D. Salmonids and the Riparian Ecosystem

Introduction

Salmon are one of the most important natural resources for the economy of the state of Washington. The resource is exploited by three main fishing groups: nontreaty commercial, treaty (Indian) commercial, and recreational fishers. From 1981 to 1990, the total marine and freshwater salmon catch for Washington averaged 7.2 million fish per year (Palmisano et al. 1993). According to historical records, the peak harvests between 1961 and 1979 were 57 percent lower than those between 1864 and 1922 (The Wilderness Society 1993). This large reduction in the productivity of the Pacific Northwest salmon fishery has been attributed to many factors, including large-scale water projects (dams), poor fisheries management (overfishing and hatchery practices), urbanization, agriculture, and detrimental forest practices (Palmisano et al. 1993; Nehlsen et al. 1991). As a consequence, some stocks east of the area covered by the HCP have been listed by the federal government as threatened, and several stocks in the area covered by the HCP are candidates for federal listing.

Bull trout (*Salvelinus confluentus*) and seven species of anadromous salmonids inhabit the rivers and streams of western Washington: sockeye salmon (*Oncorhynchus nerka*), pink salmon (*O. gorbuscha*), chum salmon (*O. keta*), chinook salmon (*O. tshawytscha*), coho salmon (*O. kisutch*), steelhead trout (*O. mykiss*), and sea-run cutthroat trout (*O. clarki*). Anadromous fish spend part of their life at sea and return to freshwater to reproduce. During the portion of their life cycle spent in rivers and streams, these fish are vulnerable to forest practices that affect the integrity of riparian ecosystems (Hicks et al. 1991).

The life cycles of anadromous salmonids and bull trout are reviewed separately below, followed by a discussion of general salmonid habitat needs and the riparian ecosystem. The section ends with a review of current status and distribution of these species.

Anadromous Salmonid Life Cycle

Sockeye, pink, chum, chinook, and coho salmon and steelhead and sea-run cutthroat trout each have unique geographical distributions, life cycles, and habitat requirements. But from the perspective of forest land management, the similarities among the anadromous species of the family Salmonidae far outweigh the differences. There are few significant differences in the ways that forest practices impact each species. Therefore, in the following discussion, distinctions among the life cycles of these species are not emphasized. For additional information, the natural history and habitat requirements of salmonids are thoroughly reviewed by Groot and Margolis (1991) and Meehan (1991). The effects of forest management on salmonid freshwater habitat are reviewed by Salo and Cundy (1987), Meehan (1991), and Naiman (1992).

The salmonid life cycle consists of seven principal stages: egg, alevin, fry, parr, smolt, subadult, and adult. Eggs are laid in a nest, or redd, constructed by an adult female in a gravel streambed. After the eggs are laid and fertilized, the female covers them with gravel. Alevins hatch from the eggs after about three months of incubation (Meehan and Bjornn 1991). This larval stage is characterized by the presence of a yolk sac. Alevins can reside in the gravel for several months and emerge upon becoming fry, the next stage in their development (Meehan and Bjornn 1991). Because fry are small and weak, they are highly susceptible to predation. They are unable to swim against strong currents and therefore tend to stay along the stream margins in channel pools and eddies. Pink and chum juveniles remain in freshwater for a short period (0 to 30 days). Other species, in particular coho, steelhead, and cutthroat, remain in freshwater for 1 to 4 years (Palmisano et al. 1993). As fry become larger and stronger, they develop dark vertical bars on their sides called parr marks, and hence are known as parr. Parr venture away from the stream margins into swifter currents where larger prey are more prevalent. The juveniles of coho, steelhead, and cutthroat spend the summer months competing for food and space (Chapman 1966). Juveniles of some species (particularly coho) overwinter in tributaries, sloughs, and side channels (Emmett et al. 1991). Depending on the species, these juvenile freshwater stages end a few days to four years after leaving the redd and are marked by migration toward the sea (Meehan and Bjornn 1991).

Parr become smolts as they migrate to estuaries, where they remain until they complete the physiological changes needed to survive in the marine environment. Subadults spend one to four years in the ocean (Meehan and Bjornn 1991). During this time, individuals undertake long migrations, some traveling more than 1,000 miles. The path and distance are affected by ocean currents and abundance of prey. Some salmonid species migrate as far as the western portions of the Gulf of Alaska (Emmett et al. 1991). The vast majority of subadults return to the stream of their origin, but some natural straying into non-natal streams does occur (Waples 1991). The timing of this upstream migration varies among species and stocks.

Just prior to entering freshwater, individuals begin a dramatic metamorphosis to the adult or spawning stage. Most species develop a noticeable difference between sexes (sexual dimorphism). Spawning typically occurs in shallow riffle areas of a stream. Both sexes may mate with several partners before dying. In some species, females may guard the redd. Trout species can survive after spawning, migrate back to the ocean, and return to spawn one or two more years (Emmett et al. 1991). Chemical nutrients released through the decay of adult carcasses may be critical to the health of riparian ecosystems and probably sustain the productivity of the next generation of juvenile salmon (Willson and Halupka 1995). Some differences among life cycles of western Washington anadromous salmonids are summarized in Table III.9.

Bull Trout Life Cycle

The bull trout is a candidate for federal listing. The genus *Salvelinus*, also known as charr, belongs to the family Salmonidae. One other member of this genus is native to Washington, the Dolly Varden (*S. malma*). Until 1978, when it was recognized by Cavender (1978) as a separate species, bull trout was considered to be Dolly Varden. The separate classification was officially recognized in 1980 (Mongillo 1993). However, the geographic range of the two species overlaps in Washington and British Columbia (Goetz 1989), and the two species use the same freshwater habitat (Mongillo 1993; Brown 1994), have similar life histories, are known to hybridize (Mongillo 1993; Goetz 1989), and are difficult to distinguish. Information on geographical distribution and population status developed by the Washington Department of Fish and Wildlife is recorded as bull trout/Dolly Varden (Mongillo 1993; WDFW 1994b).

Bull trout populations exhibit anadromous, adfluvial, fluvial, and resident behaviors. Anadromous forms mature at sea, adfluvial in lakes, and fluvial in the main stem of rivers. The life cycle and freshwater habitat of bull trout are similar to that of salmon (genus *Oncorhynchus*). (See the preceding discussion of salmon life cycle and the following discussion of habitat needs.)

Table III.9: Life cycles of western Washington anadromous salmonids in freshwater, by species and run

(Source: Palmisano et al. 1993)

Species (Run)	Age at return (years)	Time of return	Spawning season	Area of juvenile development	Time in freshwater	Place of origin
Chinook salmon (Spring)	2 - 6	Mar - May	Early fall	streams, rivers, estuaries	90 days to 1 yr	hatchery & wild
Chinook salmon (Summer)	2 - 5	Jun - Jul	Late Sep - Nov	streams, rivers, estuaries	90 - 180 days	hatchery & wild
Chinook salmon (Fall)	2 - 5	Aug - Sep	Fall	streams, rivers, estuaries	90 - 180 days	hatchery & wild
Sockeye	3 - 5	Mar - Jul	Sep - Jan	lakes	1 - 2 years	wild in lakes
Coho salmon	2 - 3	Aug - Nov	Oct - Dec	streams, rivers, lakes	1 year	hatchery & wild
Chum salmon	3 - 5	Sep - Mar	Sep - Mar	estuaries	0 - 30 days	hatchery & wild
Pink salmon	2	Aug - Sep	Sep - Oct	estuaries	0 - 7 days	wild
Steelhead trout[1] (Winter)	4 - 6	Nov - Apr	Jan - Jun	streams, rivers	2 - 3 years	hatchery & wild
Steelhead trout[2] (Summer)	3 - 5	May - Oct	Jan - Jun	streams, rivers	2 years	hatchery & wild
Cutthroat trout[1] (Sea-run)	2 - 6	Jul - Dec	Dec - Jun	streams, rivers	1 - 4 years	hatchery & wild

[1] Less than 5 percent of returning fish are repeat spawners.

[2] Less than 1 percent of returning fish are repeat spawners.

Adults spawn in September and October (Brown 1994). Typically, redds are built by a single pair. Eggs incubate until about March (Brown 1994), when fry emerge from the gravel and become free-swimming (Goetz 1989). Juveniles are territorial. They are found immediately above, on, or within the stream bed (Pratt 1992), often in pockets of slow water formed by cobbles and woody debris. Individuals less than about 4.3 inches long feed on aquatic insects, and their diet includes more fish as they become larger. Anadromous, adfluvial, and fluvial juveniles migrate downstream at age two or three (Brown 1994). Adfluvial bull trout mature for two to three years before they are ready to spawn (Brown 1994).

Adult bull trout move upstream beginning in April, and the majority reach tributary streams in August. The strength of homing to natal streams may vary with each population (Goetz 1989). Once there, they seek cover in deep pools, large woody debris, and undercut banks until it is time to spawn. Males may spawn more than once in a single season (Goetz 1989), and both males and females, can spawn in either successive or alternate years (Brown 1994). After spawning, adults return to the sea, lake, or mainstem river, depending on their life history.

Bull trout are a cold-water species; they are often found near cold perennial springs. The development of eggs and alevins requires very cold water, optimally between 35.6° and 39.2° F (Goetz 1989). In Washington, the most intense spawning occurs in water that is 41° to 42.8° F (Brown 1994). Adults prefer deep pools of cold water and are seldom found in streams warmer than 64.4° F (Brown 1994).

Eggs, alevins, and fry require clear water. The embryonic stages remain in the redd for about 223 days (Goetz 1989), and this prolonged period makes them highly susceptible to the deposition of fine sediments, which can reduce the flow of oxygenated water through the redd or can entomb emerging fry (Pratt 1992). Fry are bottom dwellers and prefer small pockets of slow water formed by cobbles and large woody debris. When sediment fills these pockets, they become less suitable as rearing habitat. Juvenile densities decline as this occurs (Pratt 1992).

Habitat complexity provided by woody debris affects stream carrying capacity and survival rates. Population densities increase or decrease with the amount of woody debris (Rieman and McIntyre 1993) that provides protection from predators and enhances overwinter survival (Rieman and McIntyre 1993).

Bull trout are adversely affected by human activities in the same ways that salmon are. Removing riparian vegetation can lead to higher water temperatures, increased sediment loads, and decreased amounts of instream large woody debris (Ratliff and Howell 1992; Murphy and Meehan 1991). The requirements of the eggs and alevins make them highly susceptible to habitat degradation. Juvenile rearing habitat may be an ecological bottleneck that affects the viability of populations (Brown 1994). Of the 46 bull trout/Dolly Varden populations identified within the five west-side planning units and the Olympic Experimental State Forest, 56 percent are impacted by forest management (Mongillo 1993).

Bull trout populations have also been harmed by dams, overfishing, and agriculture as well as by exotic species. Dams block or delay migration, affecting 21 percent of the 77 bull trout/Dolly Varden populations in Washington (Mongillo 1993). Overharvesting by sports fishermen (Mongillo 1993) affects 27 percent of the populations. Agriculture, including grazing, affects 25 percent of the populations. Through competition and hybridization, brook trout (*S. fontalis*), a closely related species introduced to Washington from the eastern United States, poses a threat to 31 percent of the populations (Mongillo 1993).

Salmonid Habitat Needs and the Riparian Ecosystem

Because the life cycles and freshwater habitat needs are similar for the various western Washington anadromous salmon species and bull trout, the following discussion applies to all of them. All freshwater life stages of salmonids require moderate stream flows; cool, well-oxygenated, unpolluted water; low suspended-sediment load; adequate food supply; and structural diversity provided by submerged large woody debris (Cederholm 1994). Well-functioning riparian ecosystems are necessary to satisfy these habitat needs.

The riparian ecosystem is where aquatic and terrestrial ecosystems interact. From water's edge to upland, there exists a continuum of physical and biological characteristics. Nevertheless, the riparian ecosystem can be effectively modeled as three unique zones: an aquatic zone, a riparian zone, and a zone of direct influence (Naiman et al. 1992; see Figure III.1). The aquatic zone is the location of aquatic ecosystems. Adjacent to the aquatic zone is the riparian zone, a narrow band of moist soils and distinctive vegetation. Beyond the riparian zone lie upland areas, and the spatial extent of upland influences on aquatic ecosystems delineates the direct influence zone. The health of the aquatic ecosystems is affected by terrestrial products and processes, most notably shade, soil erosion, litter (e.g., fallen leaves, twigs, and conifer needles), and large woody debris (e.g., tree trunks) (Cederholm 1994). Salmonids inhabit the aquatic zone, but, in effect, their habitat encompasses the entire riparian ecosystem.

THE AQUATIC ZONE

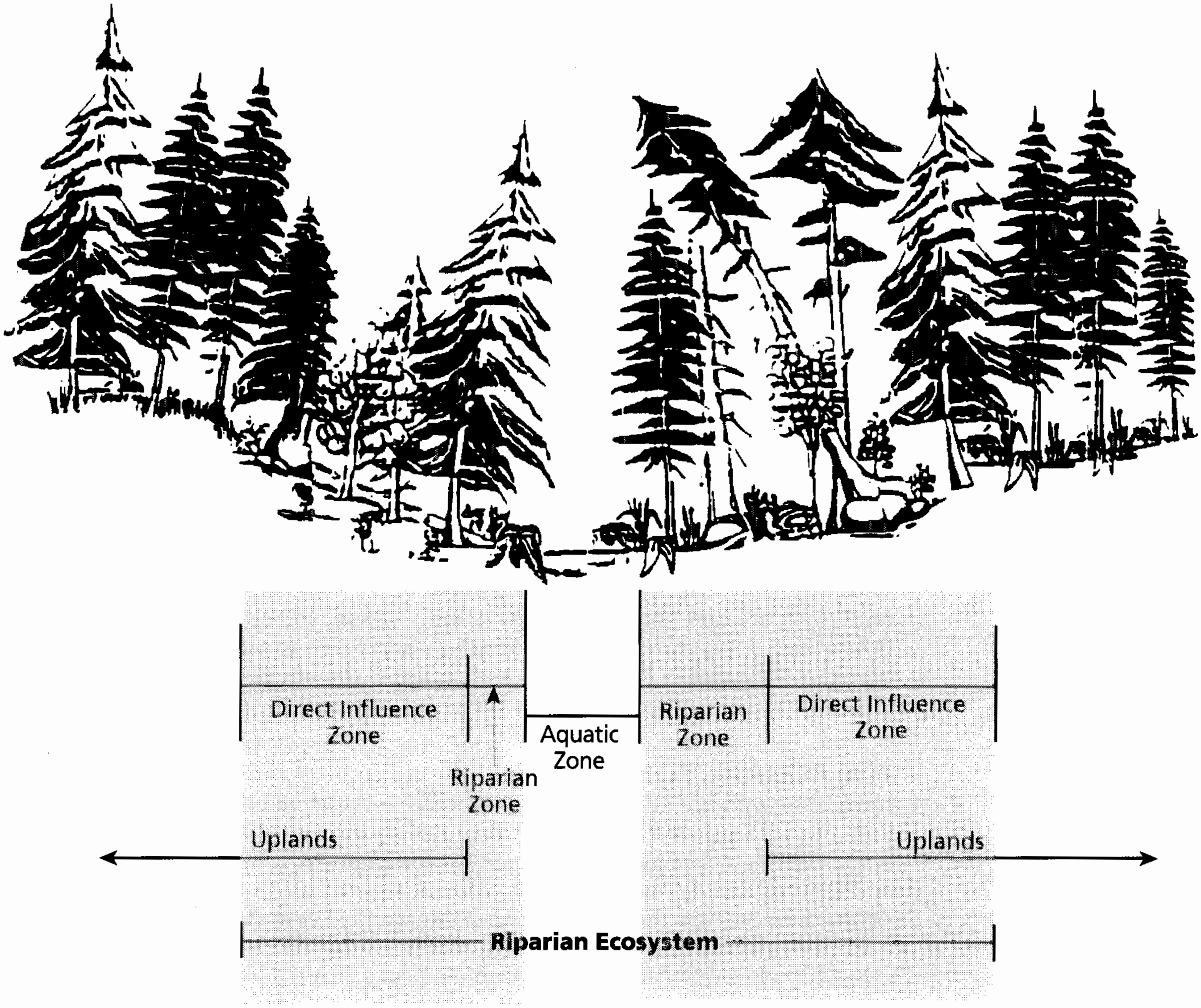
Each salmonid life stage has slightly different critical habitat requirements, and a lack of suitable habitat for a single life stage could affect the viability of an entire stock. Eggs incubating in a redd require a high concentration of dissolved oxygen, which is a function of several environmental variables: water temperature, biological oxygen demand, stream flow, and sediment load (Bjornn and Reiser 1991). High water temperatures decrease the solubility of oxygen in water. High biological oxygen demand, caused by microbial decomposition of organic materials, also decreases the amount of oxygen available to the developing egg. Inadequate streamflow reduces the circulation of fresh oxygenated water through the gravel to the redd as well as the removal of the egg's metabolic wastes (Bjornn and Reiser 1991). Fine sediments settle into the spaces between gravel, which also impedes the flow of water to the eggs (Everest et al. 1987). Excessive streamflow (floods) can destroy redds.

Alevins reside in the redd and have similar needs for clean, cool, well-oxygenated water. Sediment load can affect alevins in an additional way. If the spaces between gravel are blocked by fine sediments, then emerging in dividuals may be entombed within the redd (Everest et al. 1987).

The survival of fry and parr is determined by water quality (temperature, dissolved oxygen, and suspended sediment), food, cover, and space (Bjornn and Reiser 1991). Water temperature affects the rate of growth and development — all cold-water fish cease growth at temperatures above 68.5° F (Reiser and Bjornn 1979). Salmonids are cold-water fish, and their preferred temperature range is between 50° and 57° F (Bjornn and Reiser 1991).

Figure III.1: The riparian ecosystem

Although the riparian ecosystem is a continuum from water's edge to upland, the lines approximate the natural zonation of a riparian forest landscape, i.e., the extent of the riparian ecosystem and the zones within the ecosystem. (Adapted from: Sedell et al. 1989)



The upper lethal temperature limit lies between 73.4° and 78.4° F (Reiser and Bjornn 1979), and the lower lethal temperature limit is near 32° F (Bjornn and Reiser 1991).

Large amounts of small organic material, high temperatures, and low flows can reduce dissolved oxygen to harmful levels (Bjornn and Reiser 1991). High loads of suspended sediment may abrade and clog fish gills (Reiser and Bjornn 1979). Too much fine sediment may indirectly affect juveniles by destroying their food supply (Reiser and Bjornn 1979).

Stream productivity and riparian vegetation are two factors that affect the density of insects, the principal prey of juveniles. The amount of small organic material, or detritus, present in a stream is an important variable affecting stream productivity (Bjornn and Reiser 1991). High stream productivity leads to high densities of herbivorous aquatic insects. Terrestrial insects enter streams by falling or being blown off vegetation; this input has been found to be an important component of the prey base (Reiser and Bjornn 1979).

Depending on the species, juveniles exhibit varying degrees of territorial behavior (Emmett et al. 1991). Territoriality limits the amount of space shared among individuals of the same species, and therefore, as species become more territorial, stream carrying capacity becomes more a function of space. In addition to habitat complexity, space is a function of streamflow and water depth (Bjornn and Reiser 1991). Off-channel areas function as essential over-wintering habitat for juveniles. Side-channels and wetlands are used by juveniles to escape high flows in the main channel.

Juveniles are highly susceptible to predation by other fish and terrestrial animals. Riparian vegetation, undercut banks, submerged boulders and logs, turbulent water, and aquatic vegetation create places where fish can avoid predators (Bjornn and Reiser 1991). Cover also creates shaded areas that provide the preferred microclimatic conditions of many juvenile salmonids (Reiser and Bjornn 1979).

The survival of smolts is affected by many factors. Smolts require stream flows adequate to direct their migration (Bjornn and Reiser 1991). Relatively high temperatures may interfere with the parr-to-smolt transition (Bjornn and Reiser 1991). Smolts use pools to rest and cover to reduce the threat of predation.

Stream flow, barriers, and water quality are the main factors that can affect the upstream migration of returning adults. If the environment along the migration route is too stressful, then adults may not survive the migration or possess sufficient energy for spawning. Adults may halt migration if water is too warm, too turbid, or poorly oxygenated (Bjornn and Reiser 1991). Barriers (dams, culverts, log jams) and inadequate stream flows may impede or completely block the movement of adults upstream. Adults use pools for resting and the security of cover. Because adults feed infrequently or not at all during their spawning migration, the prey base is less important during this stage of the life cycle.

Suitable spawning habitat requires the proper substrate and adequate cover, stream flow, and water quality. The different species of salmonid typically spawn in different parts of the stream network. Cutthroat trout and coho generally use small tributaries, while steelhead trout, pink, and chinook salmon use larger tributaries and the upper reaches of mainstream stems. Sockeye use stream areas linked to lakes. Bull trout use cold water tributaries. The size of preferred spawning gravel and the depth and velocity of water at spawning sites is related to adult size. Lengths of adult salmonid species range from about 8 inches for cutthroat to 58 inches for chinook (Emmett et al. 1991). This results in preferred spawning conditions ranging from sand and pebbles (for cutthroat) to cobble (for chinook), as well as the occurrence of redds in nearly all fishbearing streams containing suitable habitat. Most species spawn in gravel between 0.5 inches and 4 inches in diameter. The area utilized for spawning also varies across species. A single pair of chinook requires about 24 square yards; a trout pair needs about 2 square yards.

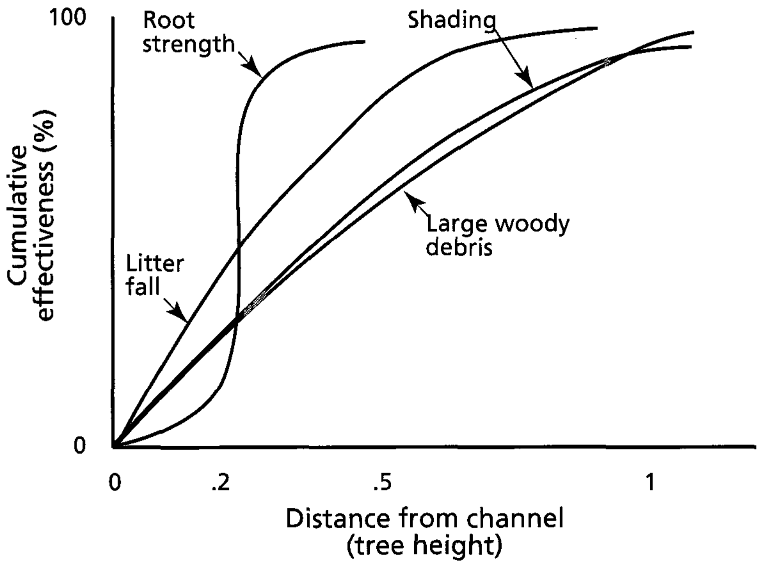
Salmonids benefit in each stage of their life cycles from high structural complexity. High structural complexity corresponds to high diversity in the size, location, and variety of physical, hydrological, and biological elements. A variety of gravels, pools of various depths, riffles, eddies, side channels, undercut banks, boulders, aquatic vegetation, amount of cover, and large woody debris are among the elements that contribute to structural complexity. The most important of these is large woody debris (Cederholm 1994). For streams coursing through intact riparian ecosystems, large woody debris continually influences the physical and biological processes affecting salmonid habitat. The importance of large woody debris to riparian ecosystems is discussed below.

THE DIRECT INFLUENCE ZONE

The degree to which aquatic ecosytems and terrestrial ecosystems interact decreases as the distance from surface water increases (FEMAT 1993; Cederholm 1994) (Figure III.2). The finite width of the riparian ecosystem is a result of this inverse relation. The terrestrial ecosystem principally affects water temperature, stream bank stability, sediment load, and detrital nutrient load of the aquatic ecosystem, and it is the source of large woody

Figure III.2: Relation between effectiveness of terrestrial elements of salmonid habitat and distance from stream channel

Root strength influences stream bank stability. Litter fall contributes organic nutrients to the aquatic food chain. Large woody debris performs many physical and biological functions essential to habitat quality. (See text.) (Modified from FEMAT 1993)



debris (Cederholm 1994; FEMAT 1993). Suitable salmonid habitat exists within ranges of variability for each of these key habitat elements and is best described by the natural regime under unmanaged conditions. From the perspective of forest management, the demonstrable effects of the direct influence zone on these key elements of salmonid habitat provide a guide for the development of riparian conservation strategies.

Water Temperature

Water temperature is principally a function of vegetative cover. Overstream riparian vegetation moderates energy flow into and out of aquatic ecosystems (Chamberlin et al. 1991). Removing riparian vegetation and the shade it provides increases summer water temperatures. Lower winter water temperatures may also occur because removing riparian vegetation (Chamberlin et al. 1991) allows heat to escape. Steinblums et al. (1984) found that local topography (slope) and forest stand density (basal area) were the most statistically significant variables determining the amount of stream shading (angular canopy density). In general, riparian buffer widths are not a good predictor of shade protection (Steinblums et al. 1984; Beschta et al. 1987). Nevertheless, Beschta et al. (1987) claim that buffer widths of 100 feet or more will provide the same level of shading as that of an intact old-growth forest stand, whereas Steinblums et al. (1984) showed that in some cases buffer widths of 125 feet or more may be necessary to achieve this level of shading.

The degree to which water temperature is affected by riparian vegetation is a function of stream size (Chamberlin et al. 1991). For example, the temperature of shallow water bodies responds more quickly to changes in air temperature, and the temperature of small streams is more sensitive to changes in riparian vegetation because the forest canopy covers a higher proportion of the stream's surface (Chamberlin et al. 1991).

Stream Bank Stability

Riparian vegetation stabilizes stream banks. Therefore, removing vegetation leads to increased mass wasting (such as landslides) and sediment loading (amount of suspended and deposited sediments). The strength and density of the root network play a critical role in stream bank stability. Root strength declines appreciably at distances greater than one-half a tree crown diameter (FEMAT 1993). Therefore, the most important trees for bank stability lie within one-half a tree crown diameter from the stream bank. Likewise, the size and density of trees growing along a stream should be key variables determining bank stability, but no studies have investigated the relationship between relative density and stream bank stability.

Sediment Load

Sediment load can be increased by natural mass-wasting processes, timber harvesting, and roads (Cederholm 1994; Chamberlin et al. 1991). Riparian buffers can intercept sediments flowing from upland human-caused disturbances. Studies (Lynch et al. 1985; Moring 1982) have found that buffer strips of approximately 100 feet are effective in intercepting sediments from clearcuts. Broderson (1973) suggested that on slopes less than 50 percent (27 degrees), a riparian buffer at least 50 feet wide is needed to control the overland flow of sediments. On steep slopes greater than 50 percent, he suggested that buffers as wide as 200 feet would be effective in protecting water quality. Further discussion of sediments appears in the subsection titled Upland Influences on Salmonid Habitat.

Nutrient Load

The amount of instream small organic material, or detritus, affects stream productivity (Bjornn and Reiser 1991). Higher stream productivity leads to higher densities of herbivorous aquatic invertebrates. In forested small- and medium-order streams, riparian vegetation is the primary source of detritus (Gregory et al. 1987; Richardson 1992). Removal of vegetation along headwaters will lessen this input and may significantly affect stream productivity throughout a watershed. For a watershed in eastern Quebec, estimates showed that approximately 23 percent of the annual particulate organic load collected at the bottom of the watershed was contributed by first-order streams (comparable to Types 4 and 5 streams as defined in WAC 222-16-030) (Conners and Naiman 1984). This finding suggests that upper headwater areas without fish contribute detrital input to downstream segments that support fish. However, the importance of this upstream contribution to detrital input is not known.

Stand age and canopy cover significantly influence detrital input to a stream system. Old-growth forests contribute approximately five times as much detritus to streams as clearcut forests (Bilby and Bisson 1992). Richardson (1992) found that old-growth forests contributed approximately twice as much detritus as either 30- or 60-year-old forests. However, even though streamside timber harvest reduces detrital input, the resulting reduction in forest canopy in the riparian zone leads to increased light levels and algae production in the aquatic zone, which in turn produces detritus in the stream (Bilby and Bisson 1992).

Richardson (1992) estimated that 70 to 94 percent of all leaves that enter a stream segment are transported downstream. Some detritus added to streams originates from beyond the immediate streamside area. The maximum source distance of instream detritus is not known, but it has been estimated that 14 to 25 percent of the total litter input is blown in (Richardson 1992).

Erman et al. (1977) found that the composition of invertebrate communities in streams with riparian buffers wider than 100 feet was indistinguishable from those of unlogged streams. From this result, FEMAT (1993) inferred that riparian buffers at least 100 feet wide delivered sufficient small organic material to maintain a diverse aquatic community (Figure III.2).

Large Woody Debris

Large woody debris is the most important link between terrestrial and aquatic ecosystems, acting on stream flows to create essential elements of salmonid habitat — pools, riffles, side channels, and undercut banks (Swanston 1991; Maser et al. 1988). Large woody debris causes lateral migration of the stream channel, creating backwaters along stream margins and increasing variations in depth (Maser et al. 1988). Large woody debris also serves as cover from predators and competitors (Bjornn and Reiser 1991), and this cover may create preferable microclimatic conditions as well. Large woody debris moderates the energy of stream flows, thereby decreasing streambed scour and bank erosion. Dams formed by logs perform at least three functions:

(1) They store fine sediments in Types 4 and 5 streams that would adversely affect downstream spawning areas and invertebrate populations.

(2) They retard the flow of nutrients down the channel, thus increasing stream productivity.

(3) They retain gravel of various sizes essential to spawning (Bisson et al. 1987).

Gravel and nutrients retained by large woody debris are the substrate for the growth of some aquatic vegetation.

During floods, large woody debris in the riparian zone is important for the maintenance and development of riparian soils. Large woody debris performs at least three functions during floods:

(1) it moderates the energy of stream flows,

(2) it stabilizes soils, and

(3) it traps suspended sediments and organic nutrients.

The saturated soils of some riparian zones may impede the regeneration of conifer species. Large woody debris enhance conifer regeneration by acting as nurse trees.

Through stream bank erosion, windthrow, tree mortality, and beaver activity (Bisson et al. 1987), the riparian zone supplies nearly all large woody debris. The probability that a falling tree will enter a stream is a function of distance from the channel and tree height (Van Sickle and Gregory 1990). For a riparian forest stand of uniform height, mathematical models demonstrate that large woody debris input to streams is theoretically maximized when the riparian buffer width is equal to the height of the forest stand (Van Sickle and Gregory 1990). The same models show that the function relating input of large woody debris to buffer width is nonlinear. Ninety percent of the theoretical maximum is reached when a buffer width equals approximately 40 percent of the forest stand height (Van Sickle and Gregory 1990).

In old-growth forests of southeastern Alaska, Murphy and Koski (1989) found that the sources of 90 percent of instream large woody debris were within approximately 50 feet (slope distance) of the stream bank. The approximate average height of trees along the streams in this study area was 130 feet. In effect, Murphy and Koski (1989) showed that riparian buffer widths equal to 40 percent of an average tree height will recruit almost all potential large woody debris. Measurements from sites in western Washington and Oregon indicate that in old-growth conifer forests (average tree height 189 feet, range 164 to 262 feet) riparian buffers 120 feet wide (slope distance) would be 90 percent effective in delivering large woody debris to aquatic ecosystems, and that in mature conifer forests (average tree height 157 feet, range 131 to 213 feet) the same level of effectiveness would be provided by buffer widths of 90 feet (McDade et al. 1990). In terms of tree height, McDade et al. (1990) show that 90 percent of the potential large woody debris lies within a zone whose width is about 60 percent of the height of the average tree in the riparian ecosystem.

To date, studies making forest management recommendations for the recruitment of large woody debris have not considered the lateral migration of the stream channel (Murphy and Koski 1989; Robison and Beschta 1990; McDade et al. 1990; WFPB 1994). Stream channels are dynamic, and static riparian buffers, which today provide adequate large woody debris, may fail to do so after decades of stream migration. For long-term protection of larger streams (Types 1, 2, and 3) in low-gradient unconfined channels, riparian buffers may need to exceed the recommended minimums.

Instream stability and longevity of large woody debris are assumed to be important for its ecosystem function (Bisson et al. 1987). Stability is a function of size, with debris length relative to stream width having the greatest effect (Bisson et al. 1987). Instream longevity of large woody debris is a function of both size and species: larger pieces are more resistant to breakage, and conifers are more resistant to fragmentation and decomposition than red alder (Bisson et al. 1987), a hardwood often associated with riparian areas. Short harvest rotations in managed forests along streams produce trees that are too small to function properly as instream large woody debris.

UPLAND INFLUENCES ON SALMONID HABITAT

Hydrology and geomorphology link upland areas with the riparian ecosystem. Upland areas contribute water and sediment to the riparian ecosystem, and forest practices alter the physical processes that control delivery rates.

Water Quantity

Water quantity, or stream flow, can be modeled as annual precipitation minus annual evapotranspiration (Swanston 1991). The model is a useful approximation of real hydrological processes and has an important implication: there is a strong causal link between forest cover and stream flow. Within a watershed, the fraction of land that is forested is one of the most important variables affecting annual runoff (Chamberlin et al. 1991; Hicks et al. 1991). Forest harvest reduces the amount of both intercepted precipitation and evapotranspiration. In some cases, this produces an increase in annual water yield and stream flow during seasons of low flow, which is thought to have a short-term beneficial effect for some aquatic resources (Cederholm 1994). In other cases, a reduction in fog interception and drip may decrease water yield and summer low flows (Harr 1982).

Excessive peak flows can produce dramatic changes in stream channel form and function. Forest management that significantly increases the magnitude or frequency of peak-flow events can result in long-term damage to riparian ecosystems and the loss of salmonid habitat. Peak-flow events can destabilize and transport large woody debris, fill pools with sediments, and destroy salmon redds. Structurally complex channels containing large woody debris and composed pools, riffles, and side channels can be transformed to simple uniform channels with limited habitat value to salmonids.

After timber harvest, annual water yield in a watershed changes. When annual water yield returns to pre-harvest levels, the forest stand is said to be “hydrologically mature” with respect to those processes (principally interception and evapotranspiration) that affect annual water yield. In other words, when a given hydrologic variable (e.g., annual water yield, low and peak flow levels) for a young forest stand is similar to that of a mature forest stand, then the young stand is said to be hydrologically mature with respect to those processes that affect that variable.

Forest practices that affect winter snow accumulation and melt can have significant long-term detrimental impacts on aquatic resources. Basin-wide cumulative effects of reducing mature forest cover may lead to peak flows that damage stream beds when the windy and warmer conditions associated with large rainstorms cause the quick melting of shallow snowpacks that have accumulated during the winter. These are known as rain-on-snow events. The initiation of many landslides is linked to rain-on-snow events. For example, Harr (1981) reported that 85 percent of all landslides in small watersheds in western Oregon were associated with rain-on-snow events. In western Washington, rain-on-snow events are most common and most severe between 1,200 feet and 4,000 feet in elevation — the rain-on-snow zone (WFPB 1994). Forest canopy density is the principal feature determining the hydrologic maturity of a forest stand with respect to rain-on-snow discharge (Harr 1981; Coffin and Harr 1992). Young conifer forests reach hydrological maturity with respect to rain-on-snow peak flows between ages 25 and 35. The state Forest Practices Board (WFPB 1994) defines maximum rain-on-snow hydrological maturity as a forest stand with greater than 70 percent crown closure and less than 75 percent of the crown in hardwoods or shrubs.

Wetlands are a primary part of the permanent soil and ground water hydrology of forests in many watersheds. Their influence on stream flow has been repeatedly demonstrated (Winter 1988; Waddington et al. 1993). Wetlands also moderate storm flow and store the water for future discharge (Richardson 1994). Specifically, wetlands augment low flows by releasing stored water to streams or ground water. Modification of wetlands through channelization or timber harvest can increase storm discharge, produce more frequent channel eroding flows downstream, and reduce water storage and discharge during summer low-flow periods.

Water quality is also influenced by wetland function. Because wetlands slow water flow, they allow sediments to precipitate or adhere to vegetation. Oberts (1981) found that watersheds with less than 10 percent wetlands had suspended-solid loading rates per unit area that were as much as 100 times greater than those of watersheds with more than 10 percent wetlands.

Sediments

Sediments are delivered naturally from uplands to riparian ecosystems primarily through landslides. These large-scale random events add large quantities of material to the stream network rapidly. In undisturbed watersheds, the concentration of sediments increases substantially during storms, and much of this increase is the direct result of soil mass-wasting (landslides) (Swanston 1991). Mass-wasting occurs when gravitational force overcomes the strength of soil materials. Slope stability is strongly affected by the steepness and form of the slope, thickness of the soil layer, and amount of moisture in the soil. Typically, landslides occur where local changes in the water table increase soil saturation, which in turn decreases the friction between soil particles to the point that they slide down the slope under the force of gravity. Three groups of general mass-wasting processes affect riparian ecosystems: slumps and earth flows, debris avalanches, and debris torrents. Slumps are deep-seated failures that generally develop as a result of long-term water accumulation. Earth flows typically begin with a slump and are slow moving — from 1 inch to 90 feet per year (Swanston 1991). Debris avalanches are shallow rapid landslides and constitute some of the most common soil mass movements (Swanston 1991). Debris torrents are large quantities of soil, rock, and large woody debris suspended in a slurry that rapidly flows down steep stream channels. Debris torrents are typically a consequence of the flood outburst when dams created by debris avalanches fail.

The presence of clearcut units in a watershed increases the likelihood of mass-wasting events (Swanson and Dyrness 1975; Swanson et al. 1987). Timber harvest affects the landsliding process in four ways. First, transpiration is decreased with tree removal. Decreased transpiration increases soil moisture and tends to raise water-table levels, thus increasing the risk of slope failure. Second, the forest canopy can intercept significant quantities of precipitation, and its removal leads to increases in soil moisture. Third, timber harvest may disturb the soil in such a way as to create macropores in the soil; these macropores act as conduits that facilitate soil saturation. Fourth, tree harvest results in stump roots that decay, which decreases soil strength and can increase the frequency of landsliding until new root systems are established. This period of decreased stability lasts for approximately 5 to 20 years after harvest (Sidle et al. 1985).

Roads in upland areas have significant detrimental impacts on salmonid habitat. In few locations can roads be built that have no negative effects on streams (Furniss et al. 1991). Landslides resulting from road construction are considered a significant source of sediment input into streams (Wu and Swanston 1980; Chesney 1982; Everest et al. 1987; Sidle 1985). In the Pacific Northwest, roads appear to contribute more to landslides than clearcutting, although this association varies substantially with location (Sidle et al. 1985) and seems to be highly dependent on watershed hydrology and geomorphology (Duncan and Ward 1985). Cederholm et al. (1981) reported a significant positive correlation between fine sediment in spawning gravels and the percentage of basin area covered by roads.

Status and Distribution

In western North America, anadromous salmonids range from mid-California to the Arctic Ocean (Meehan and Bjornn 1991). Their historic distribution included southern California and Mexico (Wilderness Society 1993). Freshwater salmonid habitat extends eastward into Idaho, i.e., the Snake River and its tributaries. All species from the Pacific Northwest migrate out into the Pacific Ocean, some traveling as far north as the Bering Sea. Anadromous salmonids occupy all of Washington except the area north of the Snake River drainage and east of the Columbia River in central Washington and the area east of the Okanogan Highlands in northeastern Washington (WDF 1993).

Bull trout are found in the Rocky Mountains, Cascade Range, and Olympic Mountains of the northwestern United States and southwestern Canada (Meehan and Bjornn 1991). Populations exist in Washington, Oregon, Idaho, western Montana, northern California, northern Nevada, British Columbia, and Alberta.

STOCKS AND EVOLUTIONARILY SIGNIFICANT UNITS

Fisheries management of salmon is normally done according to runs, which are aggregations of stocks. A stock is a discrete breeding population. The Washington State Salmon and Steelhead Stock Inventory (WDF et al. 1993) has defined stock to be:

> The fish spawning in a particular lake or stream(s) at a particular season, which fish to a substantial degree do not interbreed with any group spawning in a different place, or in the same place at a different season (p. 10).

The spatial or temporal reproductive isolation required by this definition is reflected in the names given to stocks, e.g., "Nisqually River winter steelhead" or "Snohomish River fall chinook". Stocks may possess distinct biological characteristics (e.g., physical appearance, habitat preferences, genetics, or population demography), but not necessarily. As noted by Meehan and Bjornn (1991), "stock" can be considered synonymous with "subspecies."

The Endangered Species Act defines species as “any distinct population-segment of any species of vertebrate fish or wildlife which interbreeds when mature” (16 U.S.C. 1532(15)). For purposes of the Endangered Species Act, salmon stocks are grouped into populations known as Evolutionarily Significant Units (ESU). If conditions warrant federal listing of a salmon, it is the stated intention of National Marine Fisheries Service to list ESUs, rather than an entire salmon species or individual stocks (Federal Register v. 56, p. 58612-8). (Bull trout have not been separated into ESUs.)

An ESU is a population that (1) is substantially reproductively isolated from other population units of the same species and (2) represents an important component in the evolutionary legacy of the species (Waples 1991). The first criterion is essentially the same as the Washington State Salmon and Steelhead Stock Inventory (WDF et al. 1993) definition of a stock. The second criterion requires that sub-populations in separate ESUs possess significant genetic or other biological differences. As a result, many stocks are lumped into a single ESU. For example, agencies in Washington, Oregon, and California have identified more than 200 distinct stocks of coho salmon. These stocks have been grouped into six ESUs. Washington contains at least 90 stocks of coho (WDF et al. 1993), and these are distributed among three ESUs.

SALMONID STATUS IN THE PACIFIC NORTHWEST

Nehlsen et al. (1991) assessed extinction risks for 214 native naturally spawning salmonid stocks occurring in Idaho, Washington, Oregon, and northern California. They defined three risk categories: high risk of extinction, moderate risk of extinction, and special concern. Stocks with a high or moderate risk of extinction have likely attained the threshold for listing under the Endangered Species Act. Stocks with a moderate risk have a larger number of spawning adults each year than do stocks with a high risk. Stocks of special concern have not attained the threshold for listing, but do face some risk of extinction or possess some unique characteristic that requires attention. Nehlsen et al. (1991) estimated that 101 stocks in the Pacific Northwest had a high risk of extinction, 58 had a moderate risk, and 54 were of special concern.

Under the Endangered Species Act, the National Marine Fisheries Service regulates salmon, and it has declared several different salmonid populations as threatened or endangered. The agency listed Sacramento River winter chinook as threatened in 1990 (Nehlsen et al. 1991) and Snake River sockeye as endangered in 1991 (Federal Register v. 56, no. 224, p. 58619-24). Spring/summer and fall runs of Snake River chinook were listed as threatened in 1992 (Federal Register v. 47, no. 78, p. 14653-5). In March 1995, the steelhead populations in the Klamath Mountain of northern California were proposed for listing as threatened (Federal Register v. 60, no. 51, p. 14253-61).

The National Marine Fisheries Service initiated status reviews for west coast steelhead trout in May 1993 and coho salmon in October 1993 (Federal Register v. 58, no. 206, p. 57770-1; v. 59, no. 102, p. 27527-8). The status review for steelhead is expected to be completed in 1996. The status review for coho, completed in July 1995, proposed that the species be federally listed in Oregon and California, but not in Washington (Federal Register v. 60, no. 142, p. 38011-30).

The federal government initiated coastwide status reviews for the other five anadromous salmonids in September 1994 (Federal Register v. 59, no. 175, p. 46808-10). The first of these reviews, for pink salmon, was to be completed in 1995. Completion of the status reviews for chum, sockeye, and chinook salmon, and sea-run cutthroat will probably occur in 1996. The federal listing of salmonid species could be followed by federal regulations pertaining to forest practices on nonfederal lands.

The bull trout is regulated by the U.S. Fish and Wildlife Service and was made a category 2 candidate for federal listing in 1985 (Federal Registery, v. 50, no. 181, p. 37958-67). In response to petitions, the U.S. Fish and Wildlife Service began a rangewide status review in May 1993. This review, completed in June 1994, concluded that the status of the bull trout warranted its listing as a threatened species, but listing was precluded by other higher priority actions. At that time, the species was assigned a listing priority number of 9 (on a scale of 1 to 12, with 1 being the highest priority) and made a category 1 candidate. In April 1995, the species was moved up to a listing priority number of 3. Dolly Varden is not a federal candidate.

SALMONID STATUS IN WASHINGTON

The Washington State Salmon and Steelhead Stock Inventory (WDF et al. 1993) identified 435 distinct salmonid stocks in Washington. Information for 322 stocks was adequate to assess their status, and of these, 38 percent were classified as depressed, 4 percent as critical, and 58 percent as healthy (WDF et al. 1993). A depressed stock is one “whose production is below expected levels based on available habitat” (WDF et al. 1993 p. 30), and a critical stock is one for which “permanent damage to the stock is likely or has already occurred” (WDF et al. 1993 p. 30).

Nehlsen et al. (1991) compiled a list of Pacific Northwest salmon stocks threatened with extinction. For stocks in Washington, their list describes 47 as having a high risk of extinction, 18 as having moderate risk, and 27 as being of special concern. A partial list of extinct stocks (Nehlsen et al. 1991) includes 42 stocks from Washington.

Using a different definition, Williams et al. (1989) listed the bull trout as a species of special concern. In Washington, 77 separate bull trout/Dolly Varden populations have been identified (Mongillo 1993). Information was adequate to determine the status of only 34 populations. Of these, nine were considered to have a high risk, six a moderate risk, and 13 a low risk of extirpation.

SALMONID STATUS IN THE AREA COVERED BY THE HCP

The riparian conservation strategies proposed under this HCP will be applied to only the HCP planning units west of the Cascade crest. Therefore, the discussion of stock status in the area covered by the HCP is confined to those planning units. There are 387 distinct salmonid stocks in these HCP planning units (WDF et al. 1993). The status of these stocks is summarized in Table III.10. For those 277 stocks for which a status could be determined, 32 percent were depressed, 4 percent were critical, and 64 percent were healthy (WDF et al. 1993). Nehlsen et al. (1991) rated 40 stocks as having a high risk of extinction and 12 as having a moderate risk. Bull trout and Dolly Varden were not included in either the Washington State Salmon and Steelhead Stock Inventory or Nehlsen et al.

DISTRIBUTION ON DNR-MANAGED LANDS IN THE FIVE WEST-SIDE AND THE OLYMPIC EXPERIMENTAL STATE FOREST PLANNING UNITS

To determine the distribution of species of anadromous salmonids on DNR-managed lands covered by the HCP, DNR staff performed an analysis using the agency’s computerized geographic information system with input from

Table III.10: Status of salmonid stocks in the five west-side planning units and the Olympic Experimental State Forest

Species[1]	Status (Source: WDF et al. 1993) Healthy	Depressed	Critical	Unknown	Extinction risk (Source: Nehlsen et al. 1991) High	Moderate	Special Concern
Coho	37	33	1	18	7	0	1
Chinook	46	17	4	14	15	0	1
Chum	48	3	2	18	4	3	0
Sockeye	1	4	1	1	1	1	0
Pink	9	2	2	2	2	1	0
Steelhead	36	30	1	57	9	7	10
Sea-run cutthroat[2]	—	—	—	—	2	1	8
Total stocks	**177**	**89**	**11**	**110**	**40**	**12**	**21**

[1] Bull trout and Dolly Varden were not included in the WDF et al. (1993) or Nehlsen et al. (1991) studies

[2] Species not included in WDF et al. (1993)

the Washington Department of Fish and Wildlife's Washington Rivers Information System, which identifies all streams that salmonids are known or expected to inhabit. Digital data are to the 1:100,000 scale, and the presence of fish species is recorded by river reach.

Using this database, all Watershed Administrative Units (WAUs) that are known or thought to contain salmonids were tabulated. Over 80 percent of DNR-managed lands west of the Cascade crest in the area covered by the HCP are in WAUs that contain coho, chinook, and steelhead (Table III.11). Smaller percentages of DNR-managed lands are in WAUs that contain the other four anadromous salmonids and bull trout/Dolly Varden. All DNR-managed lands in the Olympic Experimental State Forest are in WAUs that contain coho and steelhead (Table III.11). With the exception of the South Puget Planning Unit, all west-side planning units have at least 80 percent of their DNR-managed lands within WAUs that contain a salmonid species.

WAUs range in size from 10,000 to 50,000 acres. Given the relatively small area of WAUs compared to HCP planning units, DNR staff assumed that all fishbearing streams (Types 1, 2, and 3) in a WAU identified as containing a salmonid species are actually inhabited by that species. Using this extrapolation, the assessment shows that more than 1,000 miles of fishbearing streams on DNR-managed forest land in the five west-side and Olympic Experimental State Forest planning units potentially contain coho, steelhead, chinook, chum, and sea-run cutthroat (Table III.12). On the basis of stream miles, the density and distribution of salmonids vary widely among planning units. For example, the DNR analysis shows that the Olympic Experimental State Forest has more than 400 stream miles occupied by anadromous salmonids, whereas the North Puget Planning Unit has about 250 miles. All the fishbearing stream miles on DNR-managed land in the Olympic Experimental Forest and South Coast planning units contain at least one species of anadromous salmonid. At least 90 percent of fishbearing streams on DNR-managed land in the Straits, North Puget, and Columbia planning units contain a species of anadromous salmonid.

To estimate the potential impacts of forest practices activities on DNR-managed land, DNR staff assumed that (1) all managed land within a WAU affects salmonid habitat, and (2) impacts by individual landowners are proportional to the amount of land they manage within a WAU. For some WAUs, these assumptions may be weak. For example, DNR may manage 10 percent of a WAU, but that 10 percent affects 90 percent of the salmonid spawning habitat in that WAU. Nevertheless, this analysis provides a useful estimate of DNR's potential impacts on salmonid populations. DNR staff calculated the total area of WAUs identified as containing salmonid species as well as the total area of DNR-managed land within these WAUs. The ratio of these two numbers is the proportion of DNR-managed land that could affect salmonids. This proportion suggests the magnitude of the potential impact that DNR forest management may have on these species. For example, in the Olympic Experimental State Forest, on average, about 26 percent of all land that could impact salmonids is managed by DNR (Table III.13). For the five west-side planning units, on average, about 11 percent of all land that could affect salmonids is managed by DNR.

Differences in impacts by individual planning units among species reflect their geographical distribution (Table III.13). For example, pink salmon generally spawn in the lower reaches of coastal rivers (Emmett et al. 1991), and therefore, planning units with DNR-managed lands near the coast have a greater impact on this species. In the OESF, 33 percent of all land that could impact pink is managed by DNR, but in the South Puget Planning Unit, only 2 percent is managed by DNR.

Table III.11: Percent of DNR-managed forest land west of the Cascade crest in Watershed Administrative Units that contain salmonids

The five west-side planning units consist of South Coast, Straits, North Puget, South Puget, and Columbia. OESF is the Olympic Experimental State Forest. Each HCP planning unit contains several WAUs. (For more information on this, see the section in Chapter I titled Organization of the Planning Area.)

(Source: DNR GIS April 1995)

Planning Unit	**Coho**	**Chinook**	**Chum**	**Sockeye**	**Pink**	**Steelhead**	**Sea-run Cutthroat**	**Bull Trout/ Dolly Varden**	**Total DNR-managed acres**
South Coast	100	97	91	3	1	97	96	5	238,700
Straits	98	93	93	18	67	90	98	26	111,700
North Puget	82	80	77	48	62	81	37	74	396,400
South Puget	73	73	63	9	18	71	52	23	145,500
Columbia	81	67	39	25	0	78	81	23	289,300
Total for five west-side planning units	86	80	70	26	29	83	67	37	1,181,600
OESF	100	94	52	74	13	100	98	33	267,000
Total five west-side and OESF planning units	**88**	**83**	**67**	**35**	**26**	**86**	**73**	**36**	**1,448,600**

Table III.12: Estimated miles of fishbearing streams on DNR-managed lands west of the Cascade crest

Only Types 1, 2, and 3 waters are considered. OESF is the Olympic Experimental State Forest.

(Source: DNR GIS April 1995)

Planning Unit	**Coho**	**Chinook**	**Chum**	**Sockeye**	**Pink**	**Steelhead**	**Sea-run Cutthroat**	**Bull Trout/ Dolly Varden**	**Total stream miles**
OESF	418	388	232	326	63	418	410	121	418
South Coast	240	236	222	33	2	240	230	15	240
Straits	94	70	91	22	71	91	94	24	95
North Puget	258	239	245	138	198	258	84	233	284
South Puget	89	89	84	3	15	88	73	17	117
Columbia	236	208	144	76	0	227	230	91	263
Total	**1,335**	**1,230**	**1,018**	**598**	**349**	**1,322**	**1,121**	**501**	**1,416**

Table III.13: Percent of total land area west of the Cascade crest that impacts salmonids and is managed by DNR

DNR-managed lands in the Columbia Planning Unit have no pink salmon. The five west-side planning units consist of the Straits, North Puget, South Puget, South Coast, and Columbia. OESF is the Olympic Experimental State Forest.

(Source: DNR GIS April 1995)

Planning Unit	**Coho**	**Chinook**	**Chum**	**Sockeye**	**Pink**	**Steelhead**	**Sea-run Cutthroat**	**Bull Trout/ Dolly Varden**
South Coast	13	15	15	4	5	13	13	3
Straits	15	15	15	11	13	15	15	8
North Puget	13	14	15	14	13	13	15	14
South Puget	5	5	5	1	2	5	6	3
Columbia	14	13	13	16	—	14	13	15
Total for five west-side planning units	12	12	12	10	10	12	13	10
OESF	25	25	23	28	33	25	24	22