also originate in upland areas where bare soil is exposed to rainfall and runoff. Agricultural activities such as row-crop farming and livestock grazing can be significant sources (Lowrance et al., 1984). In addition, construction sites can also be sources of sediment pollution if proper erosion-control BMP's are not utilized (Horner, 1995). Once sediment enters the stream system, it can remain in the channel for an extended period or be flushed rapidly through the system.

With regard to sediment trapping and removal, there is a wide variation in "effective" buffer widths based on research studies to date. Much of this variation is likely due to differences in vegetation type/quality, differences in slope, and soil types involved in the research studies. In general, the ability of a riparian buffer to remove fine sediment from runoff is a function of buffer width, soil type, side-slope gradient, local topography, and vegetation conditions. In addition to vegetation differences, there are also differences in measures of effectiveness in the studies that can make comparisons of results difficult. Some studies use a gross measure of sediment, while others monitor turbidity or TSS (Desbonnet et al., 1994). However, one of the biggest variations between studies involves whether natural riparian vegetation was tested or some form of cultivated vegetation was used. The most frequent occurrence of this involves the use of *vegetated filter strips* (VFS) to treat runoff from agricultural or urbanized areas.

Grass filter-strips or biofiltration strips and swales can be quite effective and are commonly used to treat stormwater runoff for the removal of a variety of pollutants, including fine sediment (Horner and Mar, 1982). These *best management practices* (BMP) can be quite effective if properly maintained and if not overloaded with sediment inputs (Horner, 1996). In general, VFS increase in effectiveness with width (or treatment length) and do better at low to moderate slopes (although they can be effective on slopes as high as 20%). VFS rely on maintaining sheet-flow for optimum treatment and channelization-erosion can be a problem at moderate to high slopes. Most VFS are designed to work in the range of 2-10% slope and must have a retention time greater than 9 minutes for an average 80% TSS removal efficiency (Horner, 1996). These so-called "bio-filters" can be very effective water quality treatment BMPs, but they have some important operational constraints. Biofiltration BMPs have been shown to fail if they are subject to large single-event or prolonged inputs of sediment and can be damaged by concentrated flows. Bio-filtration systems also require periodic inspections and maintenance (Horner, 1996).

Several studies cited in Table 3 involve some form of VFS (most use grass as a filter medium, but some use shrubs or trees) and should not be compared directly to studies involving natural riparian vegetation (see comments in Table 3). The use of VFS in urban or agricultural watersheds would be an excellent water quality treatment BMP for sediment and pollutant removal, but they are limited to this function only and should not

be used as a substitute for natural riparian forest or wetland. This is because they typically do not meet any of the other riparian functions discussed previously. The use of VFS to “pre-treat” runoff prior to it being allowed to flow into a buffer of natural vegetation, and then on into the stream-riparian ecosystem would be an excellent BMP for dealing with agricultural areas or developed watersheds where fine sediment and other pollutants (nutrients, pesticides, metals, etc.) are of concern.

Most of the research cited in Table 3 was also from short-term studies. Very few studies have looked at the long-term effectiveness of buffers in removing sediment from runoff. Based on current literature, three studies have looked at long-term sediment removal capability of riparian buffers (Lowrance et al., 1986; Lowrance et al., 1988; Cooper et al., 1987). These studies all found that riparian buffers are effective sediment traps (although quite variable depending on vegetation conditions, soil type, and slope), but the width required for long-term retention of sediments needs to be significantly larger than the minimum required for short-term sediment removal. Slope can be especially critical to the success of a buffer in that channelization can not only “short-circuit” any treatment, but it can also mobilize sediment from within the buffer and transport it to the stream channel thus turning the buffer area from a sediment sink to a source area. In addition, to be effective, wider buffers and VFS are required for steeper slopes and for areas where local soils and topography do not promote infiltration.

In addition, as can be seen from Table 3, by far the most research has been done on the use of riparian buffers and vegetation (VFS) to remove fine sediment from stormwater and agricultural runoff. The use of VFS to treat runoff has merit, but this treatment should be done outside the boundaries of the stream-riparian ecosystem. Controlling input of sediment into the stream channel by preventing excessive streambank erosion and filtering runoff, is one of the functions of riparian areas, but it is not the only function. In fact, in naturally forested watersheds, the need for sediment filtration is fairly infrequent and episodic. In contrast, agriculture, timber harvest, road maintenance, and construction tend to produce fairly high levels of sediment for extended periods. The best defense against fine sediment loading into the stream channel is to prevent bare soil exposure and to minimize transport of sediment at the source. Erosion and sediment control (ESC) BMPs for agriculture and construction are well understood and relatively easy to accomplish (WA-DOE, 2002).

Nutrient and Pollutant Removal

Riparian vegetation can be effective in trapping excess nutrients, such as nitrogen and phosphorus found in fertilizers, and pollutants such as insecticides, herbicides and industrial chemicals carried in stormwater runoff. Riparian vegetation functions as a natural nutrient filter by retaining sediment from overland flow (Swanson et al., 1982; Naiman and Decamps, 1997; Kauffman et al., 2001). Pollutants can be found in either the dissolved and particulate forms, although the particulate form is more common. The removal of fine sediment and organic matter may also remove a large percentage of the pollutants found in runoff. Riparian vegetation also takes up nutrients for plant growth from soil adjacent to the stream and directly from the stream. Plants store

nutrients in the form of woody (long-term) and non-woody (short-term) plant material. Nutrients are released from dead organic matter by leaching and decomposition.

Width	Citation	Notes
5-9 m	Dillaha et al., 1988	53-98% removal by VFS; 11-16% slope
5-9 m	Magette et al., 1989	66-82% removal by VFS; 3-5% slope
9.1 m	Ghaffarzadeh et al., 1992	85% removal; 7-12% slopes using VFS
8-46 m	USDA Soil Conservation Service (SCS), 1982	Depending on slope; 0-70% slopes tested using various types of VFS
9-35 m	Dosskey et al., 2002	40-99% fine sediment removal
15 m	Wilson, 1967	Silt removal in floodplain grass
19 m	Peterjohn and Correll, 1984	90% removal; 5% slope using a VFS
20 m	Clinnick et al., 1985	Ephemeral stream bank stability
25 m	Desbonnet et al., 1994	Optimum "sediment" removal
21-27 m	Young et al., 1980	66-93% removal via VFS
30 m	Erman et al., 1977	80% removal by riparian vegetation
30 m	Moring et al., 1982	90% removal in logging areas
30 m	Davies and Nelson, 1994	Trapping of sediment from logging roads in forest management areas
30 m	Lynch et al., 1985	75-80% removal in forest management areas
30-38 m	Karr & Schlosser, 1977	75% removal by riparian vegetation
30.5 m	Wong & McCuen, 1982	90% removal via VFS
30 m	Raleigh et al., 1986	Bank erosion control
30-80 m	Lowrance et al., 1988	Long-term study
30-100 m	Cooper et al., 1987	Long-term study
30 m	Lowrance et al., 1986	Long-term study
38 m	Cederholm, 1994	Minimum to protect streambanks in high erosion or mass wasting areas
50 m	Peterjohn and Correll, 1984	94% removal; 5% slope (VFS)
50 m	Spence et al., 1996	Streambank Stabilization
50 m	FEMAT, 1993	Streambank Stabilization
61 m	Wong & McCuen, 1982	95% removal via VFS
61 m	Horner & Mar, 1982	80% removal in grassy swale
61 m	Broderson, 1973	90% removal by riparian vegetation
61 m	Terrell and Perfetti, 1989	80% removal by vegetation
60-90 m	Belt et al., 1992	50% removal by riparian vegetation
88 m	Gilliam & Skaggs, 1988	50% removal by riparian vegetation
91.5 m	Vanderholm & Dickey, 1978	80% TSS removal on a 0.5% slope
262 m	Vanderholm & Dickey, 1978	80% TSS removal on a 4% slope

Table 3: Buffer Research on Fine Sediment Removal.

Nutrient uptake also occurs during decomposition (Swanson et al., 1982). Microbial processes occurring in riparian areas may also reduce excess nutrients. These processes include immobilization of nutrients, denitrification of nitrate and degradation of organic pollutants (Palone and Todd, 1997). Denitrification is a key nitrate removal

mechanism in many riparian areas (Naiman et al., 1992; Palone and Todd, 1997; Naiman et al., 2000). Microorganisms take up or “immobilize” nutrients just as plants do, and these nutrients are re-released following the death and decomposition of microbial cells and are stored in soil organic matter. Degradation of organic pollutants occurs as microorganisms consume organic compounds as food sources (Palone and Todd, 1997).

Riparian vegetation also helps moderate streamflow by intercepting, absorbing and storing runoff (Knutson and Naef 1997; May et al., 1997; Palone and Todd 1998). Streamflow can be affected by the abundance and distribution of riparian vegetation, which creates roughness that helps slow water movement to the stream. The roots of riparian plants increase soil porosity and promote water infiltration (Swanson et al., 1982). Riparian-associated wetlands help moderate streamflow by reducing flood flows and the velocity of floodwaters. Wetlands are also important storage areas for surface water, particularly during dry seasons, when they become a source of water to the stream.

Healthy soils directly contribute to healthier water resources by storing water and nutrients, regulating the flow of water, and immobilizing and degrading pollutants (Booth, 1996; Marx et al., 1999; Moses and Morris, 2001). Soil is made up many components including inorganic mineral particles of various sizes (clay, silt and sand), organic matter in various stages of decomposition, and many species of living organisms. Healthy soils are vital in the establishment and nourishment of plants and provide habitat for millions of organisms. Areas with natural vegetation cover and leaf litter provide organic matter to the soil and usually have high infiltration rates (Marx et al., 1999). Water that is stored in soil is slowly discharged to the stream through subsurface flow.

Soil quality is typically degraded along urban stream corridors where development activities often include removal of natural riparian vegetation, compaction of soil, and placement of fill (May et al., 1997; Marx et al., 1999; Moses and Morris, 2001). Soil compaction reduces water infiltration and contributes to water runoff. Pollutants such as excess nutrients, metals, petroleum hydrocarbon compounds, and organic chemicals (pesticides, herbicides, and industrial chemicals) are commonly found in stormwater and agricultural runoff. Most of these pollutants can be found in both the dissolved and particulate forms. The dissolved form tends to be the most bioavailable form, but the bulk of pollutants usually are in the particulate form (Pitt et al., 1995). Therefore, removal of fine sediment and organic matter often removes a large percentage of the pollutant load as well (Karr and Schlosser, 1977; Peterjohn and Correll, 1985; Osborne and Kovacic, 1993). Changes in water chemistry can result in pollutants changing form (i.e. metals adsorbed to particulate can become soluble as pH changes) from particulate to dissolved.

Nutrient pollution can result in cultural eutrophication of receiving waters. This can result in rapid increases in algal biomass or algal “blooms”. These blooms can consist of toxic and non-toxic algae (Welch, 1992). The subsequent die-off and decomposition of algal biomass can also significantly reduce dissolved oxygen levels and impair or kill

freshwater biota (Welch, 1996). In the PNW, phosphorus is usually the “limiting nutrient” and therefore is of greatest concern with freshwater, meaning that this nutrient controls primary production. Although lakes can be more susceptible to eutrophication than lotic systems (streams and rivers), streams flow into other water bodies and so can transport excess nutrients. Nitrogen is often limiting in marine systems and as such is of concern in nearshore and estuarine areas. In developed watersheds, typically the largest source of excess nutrients in agricultural and residential areas is fertilizers applied to crops and lawns which washes off and runs into streams, wetlands, and lakes (Barth, 1995). Human and animal waste products also contribute to the nutrient load.

There have been numerous research studies on the use of riparian forest buffers and VFS to remove pollutants from runoff. By far the most studied group of pollutants are the nutrients, with bacterial contamination from animal or human waste a close second. In contrast, there has been little research on the removal of chemical pollutants using riparian vegetation, although biofiltration BMP’s have been shown to be effective under certain conditions. The research on pollutant removal by riparian buffers and vegetated filter strips is summarized in Table 4. A detailed discussion of buffer effectiveness in the removal of nutrients and other pollutants can be found in the most recent literature review by Wenger (1999). A brief summary is included below and in Table 4.

Riparian buffers and VFS can effectively trap particulate phosphorus (sediment) in runoff from agricultural areas or development sites, but they do not provide long-term storage and are generally not effective in removing soluble phosphorus (Peterjohn and Correll, 1984; Lowrance et al., 1997; Lowrance, 1998). Buffers and VFS can also become “saturated” with phosphorus when all soil binding sites are filled. Continued inputs of phosphorus will result in export of soluble P into the stream system (Daniel and Moore, 1997; Lowrance et al., 1997; Lowrance, 1998). Trapped phosphorus may also leach into the groundwater table over time and enter the stream in soluble form through that route (Omernik et al., 1981; Osborne and Kovacic, 1993; Mander, 1997). As is the case for sediment control, effective nutrient control (N& P) requires relatively wide and continuous buffers around all streams, including ephemeral and intermittent channels (Gilliam, 1994). Modeling in a Wisconsin agricultural watershed indicated that a continuous 100 m around all streams would reduce phosphorus by over 50% over a one year period (Sorano et al., 1996).

Nitrogen removal by riparian vegetation tends to be more effective than for phosphorus, mainly due to the natural vegetative uptake and denitrification processes that take place in riparian forests, wetlands, and groundwater (Lowrance, 1985). The amount of nitrogen reduction depends on the pathway the runoff/groundwater takes. Removal efficiencies of 50-80% are common for surface runoff and 80-95% for subsurface pathways (Wenger, 1999).

Riparian buffers alone are not enough to mitigate the effects of upland land-use activities that create soil erosion, runoff, and NPS pollution. Under natural conditions, sediment and nutrient runoff is typically very low. Buffers should be considered as backup measures to the primary best management practices that control the generation

of these pollutants at their source (Binford and Buchenau, 1993; Barling and Moore, 1994; May et al., 1997). It is usually cheaper and easier to control pollutants at their source than to treat them after they have entered the runoff stream. This means improving construction site erosion control, stormwater runoff treatment, logging practices, and agricultural practices.

Width	Citation	Notes
4 m	Doyle et al., 1997	N/P/K/FC reductions in forested buffer and grass VFS
4.6-9.1 m	Madison et al., 1992	90-96% removal of N & P using VFS; 7-12% slopes
7 m	Hubbard and Lowrance, 1992	N uptake and denitrification in forested buffer
5-9 m	Dillaha et al., 1988	54-84% removal of N & P using VFS; 11-16% slope
5-9 m	Magette et al., 1989	41-53% P removal via VFS; 3-5% slope
8-16 m	Vought et al., 1994	66-95% P removal via VFS
10 m	Xu et al., 1992	95% removal of N in forested buffer
10 m	Petersen et al., 1992	Minimum buffer width for effective P removal
16 m	Jacobs & Gilliam, 1985	Minimum buffer width for effective N removal
16 m	Osborne and Kovacic, 1993	96% N removal
19	Shisler et al., 1987	80-90% removal of P & N in coastal, forested riparian buffers; 1-2% slope
20 m	Schultz et al., 1995	Nutrient removal in a multi-species riparian buffer strip
23-92 m	SCS, 1982	FC removal in VFS
20-28 m	Mander et al., 1997	67-81% P removal
15-30 m	Wenger, 1999	N-Removal
30 m	Lynch et al., 1985	Fecal Coliform and N removal
30 m	Grismer, 1981	Fecal Coliform removal
30-43 m	Jones et al., 1988	Nutrient and Fecal Coliform removal
36 m	Young et al., 1980	Nutrient removal VFS
30 m	Terrell & Perfetti, 1989	Minimum width for effective nutrient removal in forested riparian areas
50-60 m	Lowrance, 1992	94% N removal
50 m	Peterjohn and Correll, 1984	73-84% P removal; 5% slope (VFS)
61	Terrell & Perfetti, 1989	Effective removal of animal waste (FC)
183 m	Terrell & Perfetti, 1989	Removal of nutrient pollution by herbaceous or cropland VFS
91.5 m	Vanderholm & Dickey, 1978	80% nutrient removal on a 0.5% slope
262 m	Vanderholm & Dickey, 1978	80% nutrient removal on a 4% slope
Variable	Bingham et al., 1980 Overcash et al., 1981	Found that a 1:1 ratio of VFS buffer area to livestock production area was effective in removal of nutrients and FC

Table 4: Buffer Research on Pollutant Removal.

Large Woody Debris and Organic Matter Input

Forest ecosystems adjacent to stream corridors provide a significant portion of the organic matter into aquatic food webs (Budd et al., 1987). These so-called allochthonous inputs are an important feature of stream-riparian ecosystems. Riparian plant communities determine the quantity, quality, and timing of nutritional resources delivered to the stream channel (Swanson et al., 1982; Gregory et al., 1991; Naiman and Decamps, 1997). Leaves, fruit, cones, insects and other organic matter fall directly into the stream channel from the riparian area, or move by wind, erosion or as dissolved materials in subsurface water flowing from the hyporheic zone (Gregory et al. 1991; Naiman et al. 1992; Naiman et al., 2000). A majority of the plant material input from deciduous riparian forests typically are leaves that are delivered to the stream over a six to eight week period during autumn. Cones, needles, and woody debris (large and small) make up a significant percentage of the overall organic material delivered from coniferous riparian forests (Naiman et al., 1992). Leaves from deciduous trees are generally high in nutrients and break down for processing in four to six months, whereas conifer needles may persist in streams for one to two years (Swanson et al., 1982). Shrub and herb-dominated riparian communities also provide significant input to many streams (Gregory et al., 1991). These allochthonous materials (CPOM) are processed by shredder and collector type macroinvertebrates that break down wood fragments, needles, leaves and other debris into smaller pieces (FPOM).

Large woody debris (LWD), such as branches, logs, uprooted trees, and root wads, are an important component of aquatic habitats in most forested riparian areas, both as a structural element and as cover for instream biota from predators or protection from high streamflows. Large woody debris helps form channel features such as pools, riffles, side channels, meanders, and adds hydraulic complexity. Stream complexity is essential for many aquatic organisms because at various life cycle stages they require different types of habitat.

LWD also controls the routing of water and sediment, dissipates stream energy, protects streambanks, stabilizes streambeds, helps retain organic matter, and acts as a surface for biological activity (Swanson et al., 1982; Harman et al., 1986; Bisson et al., 1997; Sedell et al., 1988; Bilby and Ward, 1989; Gregory et al., 1991; Naiman et al., 1992; FEMAT, 1993; Spence et al., 1996; May et al., 1997). Large woody debris enters streams either directly from the adjacent riparian area or from hillslopes through a variety of mechanisms including toppling of dead trees, wind-throw, debris avalanches, undercutting of streambanks and redistribution from upstream (Naiman et al. 2000). Over time, the influence of LWD may change, both in terms of its function and location within the watershed, but its overall importance is significant and persistent. The characteristics of riparian vegetation determine the age, species, diversity, and size of the woody debris entering the stream, which in turn influences the persistence of LWD in the channel. For example, hardwoods generally decompose more quickly than conifers (Naiman et al., 2000). Conifers, therefore, have a greater ability to form and maintain structural features over time (Naiman et al., 2000).

In smaller headwater streams, woody debris is generally large enough to influence instream hydraulics (Naiman et al. 1992). This results in less erosion to the streambed and banks, more sediment storage in the channel, and slower downstream movement of organic debris. By delaying transport of sediment downstream, rapid changes in sediment loading can be avoided (Swanson et al., 1982; Bilby and Ward, 1989; Naiman et al., 1992; Spence et al., 1996). The delayed transport of organic material downstream enhances its use as either a nutritional resource or habitat by aquatic organisms (Swanson et al., 1982; Bilby and Ward, 1989; Gregory et al., 1991). The ability of the stream to retain organic matter is enhanced when small woody debris, such as branches, sticks, and twigs accumulates, trapping leaves and other organic matter (Gregory et al., 1991).

Large woody debris becomes increasingly important in creating fish habitat in mid-section zones where it is a dominant channel-forming feature. In streams where LWD spans the width of the channel, it redirects the flow of water and alters water velocity, creating complexity and a number of pool types that are used by juvenile fishes during summer (Naiman et al. 1992). Large woody debris in low-gradient zones is less of a channel-forming feature than in mid-section zones. In areas where LWD commonly accumulates, such as along outside bends of riverbanks and on upstream ends of islands, it influences meander cutoffs, provides cover for juveniles, and serves as habitat for invertebrate production (Naiman et al. 1992).

LWD is an integral component of PNW streams. There is no other structural component as important to salmonid habitat as LWD. LWD performs critical functions in forested lowland streams, including dissipation of flow energy, streambank protection, streambed stabilization, sediment storage, and providing instream cover and habitat diversity (Harmon et al, 1986; Bisson et al, 1987; Gregory et al, 1991). And, although the influence of LWD may change over time, both functionally and spatially, its overall importance is significant and persistent. LWD causes a variety of physical and hydraulic changes to occur in the stream channel. These inchannel interactions can vary considerably depending on the channel gradient and type. Biological changes typically follow the physical changes (Harmon et al, 1986). The physically-induced biological influences of LWD are substantial. Fish populations have been shown to decline following LWD removal or loss (Bryant, 1983; Hicks et al, 1991; May et al., 1997). LWD in the low-gradient streams found in this region has the greatest range of functional influences (Bilby and Ward, 1989 and 1991). Keller and Swanson (1979) found that LWD fine sediment storage in low-gradient stream channels was very significant. Streambank protection and streambed stability are also controlled by LWD abundance and distribution in forested streams of this region (Bilby, 1984). Hydraulic roughness can increase by more than 50% due to disruption of flow by individual pieces of LWD or debris jams (Smith et al, 1993). Creation of high-flow refugia is also an important function of LWD. Pool formation in particular can be almost completely determined by the quantity and distribution of LWD in forested streams. Pool frequency has been shown to be directly proportional to LWD frequency and pool depth, surface area, and cover-quality are also directly related to LWD quantity and quality (Andrus et al, 1988; Robison and Beschta, 1990; Ralph et al, 1994). In general, natural stream channels of the PNW region tend to contain an abundance of LWD.

The riparian width appropriate for long-term, natural levels of LWD recruitment and retention varies from a low of 30 meters (Murphy and Koski, 1989) to a high of 55 meters (Thomas et al., 1993). Murphy and Koski (1989) also found that small (10 m) buffers only provided about 50% of the natural levels of LWD (Table 3). In a more recent study in New Zealand (Collier et al., 1995) the riparian forest width required to support instream habitat needs (LWD) was expressed as a function of “site potential tree height” (SPTH). It was determined that a minimum of one SPTH was necessary for maintaining natural levels of instream LWD and up to three SPTH may be needed in some cases. SPTH for PNW lowland streams varies from 60-90 meters, depending on the tree species and local growing conditions. It is generally accepted that a minimum riparian width of one SPTH is appropriate to meet long-term LWD recruitment requirements in PNW streams (see Table 5 and Figure 17). For the PSL eco-region, one SPTH is approximately 30-50 meters.

Width	Citation	Notes
20-30 m	Murphy & Koski, 1989	Based on natural LWD recruitment under various forest conditions
15-46 m	McDade et al., 1990	Based on natural LWD recruitment under various forest conditions
31 m	Bottom et al., 1983	Instream habitat/LWD restoration study only
45 m	Harmon et al., 1986	Comprehensive study of the ecology of LWD
46 m	Robison & Beschta, 1990	LWD Recruitment
50 m	Van Sickle & Gregory, 1990	LWD Recruitment
50 m	Collier et al., 1995	LWD Recruitment
55 m	Thomas et al., 1993	FEMAT minimum for LWD Recruitment
1 SPTH	Spence et al., 1996	LWD Recruitment
1 SPTH	FEMAT, 1993	Multiple SPTH may be required depending on site conditions for natural LWD recruitment
200 m	Hennings, 2001	Buffer width required to minimize non-native vegetation intrusion

Table 5: Buffer Research on Large Woody Debris (LWD) Recruitment.

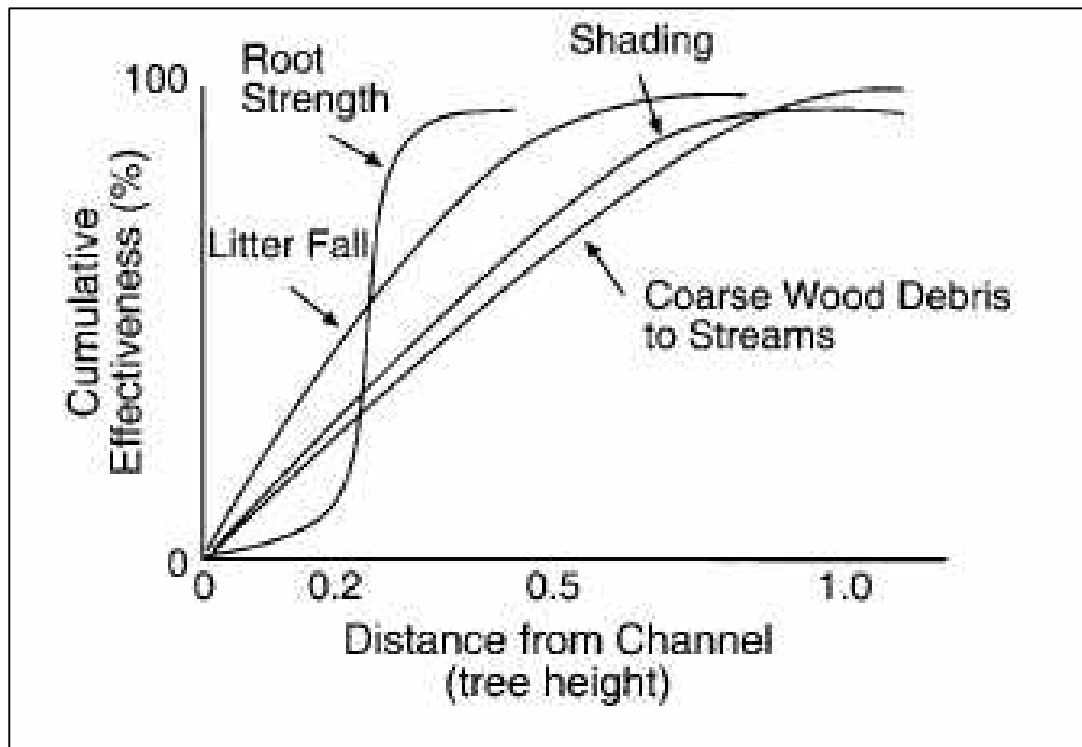


Figure 17: Cumulative Effectiveness of Riparian Forest Functions Relative to the Distance from the Edge of the Stream, expressed as Fractions of Site Potential Tree Height (SPTH). Modified from FEMAT (1993).

Wildlife Habitat

Natural riparian areas are biologically diverse and complex ecosystems that contain more plant, mammal, bird, and amphibian species than the surrounding upland areas (Kauffman et al. 2001). Wildlife use riparian corridors more than any other type of habitat (Thomas et al. 1979). Riparian areas provide several functions important to wildlife, including:

- Food and Water
- Protective Cover
- Movement corridor
- Microclimate

The ability of the riparian corridor to attract and support fish and wildlife is dependent on the structural and functional integrity of the aquatic, riparian and upland ecosystems (Brinson et al., 1981; Knutson and Naef, 1997). The influence riparian areas exert on a stream is related to the size of the stream, its location in the watershed, the hydrologic pattern and local landforms (Naiman et al., 1992). Wildlife are attracted to riparian areas because of the abundance of food sources, cover, and proximity of drinking water. Access to water is critical for both riparian-dependent wildlife and for many upland species, especially in urban areas where access can be a limiting factor.

Riparian areas are especially important areas during breeding season and provide wildlife with an energy-efficient habitat for rearing young due to the close proximity of food, water and cover, thereby minimizing energy expenditures by the adults and young.

The greater availability of water to plants in riparian areas increases plant biomass production, providing a complex and highly productive food web. Seeds, herbaceous vegetation and fruits, aquatic and terrestrial insects, and fungi are plentiful (Thomas et al., 1979; Knutson and Naef, 1997; Johnson and Ryba 1992). Riparian areas also provide predators with an abundance of prey species (Knutson and Naef, 1997). Riparian vegetation in the form of grasses, shrubs, trees and other plants provides wildlife habitat for reproduction, nesting, roosting, foraging and protection from the weather and from competitive and predatory species. Riparian areas often contain unique plant communities, both in composition and structural complexity (Kauffman et al., 2001). Structural complexity exists when there is a diversity of plant species, multiple canopy layers (e.g., deciduous vs. coniferous; shrubs vs. trees), and snags and downed woody material (Thomas et al., 1979; Knutson and Naef, 1997; Kauffman et al., 2001).

Many wildlife species are associated with specific plant communities; some require a certain age (e.g., old growth or pioneer species). Riparian zones exhibit high diversity of wildlife species because of the complexity and diversity of habitat they provide for obligate riparian species, species seeking edge habitat, and species associated with early successional plant communities (Naiman et al., 2000). Table 6 shows a summary of this information for the coastal eco-region of the PNW (Kelsey and West, 1998). In addition to *riparian obligates*, riparian zones also support *riparian generalists* or species that use both riparian and upland habitats. Riparian corridors also serve as migration or dispersal corridors for a variety of species (Kelsey and West 1998). In general, riparian obligates depend on certain habitat characteristics associated with stream size. The riparian wildlife communities that large rivers support can differ greatly from those associated with small streams. Wildlife species also respond to habitat characteristics associated with forest successional stage that is largely determined by the type, frequency, duration, and severity of disturbance (Naiman et al., 2000). For example, the presence and distribution of “snags and LWD piles in riparian zones has a positive influence on avian community diversity as well as on the species richness and abundance of small mammals (Steel et al., 1999). Some species of invertebrates, birds and mammals rely on snags (standing dead trees) and downed and dead wood for a portion of their life history. Downed and dead woody material in various stages of decay provide diversity in the environment and are of varying significance for wildlife habitat (Thomas et al. 1979). Much of the biodiversity and productivity of the riparian area would disappear without this woody debris accumulation (Naiman et al., 1992).

The linear nature of riparian areas maximizes the development of edge habitat, an area where two different plant communities, successional stages, or vegetative conditions meet (Thomas et al., 1979). Some species benefit from the availability of edge habitat because edges contain plant communities that are characteristics to each adjoining habitat (Knutson and Naef, 1997). Although edge habitat can promote high wildlife

diversity, it can also have a negative impact on some species associated with interior portions of the riparian area .

Many wildlife populations rely on their ability to move between different types of habitat along riparian corridors, especially for species that would not otherwise cross large openings (Palone and Todd, 1997). Riparian corridors, because of their linear shape, enable movement of wildlife between habitat patches (Thomas et al., 1979; Harris, 1984; Noss, 1987; Palone and Todd, 1997). Dispersal and establishment of new territories for feeding and breeding is important for many species. This allows for an exchange of genetic material between species populations and is critical for resilience to disease and other negative impacts (Cohen, 1997). At least 95 percent of all terrestrial species in North America depend on migration corridors (Cohen, 1997), many of which are also riparian corridors. Riparian corridors also play a potentially important role within landscapes as corridors for plant dispersal and, according to Gregory et al. (1991), may be an important source of most colonists through the landscape.

Historically, animals have been viewed as passive components of riparian ecosystems, merely responding to the local conditions. In many cases, however, animals are responsible for biogeochemical, successional, and landscape alterations that may persist for centuries (Naiman et al., 2000). For example, in riparian zones, the numbers of animals and the abundance and quality of food vary constantly but irregularly in time and space. These variations are connected with variations in abundance of some animals and have indirect effects on the abundance of others, thereby affecting system-level characteristics. For example, selective foraging by some large mammals such as beaver can change plant species composition, nutrient cycling rates, and soil fertility (Naiman et al., 2000). Selective browsing by deer and elk on hardwood species (e.g. maple and alder) and certain conifers (e.g. western red cedar and Douglas fir) allows less browsed conifers (e.g. Sitka spruce and western hemlock) to dominate the riparian landscape (Schreiner et al., 1996).

Pacific salmonids traditionally have been viewed primarily as products of their aquatic habitats. However, anadromous salmon play a key role in the nutrient and trophic dynamics of both aquatic and riparian ecosystems (Kline et al. 1994, Bilby et al. 1996, Ben-David

et al. 1998; Willson et al., 1998). More than 95% of the body mass of Pacific salmon is acquired in the ocean, but this material is transported and deposited in the freshwater habitats in which salmon spawn and die (Naiman et al., 2000). The significance of this nutrient and organic matter subsidy has long been recognized, however, until recently, little quantitative information was available on the contribution of salmon-derived nutrients to riparian corridors. Transfer of marine-derived nutrients (MDN) from the stream to riparian areas occurs by three processes (Naiman et al., 2000). First, elevated flows transport and deposit carcasses in the riparian area where they decompose and make their nutrients available to plants. Second, dissolved nutrients from the carcasses carried in stream water may enter the hyporheic zone beneath the riparian area. This makes the salmon-derived nutrients available to riparian vegetation via root system uptake. Third, predators or scavengers may remove salmon from the

stream and carry them to the riparian area, where they are consumed or cached for later use. Subsequent deposition of waste products by these animals can distribute MDN at great distances from the channel (Cederholm, 1989). In western Washington and southeastern Alaska, nitrogen derived from the carcasses of salmon often constitutes a substantial proportion of the nitrogen in the foliage of riparian plants (Bilby et al., 1996). Examination of the spatial distribution of MDN in riparian ecosystems of Alaska, also reveals that a substantial portion is of marine origin (Ben-David et al., 1998). The lateral extent of MDN deposition varies by site and plant species and is influenced by the presence of predators and carcass scavengers. A large number of riparian vertebrates use salmon as a food resource. Over 22 species of mammals and birds were found to feed on salmon carcasses along streams on Washington's Olympic Peninsula (Cederholm, 1989), and over 40 species have been found to forage on salmon in southeast Alaska (Willson and Halupka 1995).

Based on current research, 85% of all Washington's terrestrial vertebrates (birds, mammals, reptiles, and amphibians) utilize the stream-riparian ecosystem during some or all of their life histories (Knutson and Naef, 1997). A diverse array of wildlife species utilize the stream and riparian forest for food, water, shelter, nesting, rearing, and as a migration corridor. Generally, most wildlife researchers advocate preserving or restoring as wide a riparian corridor as possible (Schafer and Brown, 1992), but most agree that even a narrow buffer will enhance the habitat for most species (Wenger, 1999). It is important to remember that any loss of biodiversity can have significant negative impacts on entire ecosystems. As was discussed earlier, salmonids play an integral role in the stream-riparian ecosystems of the PNW. The complex linkages between salmonids and other species in this ecosystem is not fully understood (Willson et al., 1998). We would be wise and take this into account when designing riparian buffers so as to support as many interconnected species as possible and not narrowly focus on just fish habitat. Table 7 summarizes the research supporting riparian areas for wildlife. The wide range of riparian requirements supportive of various wildlife species makes selection of a buffer width quite difficult.

Riparian obligates	Upland specialists	All species	Riparian obligates	(%) ^b
Amphibians	18	7	30	60
Reptiles	3	12	19	16
Birds	78	93	231	34
Mammals	13	31	107	12
Total	112	143	387	29

^aFrom Kelsey and West (1998).

^bThe proportion of riparian obligates to all species is shown in this column.

Table 6: Numbers, by Taxonomic Class, of native Upland and Riparian Obligate Species as Compared to all Species in the Pacific Coastal Eco-Region.^b

Width	Citation	Notes
30 m	Roby et al., 1977	Macroinvertebrates
30 m	Newbold et al., 1980	Macroinvertebrates
30 m	Erman et al., 1983	Macroinvertebrates
30 m	Gregory et al., 1987	Macroinvertebrates
30 m	Raleigh et al., 1986	Chinook salmon (minimum)
30 m	Hickman & Raleigh, 1982	Cutthroat trout (minimum)
30 m	Moring, 1982	Minimum for normal salmonid egg survival
>30 m	May et al., 1997	Macroinvertebrates and salmonids
>30 m	Erman et al., 1977	Macroinvertebrates
30-70 m	Castelle et al., 1992	Salmonids
30-95 m	Rudolph & Dickson, 1990	Reptiles & amphibians
30-100 m	Allen, 1983	Beaver foraging
30-70 m	Cross, 1985	Small mammals
67-93 m	Jones et al., 1988	Small mammals
75-100 m	Gomez and Anthony, 1996	Oregon reptiles and amphibians
70 m	Kinley and Newhouse, 1997	Birds in riparian corridors of BC
20-70 m	Knutson and Naef, 1997	Salmonids
10-100 m	Harris, 1985 Groffman et al., 1990	Noise Reduction
100 m	Burbrink et al., 1998	Reptiles and amphibians
100 m	Machtans et al., 1996	Movement corridor for birds
100 m	NRCS, 1995	Beaver habitat
>100 m	Keller et al., 1993 Hodges and Kremetz, 1996	Riparian corridor bird habitat
150-175 m	Spackman and Hughes, 1995	Bird nesting and feeding
50-100 m	Hodges and Kremetz, 1996 Tassone, 1981 Keller et al., 1993	Neo-tropical bird habitat and "edge-effect"
100-200 m	Grubb, 1980 Skagen, 1980 Small, 1982 Stalmaster, 1980	Bald Eagle nesting and feeding
100-250 m	Short and Cooper, 1985	Great Blue Heron nesting and feeding
100 m	Jones et al., 1988	Minimum for migration corridor for large mammals
100 m	Environment Canada, 1998	Minimum for interior habitat and migration corridor
50-125 m	Darveau et al., 1995 Kinley and Newhouse, 1997 Tassone, 1981 Kilgoe et al., 1998 Sedgewick and Knopf, 1986 Croonquist and Brooks, 1993	Birds; nesting, migrating, and feeding
200 m	Castelle et al., 1992	Eagle Nest and Heron Rookery Deer and Elk Habitat
30-200 m	FEMAT, 1993	General Wildlife Habitat and Migration Corridors

Table 7: Riparian Research on Wildlife Habitat.

Riparian Buffers

Riparian management is often complicated by confusion over the terminology used. There should be a clear distinction made between the use of terms associated with natural riparian areas and the “buffers”. The riparian corridor, the riparian community, and the floodplain or channel migration zone (CMZ) all are ecologically defined terms that refer to components of the stream-riparian ecosystem. A riparian “buffer” refers to a strip of land that is jurisdictionally established to mitigate the impacts on the stream system from human activities in the surrounding watershed (Johnson and Ryba, 1992). The use of vegetated buffers has become a common practice in efforts to protect sensitive aquatic resources such as streams and wetlands or to mitigate the impacts of surrounding land-use activity (Castelle et al., 1994). Buffers are also commonly regulated within critical area ordinances (CAO) to mitigate for the impacts of land-use activities on steep or potentially unstable slopes and other “sensitive” areas.

In addition to the protecting the natural functions of the riparian corridor outlined in the previous section, riparian buffers can provide the following functions:

- Reducing the encroachment of human land-use activities into the stream-riparian ecosystem.
- Minimizing the water quantity and water quality impacts of stormwater runoff and non-point source (NPS) pollution on aquatic ecosystems.
- Preventing property loss or loss of human lives due to high stormflows or flooding events in the defined floodplain area.

As was discussed earlier, in some cases, vegetated “filter-strips” (primarily grass) have been used as buffers to reduce the impact of agriculture and stormwater runoff on downstream aquatic resources. These vegetated filter-strips (VFS) may also utilize trees and wetland plants to filter out sediment and pollutants. In general, VFS are designed primarily for pollutant removal and do not provide for other critical riparian functions such as organic matter recruitment, temperature control, or wildlife habitat.

Impacts of human activities on stream-riparian ecosystems are numerous and highly variable (see Table 8). The effects of land-use activities are often due to multiple stressors and are usually cumulative in their impact (May et al., 1997). The characteristics of the stream-riparian ecosystem will also influence the extent and intensity of the human-induced disturbance. Variables such as stream size, location within the watershed, stream gradient, valley configuration, valley side-slope, watershed topography, soil type, riparian vegetation conditions, rainfall patterns, and others all combine to make some stream-riparian ecosystems more or less sensitive to human impacts (Wenger, 1999). For example, a stream with an extensive floodplain area will react quite differently than a stream within a deep, steep-walled ravine. So too will streams in watersheds dominated by glacial till soils as compared to those dominated by glacial outwash soils.

Forest management activities within a watershed have been shown to have a significant negative impact of the stream-riparian ecosystem (Steinblums et al., 1984; Bilby, 1988; Meehan, 1991; NRC, 1996; Young, 2000). Timber harvest and logging roads can directly or indirectly impact the ecological integrity of the stream-riparian ecosystem. Reduced shade, increased fine sediment inputs, and reduced LWD quantity and quality all can result from poor forest management operations. Riparian buffers have been used extensively to reduce the impacts of timber harvest. In fact, much of the research on the effectiveness of forested buffers, has focused on mitigation of logging impacts (Johnson and Ryba, 1992).

Agricultural activities such as farming and livestock grazing can also have a significant negative impact on stream-riparian ecosystems (Lowrance et al., 1984; Dillaha et al., 1989; Meehan, 1991). The quality of agricultural runoff can significantly affect stream water quality. The Washington Department of Ecology (WDOE) has identified small farms in floodplain and upland areas of watersheds, as a significant source of NPS pollution, including fecal coliform (FC) bacteria from livestock waste, fine sediment from exposed soil, nutrients from fertilizers, and toxic pollutants from pesticides and herbicides. This has been identified as a significant problem in Kitsap County as well (KCHD, 1999). Improper grazing practices can also degrade the stream-riparian ecosystem in other ways, including loss of riparian vegetation due to grazing, erosion of streambanks due to livestock access, and increased turbidity from fine sediment inputs. In general, research has indicated that use of proper agricultural BMP's, limiting livestock access to the stream and riparian area using fencing and maintenance of vegetative buffers along the riparian corridor can significantly reduce the impacts of agricultural activities (Lowrance et al., 1984; Lowrance et al., 1997; Lowrance et al., 1998).

Watershed urbanization, which includes rural, suburban, and urban development can also have significant negative impacts on the ecological integrity of the stream-riparian ecosystem (May et al., 1997; Leavitt, 1998; May and Horner, 2000; Booth et al., 2001). Little is known about the effectiveness of riparian buffers in mitigating for the cumulative impacts of urbanization, but research indicates that a combination of riparian buffers, land-use controls, and an aggressive SWM program may be the best strategy (Horner and May, 1999; May and Horner, 2000; Horner et al., 2002). Due to the diverse nature of development impacts, buffers alone will not be enough. The direct impacts of development on the stream-riparian ecosystem include the following:

- Loss of riparian forest quantity and quality due to encroachment.
- Fragmentation of the riparian corridor due to road and utility crossings.
- A shift in the natural hydrologic regime from subsurface flows (groundwater and interflow) to a surface dominated regime as a result of loss of watershed forest cover and the proliferation of impervious surfaces.
- Degraded water quality due to NPS pollution and stormwater runoff.

The appropriate buffer size will depend on the spatial area necessary to maintain the desired riparian functions and on the combination of land-use activities that are influencing the stream-riparian ecosystem. For example, a wider buffer may be required

in situations where high-intensity land-use is found, than in areas of low-intensity land-use. Similarly, all else being equal, a sensitive tributary stream used extensively by aquatic biota may require larger buffers than does a mainstem stream used only as a migration corridor by wildlife.

Of equal importance to buffer size (width and extent of the corridor) is the quality of the riparian area in terms of vegetation type, diversity, physical condition, and maturity. Ideally, the riparian corridor in a developing or developed watershed should mirror that found in the natural ecosystems of that region. Due to the cumulative impacts of past and present land-use, this is often not the case (May et al., 1997). Many streams have narrow, fragmented riparian corridors that lack the mature coniferous trees, which characterize the few, pristine watersheds that remain. In general, the relatively young, riparian forests that are common in many watersheds do not provide function all of the functions that mature riparian forests do (May et al., 1997). The supply of allochthonous organic matter and woody debris provided to the stream, the rain interception capacity of the canopy, and the shade are all different than natural riparian forests. In addition, exotic and invasive vegetation is more common in impacted riparian corridors than in wide, natural corridors (Hennings, 2001). In short, the quality of riparian buffers we manage should closely mimic if not equal that of natural ecosystems.

In general, native vegetation is preferred over exotic or landscaped plantings for riparian buffers. The exception to this is the use of vegetated filter strips (VFS), usually grass to treat stormwater or agricultural runoff. These VFS can be quite effective if sheet flow is maintained, the system is not overloaded with sediment, and the soils allow for infiltration (Karr and Schlosser, 1977; Dillaha et al., 1989; Osborne and Kovacic, 1993; Daniels and Gilliam, 1996). Upland erosion control, sediment source controls, and proper maintenance are critical to the long-term effectiveness of a VFS (Dillaha et al., 1989; Barling and Moore, 1994; Horner, 1996).

Natural riparian corridors are generally nearly continuous throughout the stream-riparian ecosystem (Naiman and Bilby, 1998). In addition to buffer width and quality, management of the riparian corridor should also focus on minimizing fragmentation (see Figure 18). Road crossings, utility right-of-ways, and other breaks in the riparian corridor effectively reduce the buffer width to zero and provide a conduit for runoff and pollutants to enter the stream (Schueler, 1995; May et al., 1997; Weller et al., 1998). Breaks in the riparian corridor should be kept to a minimum so as to reduce corridor fragmentation.

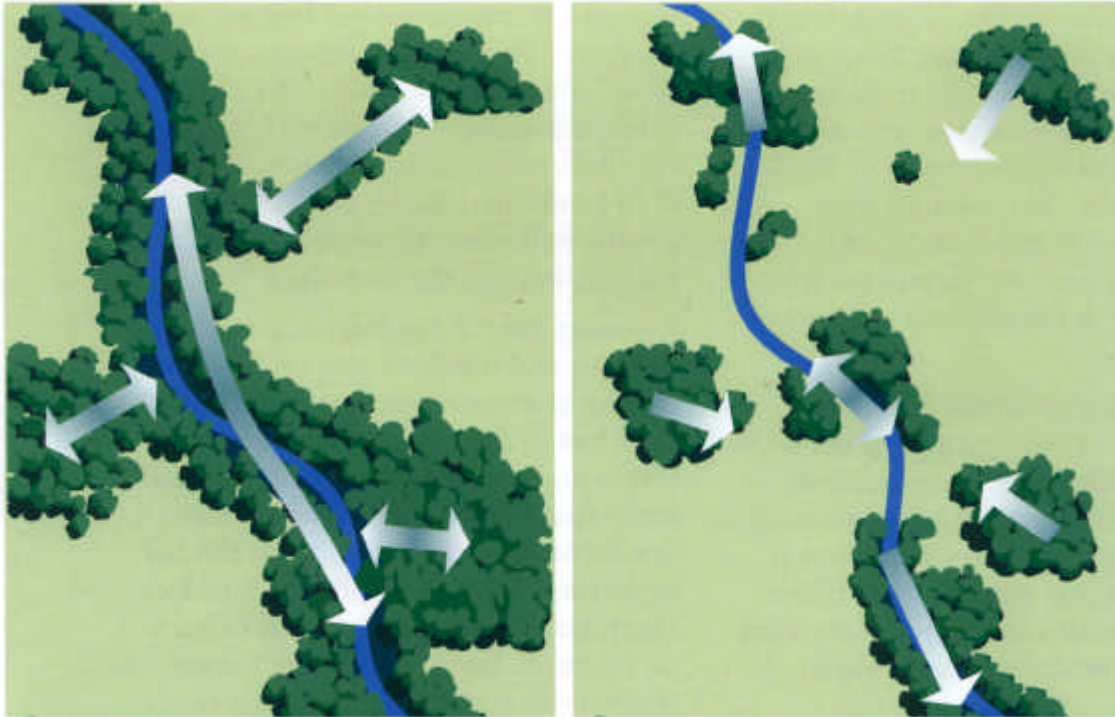


Figure 18: Riparian Corridor Fragmentation (NRCS, 1995).

Buffer Effectiveness

In order to balance conservation of our valuable natural resources with the need for continued development, we need a comprehensive management strategy. The use of riparian buffers is only one component in an effective watershed management approach. In addition to buffers along the stream-riparian corridor, we need to improve the effectiveness of our stormwater management (SWM) best management practices (BMP), reduce watershed imperviousness, and retain/enhance natural forest cover throughout our watersheds (May et al., 1997). Ecologically-based land-use and development practices appear to be our best hope for conservation of our aquatic resources. In managing our watersheds, we should establish conservation and restoration goals that support a properly functioning, natural stream-riparian ecosystem.

Buffers can be ‘fixed’ or ‘variable’ in width. Fixed-width buffers are generally the product of political compromise between protecting a natural resource and minimizing the impact on development and private-property rights. Buffers of this type, unless conservatively designed and managed, often fail to support all the ecological functions of the riparian corridor. Variable-width buffers have the potential to be more ecologically based, but are difficult to administer by jurisdictions.

Potential changes in riparian elements needed by fish and wildlife	Land use						
	Forest practices	Agriculture	Unmanaged grazing	Urbanization	Dams	Recreation	Roads
Riparian Habitat:							
altered microclimate	X	X	X	X		X	X
reduction of large woody debris	X	X	X	X	X	X	X
habitat loss/fragmentation	X	X	X	X	X	X	X
removal of riparian vegetation	X	X	X	X	X	X	X
reduction of vegetation regeneration	X	X	X	X	X	X	X
soil compaction/deformation	X	X	X	X		X	X
loss of habitat connectivity	X	X	X	X		X	X
reduction of structural and functional diversity	X	X	X	X		X	X
Stream Banks and Channel:							
stream channel scouring	X	X	X	X		X	X
increased stream bank erosion	X	X	X	X	X	X	X
stream channel changes (e.g., width and depth)	X	X	X	X	X	X	X
stream channelization (straightening)	X	X		X			
loss of fish passage	X	X	X	X	X		X
loss of large woody debris	X	X	X	X	X	X	X
reduction of structural and functional diversity	X	X	X	X	X		X
Hydrology and Water Quality:							
changes in basin hydrology	X	X		X	X		X
reduced water velocity	X	X	X	X	X		
increased surface water flows	X	X	X	X		X	X
reduction of water storage capacity	X	X	X	X			X
water withdrawal		X		X	X	X	
increased sedimentation	X	X	X	X	X	X	X
increased stream temperatures	X	X	X	X	X	X	X
water contamination	X	X	X	X		X	X

Table 8: Land-Use Impacts on Riparian Corridors.

It is generally recognized that designing an effective stream-riparian buffer involves the use of five basic criteria (Johnson and Ryba, 1992; Castelle et al., 1994; Wenger, 1999). These should include, but may not be limited to:

1. The ecological, cultural, and economic value of the resource being protected.
2. The type and intensity of the adjacent land use.
3. The vegetative characteristics (vegetation type, diversity, and maturity) of the riparian area and the buffer zone. This is often referred to as riparian quality.
4. The condition of the riparian corridor throughout the entire stream system. This addresses the cumulative impact concept of watershed management.

5. The stream-riparian functions being supported and the sensitivity of the resources being protected.

As the above criteria indicate, a “one-size-fits-all” buffer likely will not work. This would argue for a watershed-by-watershed, stream-by-stream, and site-by-site approach. A variable width buffer based on existing environmental conditions and the intensity of the adjacent land use that is generalized to the extent possible might provide the best protection of the riparian corridor while respecting private property rights (Todd, 2000). This integrated, hierarchical approach may look to be a daunting and costly task, but it probably will have to be done if we are to conserve our aquatic resources, protect of water quality, and improve our quality of life. Again, it must be emphasized that buffers alone are not enough to protect instream biota or water quality. Even the best riparian buffer cannot protect instream habitat if the channel is continuously scoured by high flows caused by runoff from impervious surfaces and routed to the stream by stormwater infrastructure.

Just as important as the width, are the activities are allowed within the riparian buffer. Some riparian buffers are implemented as setbacks within which no disturbance is allowed, with the exception of restoration activities. Other riparian buffers are considered “management areas” within which a limited amount of activity may occur. This allows for some level of development as long as guidelines are followed so as to retain riparian functions. Human activities within the riparian buffer should be limited to prevent further degradation of riparian and aquatic habitat.

Riparian Integrity

The term *riparian integrity* will be used to describe the conditions found natural stream-riparian ecosystems. These “properly functioning conditions” should be the template for preservation and recovery efforts. In addition, the riparian integrity framework can be used to evaluate current riparian conditions, set targets for rehabilitation, and provide a means of periodically monitoring riparian conditions for use in adaptive management programs. Riparian integrity includes both structural and functional elements. Such parameters as riparian width, corridor connectivity, riparian forest maturity, wetland extent, floodplain interactions, and vegetation type all combine to determine riparian integrity (see Table 9).

The riparian quality of the stream corridor is as important as the width or extent in determining how well a particular riparian area performs all of the functions required of it. Timber harvest, roads, agricultural activities, and development have significantly impacted the riparian forests of the PNW. Many riparian forests are dominated by dysfunctional stands of alder and maple rather than the cedar-hemlock forests that characterize natural riparian communities. Often all that remains of this natural, functional forest are decaying logs and stumps. Active management needs to begin now so that the next century will see a return to functional native forest corridors. We cannot afford to wait passively for the stream-riparian ecosystem to recover on its own, while instream biota that depend on these systems dwindle to extinction. The natural,

predevelopment vegetative community should be the “target” condition for restoration efforts.

The current vegetative composition and maturity must be factored into any riparian management zone (RMZ) or buffer width design effort. Areas dominated by mature, naturally complex forest have a much higher conservation potential than disturbed areas, young stands of native forest, or exotic vegetation. These mature and naturally diverse riparian areas also perform their required functions more efficiently and tend to be more resilient in recovering from disturbance. This information should factor into any assessment of riparian integrity and subsequent management decisions.

Floodplain connectivity is also critical to a properly functioning stream-riparian ecosystem. This means that the active channel migration zone (CMZ) and floodplain must be included in the RMZ. This is the area where are typically the most conflicts with development and land-use. Both from an ecological and public safety perspective, development should be excluded from the floodplain and CMZ.

Riparian corridor connectivity is also an ecologically critical and often under-emphasized component of riparian integrity. The natural riparian corridors of the PNW are nearly continuous, with few breaks and little unvegetated area. Fragmentation tends to be a direct result of human interactions with the stream-riparian network. Road crossings and land clearing are the most common human activities that fragment the riparian corridor. Riparian fragmentation must be minimized if we are to protect the remaining natural systems and restore those already compromised by human incursions. In addition to minimizing breaks in the stream-riparian corridor, we should attempt to reduce the impact of those crossings deemed necessary. Stream-riparian crossings should be designed for minimal stormwater and other impacts. In general, riparian encroachment must be prevented. This can be done through landowner education and clear delineation of RMZ and buffers.

As has been emphasized, it is also extremely important from an ecological standpoint, that the riparian corridor be nearly continuous (May et al., 1997; Naiman and Bilby, 1998; Wenger, 1999). As stated by Fischer et al. (2000): “Continuous buffers are more effective at moderating stream temperatures, reducing gaps in protection from non-point source pollution, and providing better habitat and movement corridors for wildlife.” Road crossings, utility-line gaps, and other breaks in this corridor fragment the stream-riparian ecosystem and allow direct access of surface runoff into the stream system. This not only compromises the effectiveness of the natural buffer surrounding the stream, but allows pollutants and sediment to enter the stream untreated (May et al., 1997). Near-continuous riparian corridors are especially important along smaller headwater and tributary streams, which make up the majority of stream length in any watershed. These streams are closely linked to the surrounding riparian and upland areas of the watershed. This is where organic matter, LWD, and sediment are most likely to enter the stream system. These headwater and tributary streams tend to have a significant amount of wetland habitat as well. Protection of natural corridors along small headwater and tributary streams may offer the greatest benefits to the stream-riparian ecosystem (Osborne and Kovavic, 1993; Hubbard and Lowrance, 1994; May et

al., 1997). Even ephemeral, seasonal, and intermittent streams should have protected riparian corridors. These channels can retain a significant amount of water and sediment and may carry an appreciable flow (surface and sub-surface) and sediment load during large storm events (Hewlett and Hibbert, 1967; Daniels and Gilliam, 1986; Binford and Buchenau, 1993; Wenger, 1999). In summary, the effectiveness of a riparian corridor protection program depends on the amount of stream miles that are protected; the more miles protected, the more effective a program will be (Wenger 1999).

The entire stream network functions as a system, thus removing the connection between intermittent and perennial streams may have detrimental consequences to the physical and biological components of stream ecosystems, particularly in the long term (FEMAT 1993). Naiman et al. (1992) stated that intermittent streams are an important, often overlooked, component of aquatic ecosystems. As a result, riparian buffers tend to be especially important along the small headwater streams that typically make up the majority of stream miles in any basin (Osborne and Kovacic, 1993; Binford and Buchenau, 1993; Hubbard and Lowrance, 1994; Lowrance et al., 1997; May et al., 1997; Fischer et al., 2000). These smaller streams often have more interaction with the land and riparian vegetation plays an integral role in reducing sediment and other pollutants, maintaining temperature regimes, and providing large woody debris and other organic inputs (FEMAT 1993). Riparian buffers along larger streams may actually have less of an impact on water quality, however they often need to be wider to provide better wildlife habitat (Fischer et al. 2000).

In urbanizing areas the functions of the aquatic ecosystem are generally highly altered (May et al., 1997). Increased urbanization causes an increase in negative inputs such as contaminants, stormwater flow, and also reduces the amount of large woody debris and other organic inputs required for the survival of aquatic life (Booth et al., 1996; May et al., 1997; Todd, 2000). Johnson and Ryba (1992) stated that “a large buffer in an area of high-intensity land use...is more essential than in low-intensity land use areas.”

Index of Riparian Integrity Metric	Excellent (4)	Good (3)	Fair (2)	Poor (1)
Width (lateral extent >30 m, %)	>80%	70-80%	60-70%	<60%
Width (lateral extent >100 m, %)	>50%	40-50%	30-40%	<30%
Encroachment (% <10 m wide)	<10%	10-20%	20-30%	>30%
Corridor continuity (crossings/km)	<1	1-2	2-3	>3
Natural cover (% forest or wetland)	>90%	75-90%	50-75%	<50%
Mature native vegetation or wetland (%)	>90%	75-90%	50-75%	<50%

Table 9: Measures of Riparian Integrity.

Note: These metrics are for the PNW region. Other regions should explore metrics that are specific to their regional ecological conditions.

Recommendations

The following recommendations and the proposed RMZ delineation method are designed to assist resource managers in accomplishing the objectives laid out earlier in this report. Those objectives include conservation, enhancement, and restoration of aquatic resources dependent on the stream-riparian ecosystem. These recommendations are based on the best scientific information currently available. An effort has been made to evaluate the quality and applicability of the riparian studies cited above. We acknowledge that research is limited and there are some uncertainties in the data, but there is adequate information available to make good policy decisions based on “best available science”.

The scientific principles that form the foundation for our riparian management recommendations include the following:

- Maintain or restore the freedom of movement of stream channels to move and change based on environmental and climatic conditions.
- Maintain or restore the connection of the stream to its floodplain. This includes allowing flooding events to modify channel configurations and locations.
- Maintain or restore off-channel habitat, including riparian wetlands and side-channels.
- Allow natural regenerative processes to occur without undo human intervention. Restoration efforts should not conflict with natural processes.
- Protect or enhance biodiversity and habitat complexity within the stream-riparian ecosystem. Recognize and nurture the complexity and diversity of nature. Do not try to mold streams to suit human-based constraints.
- Support or reestablish the longitudinal connections within the stream-riparian corridor. The interactions of headwater areas, mainstem channels, tributaries, and estuaries are critical to the proper functioning of the watershed.

Humans are an integral part of the watershed and ecosystem. In many cases, human actions tend to have a dominant effect on the structure and function of the stream-riparian system. Human activities must be included into the long-term management framework for these natural systems. In protecting aquatic resources, we are also making an investment in our long-term quality of life.

Based on scientific findings, but acknowledging the uncertainties in our current level of knowledge identified by cited research, some conservative recommendations for stewardship of our stream-riparian ecosystems can be made. The rationale for these recommendations is based on the previously cited scientific literature (summarized in Table 10 and Figure 19). The application of basic ecological principles and conservative judgment was also utilized extensively. The goal of these recommendations is to protect, enhance, or restore the structural and functional ecological integrity of our stream-riparian ecosystems.

The recommendations of this report will include the use of variable width riparian corridors that will include the structural and functional components of the stream-

riparian ecosystem, as well as floodplain/CMZ considerations and cumulative impacts of watershed land-use. The term “riparian management zone” (RMZ) will be used to describe this natural area. The RMZ widths shown in Table 10 were selected, based on scientific research, to achieve the optimum level of riparian function, or as close to “properly functioning conditions” (PFC) as possible. In other words, these recommended RMZ widths replicate natural conditions as much as possible, based on our current understanding of stream-riparian ecosystems.

An appropriate goal for undeveloped areas should be to retain an optimal level of riparian integrity and ecological function for those stream-riparian ecosystems, which have been designated as valuable natural resources. This may mean that extensive RMZ will be required to provide for full ecological function in some areas. In addition, significant rehabilitation efforts may be necessary in areas already degraded by past land-use activities (agriculture, timber harvest, etc.), but where development has not occurred and where riparian restoration is achievable.

In some cases, current conditions or land-use constraints may necessitate that a smaller RMZ be designated. For example, a stream may flow through an already developed area, with roads, homes, and other structures currently limiting the extent of the riparian corridor. In these cases, riparian quality may also be degraded significantly. An analysis of riparian integrity should clearly identify these problems. Possible solutions might include establishing a narrower RMZ than would be optimum, but enhancing the quality of that RMZ by extensive plantings of native vegetation. Landowners should also be educated on the importance of protecting and maintaining that riparian area and encouraged to take an active role in stewardship. As another hypothetical example, there may be a stream that has been channelized through an agricultural area. In this case stream channel restoration may be needed in addition to riparian rehabilitation. The local conservation district could assist in fencing livestock from the stream, replanting native vegetation along the stream corridor, and establishing other BMPs to reduce the impacts of farm operations on the stream-riparian ecosystem. In both these examples it may not be possible in the short-term to re-establish a fully functioning RMZ, but every effort should be made to achieve the best possible conditions. As time goes on and land-use changes occur, further restoration of riparian function may also be possible.

A decision-tree diagram (Figure 20) is provided to guide assessment of the stream-riparian ecosystem and design of the RMZ. In order to determine RMZ dimensions, a comprehensive watershed and stream assessment must be conducted. This process will establish current conditions, identify threats to the ecological integrity of the stream-riparian ecosystem, and determine reference (historical or desired) target goals. In addition, riparian integrity must be evaluated and management goals established. When the analysis is complete, RMZ area should be delineated clearly both on maps and on the ground. This will reduce the possibility of inadvertent encroachment into the RMZ during on-going land-use activities or future development.

The term “buffer” is used only in reference to measures to mitigate for the impacts of adjacent land-use activities. This also differs from a “setback” in that the use of a buffer

implies that we are actively managing vegetation to reduce our impact on the stream, whereas setbacks are typically passive mitigation measures. Buffers should be sized based on the type and intensity of external land-use activities.

Buffers are strips of vegetation located outside the RMZ, designed to protect the stream-riparian ecosystem from human encroachment. The type and intensity of surrounding land-use will determine the additional “buffer” width required to protect the RMZ and its stream-riparian ecosystem. More intense development (high-density residential, commercial, or industrial) or activities that present a greater risk of damage to the aquatic ecosystem should merit larger buffers. Specific activities such as agriculture or grazing may also call for specialized buffers or best management practices (such as VFS) to mitigate for specific impacts. Construction site erosion controls and stormwater bio-filtration BMPs also fall into the buffer category. A site-by-site evaluation will be required in almost all cases. Depending on the site conditions, a buffer may be quite narrow and could utilize non-native vegetation in the form of a VFS or landscaped area.

During the watershed assessment process discussed earlier, each stream should be divided into distinct stream “segments” based on physical parameters including gradient, channel dimensions, and valley configurations. The designation of each stream segment and its ecological characteristics will largely determine the extent of the RMZ (see Figure 9). A long-term monitoring and adaptive management program is required in all cases to ensure the RMZ and buffer is adequate.

Streams located within narrow valley areas tend to be limited in their channel migration potential. For these “ravine” type streams and those without floodplains or CMZ areas, the bankfull width (BFW) will define the channel dimensions. In general, the RMZ will be defined by the valley side-slopes and include all areas up to the break in slope. Buffers should be established around these ravine-stream RMZ areas. Steep slopes should not be included in the buffer, but instead, the buffer should be measured from the break in slope at the top of the ravine. This recommendation is based on both human safety concerns (landslides) and from an ecological perspective to reduce sediment loading into the stream channel from mass-wasting events. In addition to the protection of steep slopes, any hillside springs or seeps should be included in the RMZ and buffered as deemed necessary.

In the case of streams with floodplains or subject to channel migration, the RMZ should include the entire CMZ and floodplain area. The 100-year flood elevation or the extent of the CMZ, whichever is larger, will be used to determine the width of the RMZ. In general, impervious surfaces and structures should not be permitted within the floodplain or CMZ. This recommendation is based on both human health and safety reasons as well as for ecological considerations. Structures that currently exist within floodplain areas, CMZ, or designated RMZ should be considered for relocation as funding permits. This is especially true of residential dwellings and businesses where lives and property are at great risk. Any impervious surfaces (roads, parking lots, etc.) that currently exist within the designated RMZ should be considered for relocation as well. If this cannot be accomplished, the impervious surface area should not be

counted as part of the RMZ or the buffer. An additional buffer width and/or a specific BMP should be added around the extent of the impervious area to provide additional treatment and/or protection. Based on these recommendations, the RMZ for floodplain type streams will generally be quite extensive. In addition to the floodplain area, all riparian or palustrine wetlands adjacent to the stream channel should also be included in the RMZ.

Finally, “meandering streams” with no floodplain and with no active CMZ should be evaluated for ecological integrity and the RMZ should be sized to meet structural and functional requirements. In general, these stream segments should have a RMZ based on local conditions. This width should be based on the riparian functions discussed earlier in this report. In addition, buffers may be required if surrounding land-use dictates the need to supplemental protection.

Sensitive or regionally significant streams (such as streams with designated refugia for significant species) should receive additional protection over and above what we have discussed above. Those stream-riparian ecosystems, which are identified as critical wildlife habitat or migration corridors, may also merit additional protection. These systems may require a RMZ that not only includes the floodplain, or CMZ, but also other “critical” habitat.

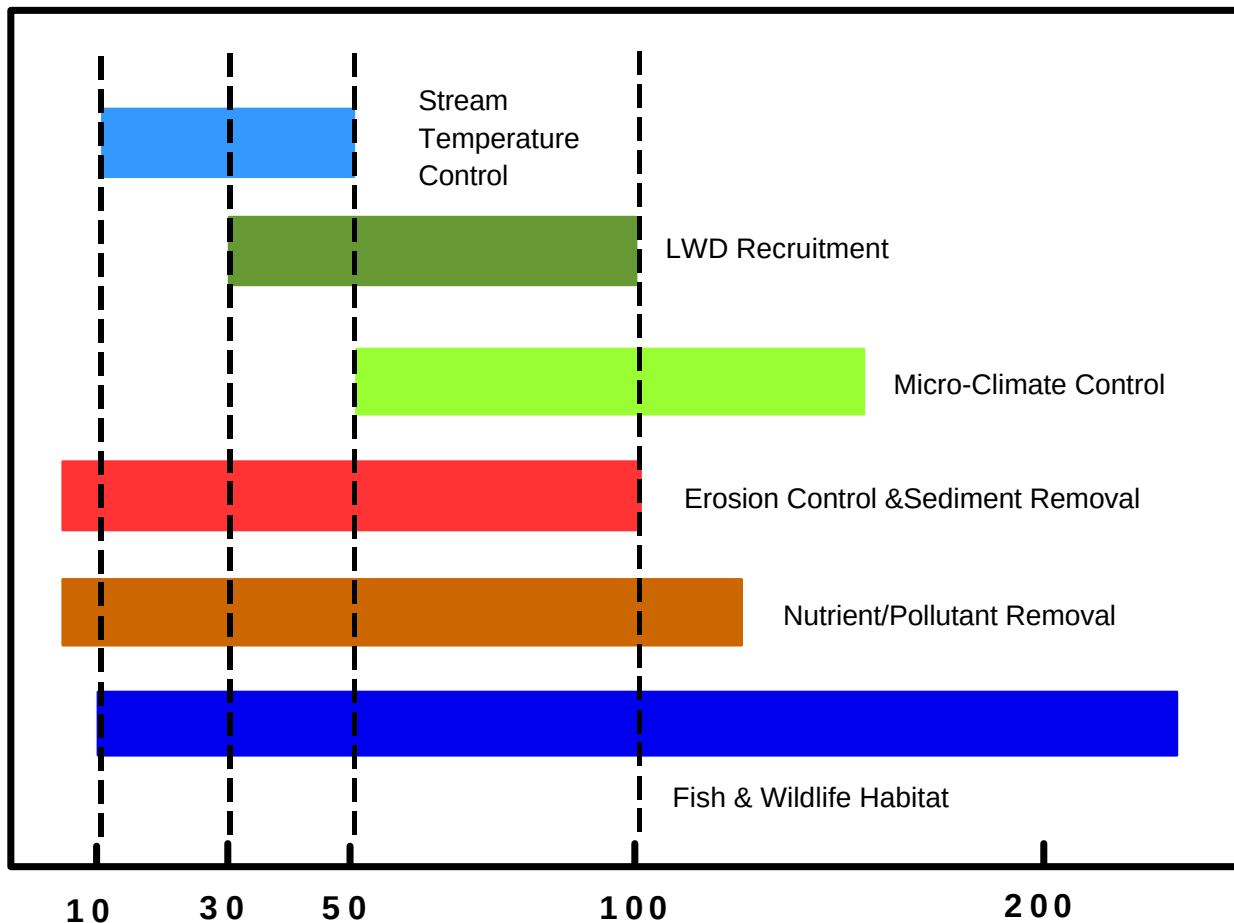
As was discussed earlier, the RMZ must include the full extent of the stream channel network. Fragmentation of the riparian corridor should be minimized to avoid hydrologic and ecological impacts to the stream-riparian ecosystem. Each stream crossing should be designed for minimal impact on both aquatic and riparian habitat. In addition, the RMZ and buffers must be clearly delineated throughout the full length of the corridor. This will minimize the possibility of encroachment and associated impacts in the future.

It is important that a watershed approach be used in the RMZ delineation process so that both human (roads, agriculture, development, etc.) needs and ecological needs can be balanced as much as possible. Any modifications to riparian areas or buffers to accommodate human activities should be based on a sound scientific foundation. In the face of uncertainty about the ecosystem structure and function, as well as the implications of human activity, the potential for harm should be anticipated and human actions should err on the side of caution. Site-specific modifications must always consider the cumulative impact of that action and how the site plan fits into the watershed as a whole. In these situations, structural BMPs can provide mitigation for some, but not all human impacts. Based on current scientific studies, it is likely that some degradation of stream-riparian ecosystem functions will result in these situations. Every effort should be made to minimize these cumulative impacts. In addition, following the precautionary principle, the absence of complete scientific information should not be used to justify potentially destructive activities or to circumvent conservation actions. Management actions for stream-riparian ecosystems should first seek to maintain or restore ecological processes, functions, and the natural disturbance regime. Following that, maintenance or restoration of structural complexity and natural habitat characteristics should be of high priority.

Riparian Function	General Range of Effective Widths (meters)	Minimum Recommended Width (meters)	Notes on Riparian Functions
Sediment Removal & Erosion Control	8-183 m	30 m	80% sediment removal
NPS Pollutant Removal	4-262 m	30 m	80% nutrient (P/N) & FC removal
Large Woody Debris (LWD) Recruitment	10-100 m	1 SPTH (~50 m)	SPTH = site potential tree height and is based on long-term, natural levels of LWD
Water Temperature Regulation	11-43 m	30 m	Based on adequate shade
Wildlife Habitat	10-300 m	100 m	Coverage for a majority, but not all, species of concern
Microclimate	45-200 m	100 m	Optimum Function

Table 10: Recommendations on Riparian Management Zones (RMZ) for Streams.

Note: Recommended minimum effective widths are based on a review of scientific literature as outlined in Tables 1-8. Full riparian function is the goal. A larger RMZ and buffer may be required in specific cases, including, but not limited to, areas with steep slopes, active floodplain systems, and streams contiguous with wetlands. Larger buffers may also be required for riparian corridors where surrounding land-use activity is potentially harmful or where human encroachment is likely. This is why a range of effective widths is given in the above table.



RMZ Width (m) on both sides of the Stream CMZ

Figure 19: Summary of riparian buffer width ranges from current scientific research. The range of effective buffers for each riparian function is shown. Dashed lines at 10, 30, and 50 meters show the most frequently required buffer widths from regional jurisdictions. Dashed line at 100 meters shows recommended minimum buffer width to achieve natural ecological levels for all riparian functions.

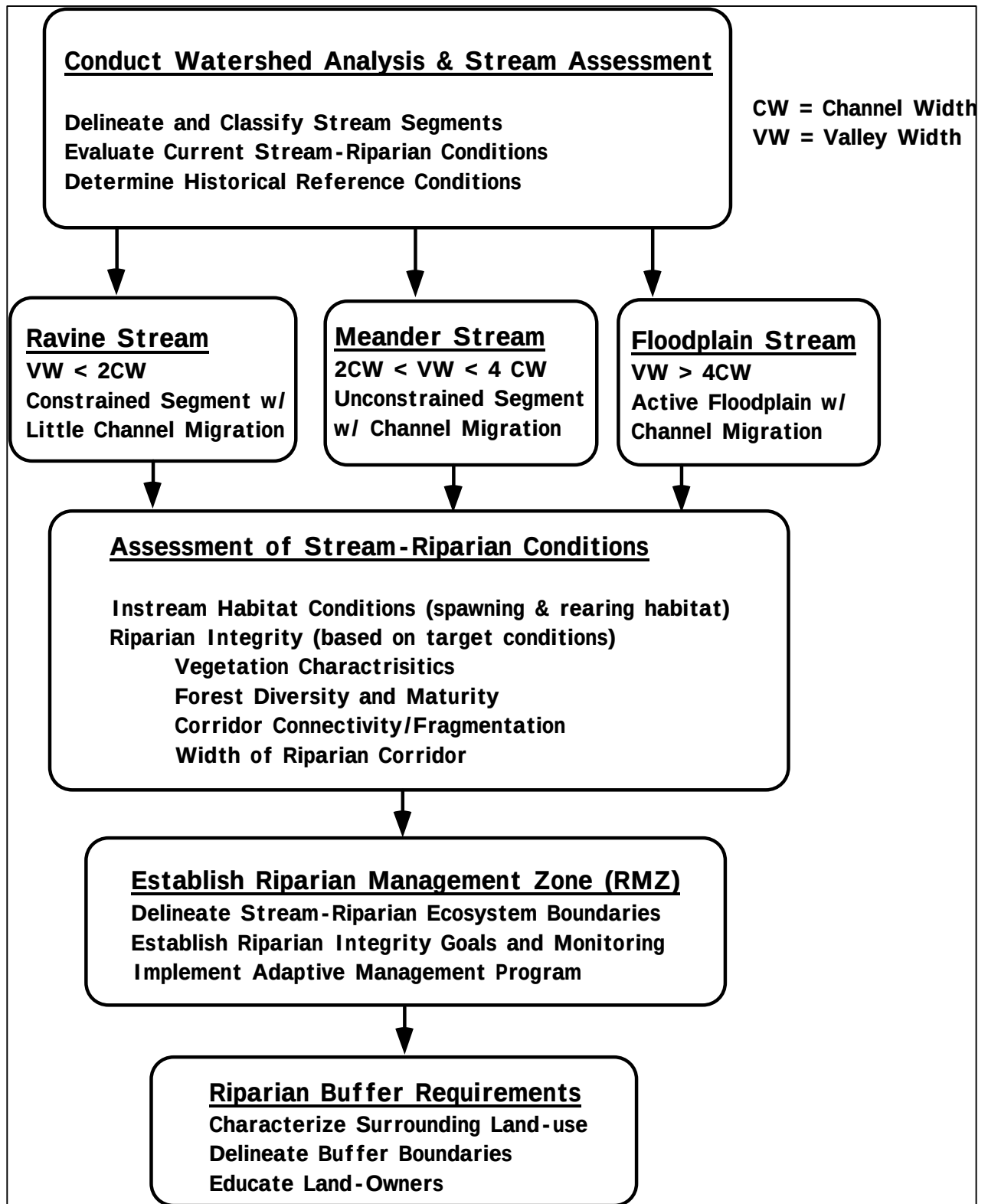


Figure 20: Riparian Management Zone (RMZ) Evaluation Decision-Tree

Summary

Riparian areas are “hot spots” of biological diversity and productivity. While they occupy a relatively small proportion of the landscape, they provide a multitude of functions vital to fish and wildlife, watershed health, and beneficial uses for humans. Beyond their essential importance to aquatic life, riparian areas and adjacent aquatic habitats generally contain more terrestrial plant, mammal, bird, and amphibian species than do surrounding uplands.

Watershed development and land-uses have resulted in the impairment of many of the functions and values provided by healthy riparian corridors. Some of these cumulative effects include riparian clearing, vegetation alteration, and corridor fragmentation. In addition, changes in basin hydrology; filling and damaging of floodplains and wetlands; stream channel modification; and reduced water quality have also taken their toll. These effects are cumulative from upstream and within a watershed. Studies show that ecosystem impairment begins at very low levels of development and continues as watersheds become more heavily urbanized (May et al., 1997; Horner and May, 1999; Booth et al., 2001; Horner et al., 2002). Deciding on appropriate widths for protection and restoration of riparian areas is a complex process. The literature provides the following guidelines in addressing this issue:

- Due to the pervasive effects of human activities in the watershed, riparian area protection and restoration is not sufficient in itself to maintain healthy stream-riparian function. Management of stormwater runoff and protection of upland forest areas is essential to protect and restore the natural hydrologic regime and the ecological health of stream-riparian ecosystems. Wider riparian corridors (and buffers) may be needed in urban areas with higher intensity land uses than compared to a rural landscape.
- To the maximum extent possible, all perennial, intermittent and ephemeral streams should be protected from surrounding land use activities. The entire stream network functions as a system, and removing the connection between intermittent and perennial streams will compromise the long-term physical and biological functioning of stream ecosystems.
- Riparian corridors should be wide enough to permit natural stream channel migration (CMZ), and should maintain ecological function and connectivity within the 100-year floodplain.
- Riparian corridors should consist of native vegetation wherever possible. Native vegetation along streams, wetlands, and rivers play an important role in urban riparian community structure and composition. In general, wider riparian forests have greater native plant diversity and abundance. Narrow forest widths were more likely to contain higher percentages of non-native or invasive plants and animals.
- Riparian wetlands and off-channel habitats are valuable for fish and wildlife and should be included in riparian management zones (RMZ).
- A range of riparian widths is recommended in the scientific literature to protect multiple riparian functions and values.
- A comprehensive protection and restoration program should be based on the RMZ needed to provide for the long-term integrity of these complex and productive

ecological systems. This should be a process-driven management strategy as outlined in this report (see Figure 19 for an overall conceptual model).

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