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Degradation and Loss of Anadromous Salmonid Habitat in the Pacific Northwest

Stanley V. Gregory and Peter A. Bisson

Abstract

Many stocks of Pacific salmon (*Oncorhynchus* spp.) have become extinct over the last century, and other stocks currently are declining and risk extinction. Habitat degradation has been associated with >90% of the documented extinction or declines of salmon stocks. Surveys of public and private lands in Washington, Oregon, Idaho, and northern California indicate that freshwater habitats for salmonids are in poor to fair condition. Fundamental aspects of habitat in the Pacific Northwest include known trends in habitat change, institutional histories and land uses, and principles for restoration of streams and rivers.

Declines of Pacific salmon stocks closely followed Euro-American settlement of the Pacific Northwest in the 19th century. Causes for declining stocks are complex, but habitat degradation has been explicitly identified as a factor in the declines of most stocks. The historical land use on both public and private lands in the Pacific Northwest has left us with a legacy of altered habitats that will require considerable time for recovery, and return to historical conditions will never occur on a large proportion of the landscape. Loss of floodplain habitats in both montane and lowland riparian forests has been one of the most pervasive and unregulated forms of habitat use.

Inconsistent development of environmental management issues or guidelines for land-use practices presents a major obstacle to managing freshwater habitats in the Pacific Northwest. Currently, Pacific Northwest states have a fragmented and uncoordinated collection of statutes relating to different land-use types, zoning, and different resource users. Effective habitat management at a landscape scale requires incorporation of the entire landscape relevant to salmon life histories and integration of management policies for both public and private lands.

The goal of restoration is to reestablish an ecosystem's ability to maintain its function and organization without continued human intervention. It does not mandate returning to some arbitrary prior state. Any restoration program should be nested within a larger program of landscape management that protects, maintains, and restores ecosystem structure and function. The most critical questions related to aquatic habitat restoration include the following: the degree to which the habitat can be repaired or restored, priorities for locations where restoration efforts will be beneficial, and ecologically sound approaches for habitat restoration. The major agent of aquatic ecosystem restoration in the Pacific Northwest is periodic flooding, and the challenge for human efforts is to supplement natural processes of restoration. In the future, our success in ecosystem management will be measured by the degree to which we are able to decrease the need for restoration programs.

Introduction

Though the causes have been strenuously debated, there is no question that anadromous salmonids in the Pacific Northwest have declined or that considerable aquatic and riparian habitat has been altered or lost since the mid-1850s (National Research Council [NRC] 1996). Recent evaluations of the status of Pacific salmon (*Oncorhynchus* spp.) have concluded that many stocks have become extinct over the last century and that many other stocks currently are declining and risk extinction (Walters and Cahoon 1985, Chapman 1986, Konkel and McIntyre 1987, Nehlsen et al. 1991, Frissell 1993, Washington Department of Fisheries et al. 1993). Habitat degradation has been associated with >90% of the documented extinctions or declines of these stocks (Nehlsen et al. 1991). No survey of public or private lands in Washington, Oregon, Idaho, or northern California has concluded that freshwater habitats for salmonids are in good to excellent condition (General Accounting Office 1988, USDI Bureau of Land Management [BLM] 1991, Nickelson et al. 1992, Thomas et al. 1993, Forest Ecosystem Management Assessment Team [FEMAT] 1993). Forest practices, agriculture, livestock grazing, road building, urbanization, and dams have diminished the ability of freshwater habitats to support anadromous stocks of salmon and trout. Factors not related to habitat (e.g., excessive commercial and sport salmon harvest, hatchery practices, disease or predation, and ocean conditions) also have contributed to the decline of Pacific salmon and are addressed in other papers (Fresh 1996, Mundy 1996, Pearcy 1996, Reisenbichler 1996).

Causes and rates of habitat change have varied across the Pacific Northwest over the last 150 years, involving many types of human activity on forested land, croplands, rangelands, residential areas, and industrial developments. Generalizations are difficult and may be misleading because the degree of habitat change ranges from short-term, localized modification to large-scale, long-term loss of habitat. In some cases, habitats have been destroyed through diking and filling, land draining, channelization, or stream rerouting. Other forms of habitat alteration significantly reduce major aspects of salmonid habitat, such as pools, wood accumulations, side channels and other lateral habitats, or floodplains. Studies often focus on immediate changes in habitat structure and composition, but alteration of ecosystems processes (e.g., hydrologic regimes, delivery of sediment, thermal loading) and ecosystem structure (e.g., riparian forests, beaver populations, wetlands) may influence habitat conditions over much larger areas and time periods (Naiman 1992).

Attempts to improve survival in other aspects of salmon life history such as upstream adult migrations or harvest reductions may have little effect if freshwater habitat for salmon is inadequate. Recovery of salmon in response to natural improvements in climate or environmental conditions in the north Pacific Ocean will be limited if freshwater habitats pose limits to the early phase of their life histories (Francis and Sibley 1991, Pearcy 1992). Freshwater streams and riparian areas are critical to the life history of the fish (e.g., clean gravels for spawning; an open gravel environment from which newly hatched fish can emerge; low velocity, shallow habitat along stream margins for rearing of young fish; overwintering habitat; refuges to survive natural flooding; deep pools; and cold water).

Environmental factors and human activities contributing to the decline of salmon differ from basin to basin. Attempts to single out practices responsible for the decline of anadromous salmonids or to rank their impacts are likely to be misleading and ultimately to weaken collective or integrated approaches for managing the common resources and landscapes of the Pacific

Northwest (Botkin et al. 1995). It is impossible to ensure the survival of the stocks of anadromous salmonids of the Pacific Coast without providing high-quality freshwater habitat for spawning, rearing, and passage of juvenile fish, and migration of returning adults. In this paper, we identify known trends in habitat change in the Pacific Northwest, describe institutional histories and land uses that influence habitat conditions and future alternatives, and explore principles and applications for restoring streams and rivers.

Historical Patterns of Habitat Alteration and Loss

Humans have occupied the Pacific Northwest for ~18,000 years, strongly influencing the distribution and abundance of native plants and animals. For example, burning of prairies and forests by Native Americans modified vegetation in local areas, such as the prairies of the Willamette Valley, Oregon, and the Puget Trough, Washington, maintaining more of an oak savannah or grassland than a forested environment (Boyd 1990). Many Native Americans subsisted on anadromous salmon as part of their food base for much of that time. Fish traps, spearing, and net fisheries at falls and other constrictions to migratory pathways had the potential to strongly alter salmon and trout populations (Stewart 1977), but Native Americans changed relatively little of the overall habitat of salmon.

Declines of Pacific salmon stocks closely followed Euro-American settlement of the Pacific Northwest in the 19th century. In 1832, Captain Nathaniel Wyeth established a commercial fishing and salt packing operation on Sauvies Island at the confluence of the Willamette River and Columbia River, but competition with the Hudson Bay Company proved too great, and he sailed back to the east coast of the United States (US) in 1835 with only half a cargo load of salmon (Cobb 1922). The first successful commercial harvest in the Pacific Northwest did not occur until 1861, when H.N. Nice and Jotham Reed began a commercial salting operation in the Columbia River 96 km below Portland, Oregon. William Hume built the first cannery at Eagle Cliff, Washington, in 1866, 2 years after he helped establish the first salmon cannery on the Sacramento River, California (Adams 1885). In that year, all returning adult salmon to the Sacramento River were eliminated by massive sedimentation caused by gold mining (Stone 1897). Forty canneries were operating in the Columbia River by 1885. Abundances of all species of salmon in the Columbia River declined by the mid-1880s, prompting Marshall McDonald (1895), the US Commissioner of Fish and Fisheries, to note:

> It is not a matter of wonder that, under the existing conditions, there has been serious deterioration in the value of the fisheries. It is, indeed, a matter of surprise that any salmon have been able to elude the labyrinth of nets which bar their course to the Upper Columbia.

Declines of salmon were attributed first to overharvest of fish in the terminal fisheries and later to habitat degradation. In 1876, hatchery development in Oregon began as an attempt to overcome the perceived loss of the natural system's ability to support natural production. McDonald (1875) further noted:

> In 1888 the U.S. Fish Commission, by direction of Congress, established a salmon hatching station on the Clackamas River, Oregon. . . . This work was undertaken on the urgent solicitation of those concerned in the salmon fisheries of the Columbia River, who realized that their fisheries were being exhausted, and it was hoped that some compensation for the deficiency in natural reproduction could be made by artificial stocking and breeding.

It quickly became evident that artificial propagation was not a simple panacea for overly aggressive commercial fishing and that land-use practices were degrading aquatic habitat conditions. Livingstone Stone (1897), founder of the first hatcheries on the Pacific coast, observed:

> When it [the Clackamas hatchery] first passed into the hands of the US Fish Commission it yielded 5,000,000 salmon eggs a year, but it was too near civilization to prosper long as a salmon-breeding station, and gradually mills and dams, timber cutting on the upper waters of the Clackamas, and logging in the river, together with other adverse influences, so crippled its efficiency that it was given up this year as a collecting point for salmon eggs. . . .

Even the value and success of the McCloud River hatchery in California, the first hatchery on the US west coast, was related to the extensive destruction of habitat in the basin by mining. Stone (1897) also noted:

> McCloud River . . . is the only cold tributary of the Sacramento that has not been roiled by gold mining, in consequence of which the salmon come into the McCloud to breed in the summer, not only from choice, but also from necessity.

Mining after the Gold Rush of 1862 destroyed critical habitat for salmonids throughout the Northwest, and water quality was impaired through degradation of ambient chemistry (e.g., oxygen, suspended sediment) and introduction or re-exposure of toxic substances (e.g., mercury, cyanide). Many laws governing mining operations have changed little over the last 100 years, as evidenced by the federal Mining Act of 1872 (Nelson et al. 1991).

Routes of early settlers into the Pacific Northwest followed the major river drainages (Fig. 1), moving westward along the Snake River system, down the Columbia River or across the Cascades into the western valleys of Oregon and Washington, and south into northern California (Nolan 1993). These same routes became the major arteries for today's transportation infrastructure and for the major centers of present human populations (Fig. 2, 3; Northam 1993). These corridors undoubtedly will dictate the pattern of future human activity and concomitant ecological changes in the region. Aquatic ecosystems along these transportation routes and urban centers will be altered more intensively than more remote habitats in rural lands or mountainous areas.

Development of towns and cities along the major rivers brought almost unbridled degradation of water quality, and by the early 1920s, John Cobb (1922) noted:

> Next to the fishing operations of man, the gravest danger to the salmon fisheries of the Pacific coast lies in the pollution of the rivers which the salmon ascend for spawning purposes. . . . The large increase in the population of the coast States within recent years, with the resulting increase of mills and factories, has greatly increased the amount of sewage from cities and towns and the waste of the manufacturing plants.

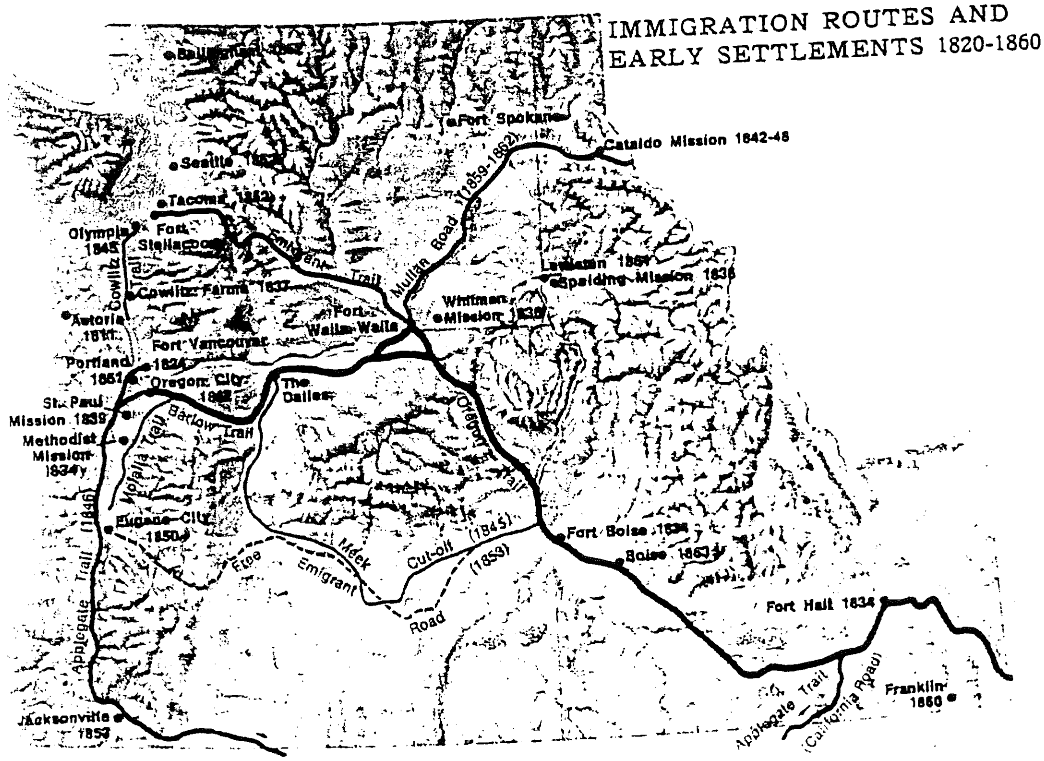

Figure 1. Routes of Euro-American settlers moving into the Pacific Northwest. Source: Nolan (1993); reprinted by permission of Oregon State University Press.

The first large dams of the Northwest were built in the 1930s, but settlers had been damming streams for power generation and mill operations since the mid-1800s. Dams were constructed with little or no regulation on their construction or locations. Their impacts on the fisheries were recognized before the turn of the century (Smith 1895). Fish passage was rarely accommodated by early dams, and even Bonneville Dam, constructed in 1933, originally was designed with no provision for passage of salmon into the Columbia River basin above Portland. Growth of factories, agriculture, and mining required enormous consumption of water, and laws on water withdrawal reflected the pioneering nature of the expansion of western society, first come, first served. Modern water allocations in the western US are still based on this principle, and water rights from the late 1800s remain in effect. Most water withdrawals were not considered in their consequences either on habitat in the streams or on fish that were diverted with the water, as noted by Cobb (1922):

> The irrigation ditch, a comparatively new product on this coast, while of great benefit in developing the arid lands in certain sections, as at present operated is a considerable menace to the salmon fisheries. But few ditches have screens at their head, and as a result many thousands of young salmon slowly making their way to the ocean home pass into and down these to an early doom.

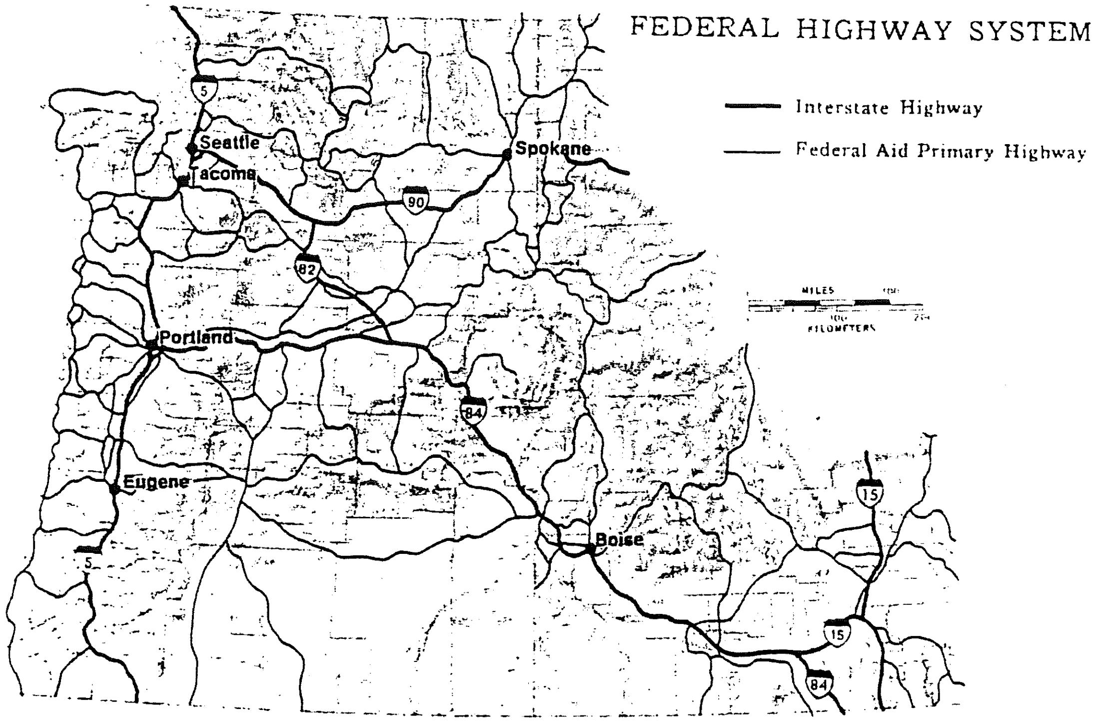

Figure 2. Modern highways and transportation routes in the Pacific Northwest. Source: Nolan (1993); reprinted by permission of Oregon State University Press.

Pollution of major rivers during the early 20th century made extensive reaches devoid of fish and most invertebrate life because of elevated temperatures, lack of oxygen, and toxic substances (Gleeson 1972). A survey of fish and water quality in the Willamette River in 1944 indicated few live fish in the 69-km reach of river from Newberg to Portland (Dimick and Merryfield 1945). The survey also noted that cutthroat trout fry died within 2 minutes after being placed in the South Fork of the Santiam River. Stream temperatures in major tributaries reached 31.7°C (89°F), and oxygen concentrations were observed as low as 0.0 mg L^{-1} and ranged from 0.6 to 1.4 mg L^{-1} in the lower river below Newberg, Oregon. Water quality in mainstem lowland rivers diminished or eliminated the access to headwater streams for adult salmon and created an almost impassable gauntlet for smolts migrating downstream.

After little more than a century of Euro-American settlement, the states and regulatory agencies of the Pacific Northwest were forced to acknowledge the destruction of freshwater habitat and water quality throughout the region. The last half of the 20th century marked a period of land-use laws, pollution regulation, mandated sewage treatment, and establishment of water rights for fish and aquatic ecosystems. Each step toward restoring the aquatic ecosystems of the Pacific Northwest has been seen as a potential infringement on the rights of individuals and continues to be fiercely debated. The momentum that drives the development of environmental regulation, land zoning, and alliances of private citizens is the recognition that our waters and anadromous salmonids are a common resource and regional heritage.

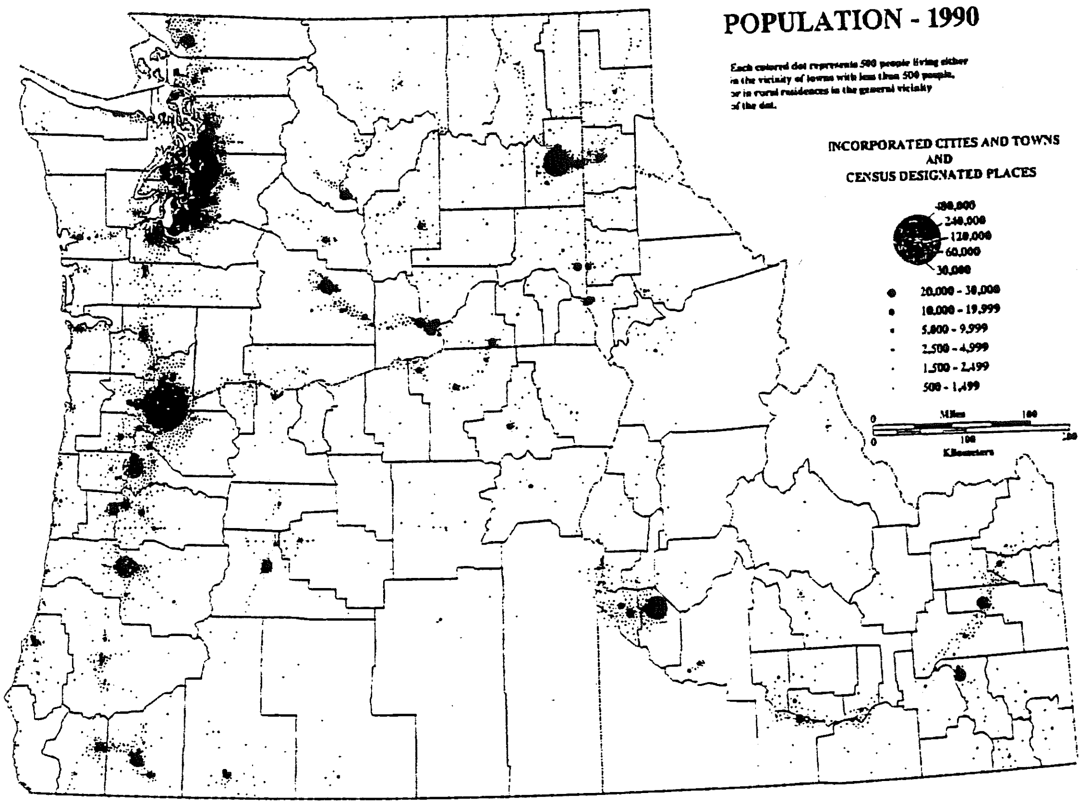

Figure 3. Major urban areas and population distribution in the Pacific Northwest. Source: Matzke (1993); reprinted by permission of Oregon State University Press.

Status of Salmon and Patterns of Their Decline

In the late 1980s and early 1990s, concerns over dwindling numbers of returning adult salmon stimulated regional evaluations of local extinctions and the status of existing stocks (Konkel and McIntyre 1987, Nehlsen et al. 1991, The Wilderness Society 1993; P. Higgins, S. Dobush, and D. Fuller, Humboldt Chapter, American Fisheries Society unpubl. data). These studies echoed 100 years of reports on habitat loss and salmon declines by regional aquatic biologists, and also attempted to quantify historical extinctions and populations at risk of extinction over broad areas, something many of the earlier reports had not done. According to Nehlsen et al. (1991), >106 stocks of anadromous salmonids have become extinct in Washington, Oregon, Idaho, and California, and 214 stocks considered to be at risk of extinction were further identified. Generally, anadromous salmonids were found to be at greater risk near the southern portions of their ranges than more northerly populations, and interior populations (e.g., upper Sacramento River, middle and upper Columbia River) were at greater risk than populations in systems draining the Coast Range (NRC 1996).

Causes for extinctions or declining stocks are complex and differ from basin to basin, but habitat degradation (including loss caused by dams) was explicitly identified as a factor in the declines of 194 of the 214 stocks and was believed to be the principal factor in the declines of 51 at-risk stocks (Nehlsen et al. 1991). No evidence was found for fishing salmon stocks to extinction even when weirs were used as a terminal fishery. Analyses of the status of individual species, such as steelhead (*O. mykiss*) (Cooper and Johnson 1992), coho (*O. kisutch*) and chinook (*O. tshawytscha*) salmon (Lichatowich 1989), and cutthroat trout (*O. clarki*) (Trotter et al. 1993) have all identified habitat loss as a widespread, significant contributor to stock declines. Protection and restoration of existing salmon stocks will require integrated efforts to address the many sources of mortality, but the quantity and quality of habitats clearly will be central issues in the future of Pacific salmon (Pacific Rivers Council 1993, The Wilderness Society 1993, NRC 1996).

The history of extinctions and threats to the survival of existing salmon stocks is not uniform across the Pacific Northwest. Regional patterns reveal the nature of past habitat change and indicate areas where greater numbers of stocks depend on future protection and restoration. The Columbia River basin, with its numerous dams and water withdrawals, accounts for 63% of the stocks that are known to have become extinct in Washington, Oregon, Idaho, and California, but 20% of the extinct stocks originally occurred in California (Nehlsen et al. 1991). This reflects both the intensity of habitat alteration in these areas and the harsher environmental conditions at the edge of these species' distributions. Stocks on the edges of the geographic range of the Pacific salmon must tolerate habitat conditions that can be marginal for the species, and even moderate levels of habitat alteration may be adequate to eliminate entire stocks.

According to Nehlsen et al. (1991), relatively few recent extinctions have been documented for stocks inhabiting the Oregon coast (10 stocks) and the Washington coast and Puget Sound (8 stocks), but each of these geographic areas contains as many stocks at risk of extinction as currently occur in the Columbia River basin (58 in Oregon coast, 60 in Washington coast and Puget Sound, 57 in Columbia River basin). The lower extinction rate of salmon in coastal areas illustrates the potential to save a greater proportion of the original species populations in coastal Oregon and Washington, but the large number of at-risk stocks reflects our recent history of land management and fisheries regulation in those parts of the Pacific Northwest with the greatest potential to support anadromous salmonids. The extent of stock declines in coastal Oregon and Washington emphasizes the need to reverse the current trend in habitat alteration in the Pacific Northwest (Moyle and Williams 1990, Frissell 1993).

Alteration of Salmonid Habitats by Land-Use Practices

Modification of aquatic habitats generally affects one or more of six fundamental components of stream ecosystems: channel structure, hydrology, sediment input, environmental factors, riparian forests, and exogenous material (Table 1). Actions that change channel structure, hydrology, or sediment delivery essentially alter the physical habitat that potentially can be occupied by anadromous salmonids. Environmental factors change either the physical environment or water chemistry, which either directly affect the physiology of salmonids or indirectly influence their food resources. Riparian forests influence numerous processes such as flood routing, sediment trapping, nutrient uptake, allochthonous inputs, wood, shade, stream temperature, and root strength (Naiman et al. 1988, Gregory et al. 1991), but a critical aspect of altering riparian forests

Table 1. Types of habitat alteration and effects on salmonid fishes in the Pacific Northwest. Based in part on Hicks et al. (1991b), Swanston (1991), and National Research Council (1996).

Ecosystem feature	Altered component	Effects on salmonid fishes and their ecosystems	Selected references

Table 1. Types of habitat alteration and effects on salmonid fishes in the Pacific Northwest. Based in part on Hicks et al. (1991b), Swanston (1991), and National Research Council (1996).

Ecosystem feature	Altered component	Effects on salmonid fishes and their ecosystems	Selected references
Channel structure	Floodplains	Loss of overwintering habitat, loss of refuge from high flows, loss of inputs of organic matter and large wood	Peterson and Reid (1984), Sedell and Froggatt (1984), Brown and Hartman (1988), Booth (1991)
	Pools and riffles	Shift in the balance of species, loss of deep water cover and adult holding areas, reduced rearing sites for yearling and older juveniles	Hawkins et al. (1983), Bisson and Sedell (1984), Sullivan et al. (1987), Bisson et al. (1988), Moore and Gregory (1988), Sedell and Everest (1991), Ralph et al. (1994)
	Large wood	Loss of cover from predators and high flows, reduced sediment and organic matter storage, reduced pool-forming structures, reduced organic substrate for macroinvertebrates, formation of new migration barriers, reduced capacity to trap salmon carcasses	Narver (1971), Swanson and Lienkaemper (1978), Bryant (1983), Cederholm and Peterson (1985), Harmon et al. (1986), Bisson et al. (1987), Andrus et al. (1988), Murphy and Koski (1989), Aumen et al. (1990), Gregory et al. (1991), Naiman et al. (1992)
	Substrate	Reduced survival of eggs and alevins, loss of interstitial spaces used for refuge by fry, reduced macroinvertebrate production, reduced biodiversity	Burns (1972), Murphy et al. (1981), Hawkins et al. (1982), Everest et al. (1987), Swanson et al. (1990), Montgomery and Buffington (1993)
	Hyporheic zone	Reduced exchange of nutrients between surface and subsurface waters and between aquatic and terrestrial ecosystems, reduced potential for recolonizing disturbed substrates	Stanford and Ward (1988, 1992), Triska et al. (1989, 1990)
Hydrology	Discharge	Altered timing of discharge-related life cycle cues (e.g., migrations), changes in availability of food organisms related to timing of emergence and recovery after disturbance, altered transport of sediment and fine particulate organic matter, reduced biodiversity	Swanson et al. (1982), Bilby and Bisson (1987), Chamberlin et al. (1991), Naiman et al. (1992)
	Peak flows	Scour-related mortality of eggs and alevins, reduced primary and secondary productivity, long-term depletion of large wood and organic matter, involuntary downstream movement of juveniles during freshets, accelerated erosion of streambanks	Cristner and Harr (1982), Berris and Harr (1987), Culp (1988), Anderson (1992), Borchardt (1993), Luchetti and Fuerstenburg (1993)
	Low flows	Crowding and increased competition for foraging sites, reduced primary and secondary productivity, increased vulnerability to predation, increased fine sediment deposition	Smoker (1955), Mason and Chapman (1965), Chapman (1966), Wissmar and Swanson (1990), Hicks et al. (1991a)

Table 1—cont.

Ecosystem feature	Altered component	Effects on salmonid fishes and their ecosystems	Selected references
Hydrology—cont.	Rapid fluctuations	Altered timing of discharge-related life cycle cues (e.g., migrations), stranding, intermittent connections between mainstem and floodplain rearing habitats, reduced primary and secondary productivity	Poff and Ward (1989), Reice et al. (1990)
Sediment	Surface erosion	Reduced survival of eggs and alevins, reduced primary and secondary productivity, interference with feeding, behavioral avoidance and breakdown of social organization, pool filling	Cordone and Kelly (1961), Burns (1972), Iwamoto et al. (1978), Noggle (1978), Bisson and Bilby (1982), Berg and Northcote (1985), Everest et al. (1987), Chapman (1988), Platts et al. (1989)
	Mass failures and landslides	Reduced survival of eggs and alevins, reduced primary and secondary productivity, behavioral avoidance, formation of upstream migration barriers, pool filling, addition of new large structure to channels	Beschta (1978), Cederholm et al. (1981), Everest et al. (1987), Swanson et al. (1987), Chapman (1988), Benda (1990), Chamberlin et al. (1991), Megahan et al. (1992)
Water quality	Temperature	Altered adult migration patterns, accelerated development of eggs and alevins, earlier fry emergence, increased metabolism, behavioral avoidance at high temperatures, increased primary and secondary production, increased susceptibility of both juveniles and adults to certain parasites and diseases, altered competitive interactions between species, mortality at sustained temperatures >23-29°C, reduced biodiversity	Brett (1952), Averett (1969), Hall and Lantz (1969), Brown and Krygier (1970), Bisson and Davis (1976), Wurtsbaugh and Davis (1977), Newbold et al. (1980), Tschaplinski and Hartman (1983), Hughes and Davis (1986), Beschta et al. (1987), Reeves et al. (1987), Holtby (1988), Platts and McHenry (1988), Bjornn and Reiser (1991), Karr (1991)
	Dissolved oxygen	Reduced survival of eggs and alevins, smaller size at emergence, increased physiological stress, reduced growth	Davis (1975), Ringler and Hall (1975), Brett and Blackburn (1981), Scrivener (1988), Bjornn and Reiser (1991)
	Nutrients	Increased primary and secondary production, possible anoxia during extreme algal blooms, increased eutrophication rate of standing waters, certain nutrients (e.g., non-ionized ammonia, some metals) possibly toxic to eggs and juveniles at high concentrations	Dimick and Merryfield (1945), Warren et al. (1964), Triska et al. (1984), Gregory et al. (1987), Bothwell (1989), Nelson et al. (1991), Bisson et al. (1992)

Table 1—cont.

Ecosystem feature Altered component Effects on salmonid fishes and their ecosystems Selected references

Table 1—cont.

Ecosystem feature	Altered component	Effects on salmonid fishes and their ecosystems	Selected references
Riparian forest	Production of large wood	Loss of cover from predators and high flows, reduced sediment and organic matter storage, reduced pool-forming structures, reduced organic substrate for macroinvertebrates	Narver (1971), Swanson and Lienkaemper (1978), Bryant (1983), Grette (1985), Harmon et al. (1986), Bisson et al. (1987), Andrus et al. (1988), Murphy and Koski (1989), Aumen et al. (1990), Shirvell (1990), Van Sickle and Gregory (1990), Bilby and Ward (1991), Gregory et al. (1991)
	Production of food organisms and organic matter	Reduced heterotrophic production and abundance of certain macroinvertebrates, reduced surface-drifting food items, reduced growth in some seasons	Mispagel and Rose (1978), Naiman and Sedell (1979), Vannote et al. (1980), Minshall et al. (1985), Gregory et al. (1987), Wissmar and Swanson (1990), Gregory et al. (1991), Bilby and Bisson (1992), Naiman et al. (1992)
	Shading	Increased water temperature, increased primary and secondary production, reduced overhead cover, altered foraging efficiency	Murphy et al. (1981), Shortreed and Stockner (1983), Wilzbach (1985), Gregory et al. (1987), Culp (1988), Bilby and Bisson (1992)
	Vegetative rooting systems and streambank integrity	Loss of cover along channel margins, decreased channel stability, increased streambank erosion, increased landslides	Burroughs and Thomas (1977), Beschta (1991), Platts (1991), National Research Council (1992), Forest Ecosystem Management Assessment Team (1993)
	Nutrient modification	Altered nutrient inputs from terrestrial ecosystems, altered primary and secondary production	Berg and Doerksen (1975), Minshall et al. (1985), Gregory et al. (1991), Stanford and Ward (1992)
Exogenous material	Chemicals	Reduced survival of eggs and alevins, toxicity to juveniles and adults, increased physiological stress, altered primary and secondary production, reduced biodiversity	Dimick and Merryfield (1945), Seiler (1989), Karr (1991), Nelson et al. (1991), Norris et al. (1991)
	Exotic organisms	Increased mortality through predation, increased interspecific competition, introduction of diseases	Li et al. (1987), Karr (1994), National Research Council (1996)

is the time required for recovery of mature forest conditions (Agee 1988). This successional process creates a context for other types of habitat modification and limits rates of recovery. Exogenous materials, including dissolved chemicals, particulate material, and exotic organisms, represent factors that commonly are not part of the evolutionary history of the aquatic ecosystems. Responses can be severe and may persist as long as the material remains in the ecosystem.

Conversion of lowland forests, coastal tide lands, floodplains, and headwater forests, as well as alteration of water quality, have affected anadromous salmonids and aquatic ecosystems throughout the Pacific Northwest (Frenkel and Morlan 1991, Lucchetti and Fuerstenberg 1993). Attention to forestry-related issues in recent years has focused the public's attention on land-use policies in the upland forests, which are predominantly public lands. Historical loss of estuaries and lowland freshwater habitats (Boulé and Bierly 1987) has been considerable. For example, Simenstad et al. (1982) identified five major estuaries in Puget Sound in which >70% of the available habitat has been lost. Much of the habitat of lower main rivers is no longer in forest lands but instead in areas zoned for agriculture, urban, and industrial development. Many of these lands have been converted from coniferous forests to grasslands, meadows, deciduous forests, or paved surfaces.

As a consequence of settlement, many historical lowland or floodplain forests have been eliminated, and recent society has little memory of the conditions of those riparian forests and the roles that they played (Sedell et al. 1990). Riparian forests in lower valley floodplains, particularly secondary channels and off-channel ponds, were particularly critical for survival of rearing salmon during winter floods and provided cold-water refuges during warmer periods of the year (Ward et al. 1982, Peterson and Reid 1984, Brown and Hartman 1988).

Floodplains also provide coarse beds of alluvial sediments through which subsurface river flow passes much like a trickle filter in wastewater treatment plants (Stanford and Ward 1992). This hyporheic zone, the subsurface flow between surface water and the water table, serves as a filter for nutrients and maintains high water quality (Triska et al. 1989). Human activities have altered lowland rivers incrementally in small patches by numerous practices such that existing channels and floodplains are minor relicts of original conditions. As a result of these "diffuse" alterations over space and time, the degree and consequences of habitat alteration are rarely recognized.

Few quantitative studies of salmonid habitats were conducted prior to World War II, and historical reconstructions of riverine conditions are scarce; thus, accurate assessment of habitat loss is difficult. Comparison of current conditions of the upper Willamette River with maps constructed by the cadastral land survey of the 1850s reveals extensive simplification (Sedell and Froggatt 1984). Sections of the river that originally were braided and contained side channels and floodplain lakes are now single channels with little or no lateral connections. Lowland streams and rivers have been simplified and channelized so extensively that it is rare to find reaches that resemble natural channels and floodplain forests. A survey of 43,000 km of streams in Oregon indicated that 55% were either moderately or severely impacted by nonpoint source pollution (Edwards et al. 1992).

Despite the scarcity of quantitative historical studies, it is clear that habitat availability and quality have significantly declined and that current environmental protection and resource management policies have not been able to reverse that trend (Hicks et al. 1991b, Bisson et al. 1992). Land-use practices differ in their impacts and the portions of the landscape and river drainages that are altered. Forested lands make up 46% of the land cover of Washington, Oregon, and

Idaho, and the federal government manages or supervises ~60% of the forest lands (Table 2; Jackson and Kimerling 1993). Rangelands account for 32% of the land base, and croplands and pasture make up another 20%. Only 2% of the Pacific Northwest is represented by urban or developed lands. These general trends in land use are consistent throughout the states of the region, but proportions of federal and non-federal lands within a land-use type differ substantially between states (Table 2).

Habitat Loss Associated with Forest Management

Forest practices (e.g., timber harvest, yarding, road building) alter many components and processes of aquatic ecosystems and the land-water interface. These interactions have been evaluated and synthesized in several major symposia, reports, and books (Krygier and Hall 1971, Karr and Schlosser 1977, Iwamoto et al. 1978, Salo and Cundy 1987, Raedeke 1988, Hartman and Scrivener 1990, Meehan 1991, Naiman 1992, Peterson et al. 1992). These works provide detailed reviews of the effects of forest practices on aquatic ecosystems, and the following section simply highlights some of the major changes related to habitat alteration on forest lands (Table 1).

Habitat Change

When commercial logging began in the mid-19th century, there were no roads for moving logs to the sawmills, and rivers served as the early routes for transportation (Sedell and Luchessa 1982). Splash dams were constructed to generate sufficient flows for moving the logs down

Table 2. Areas of different land-use types in three Pacific Northwest states. Modified from Jackson and Kimerling (1993).

Land use	Ownership	Oregon km^2	Oregon %	Washington km^2	Washington %	Idaho km^2	Idaho %
Forests	Federal	75,669	30	38,340	22	67,745	30
	Nonfederal	47,984	19	51,128	29	16,475	7
Rangeland	Federal	53,160	21	6,750	4	63,463	28
	Nonfederal	37,037	15	22,557	13	26,693	12
Cropland	Nonfederal	24,682	10	37,968	22	40,590	18
Pasture	Nonfederal	7,754	3	5,747	3	5,480	2
Urban land	Nonfederal	3,808	2	6,329	4	1,930	1
National parks	Federal	683	<1	7,329	4	393	<1
Total landbase	Federal	129,512	51	52,419	30	131,600	59
	Nonfederal	121,265	49	123,729	70	91,168	41
	Combined	250,777	100	176,148	100	222,768	100

ream channels. During relatively low flow conditions, a slurry of water and logs was suddenly leased, destroying riparian zones and aquatic communities as it moved downstream. Structurly complex habitats within these streams were channelized and cleared to facilitate transportaon. The techniques of splash damming and log driving down rivers had been used in timber arvest across the North American continent as settlers moved west and had also been used in urope for centuries. At the same time that log drives were first appearing in the Pacific Northrest, detrimental effects of log drives were being documented in Sweden (Malmgren 1885). plash damming and log drives from the 1870s through the 1920s altered streams and rivers to uch an extent that they have not yet fully healed (Sedell et al. 1991).

The history of logging on both public and private lands in the Pacific Northwest left a egacy of altered habitats that will require considerable time for recovery (Cordone and Kelly 961), and the return to historical conditions will probably never occur on a large proportion of he forested landscape. Stream surveys by federal agencies have shown that habitat is in fair to oor condition (BLM 1991, FEMAT 1993, Hessburg 1993, Thomas et al. 1993). The BLM stimated that 64% of the riparian areas on their lands in Oregon and Washington and 45% of heir riparian areas in Idaho did not meet the objectives of their management policies (BLM 991). FEMAT (1993) concluded that "aquatic ecosystems in the range of the northern spotted wl exhibit signs of degradation and ecological stress. . . . Although several factors are responsible for declines of anadromous fish populations, habitat loss and modification are major determinants of their current status." In addition, evaluations sponsored by the forest industry acknowledged the overall decrease in stream habitat quality on forest lands (Kaczynski and Palmisano 1992, Palmisano et al. 1993).

One of the few quantitative studies of habitat change was based on a survey of pools in Pacific Northwest streams, conducted by the US Fish and Wildlife Service from 1934 to 1946 (Rich 1948). The Pacific Northwest Research Station of the USDA Forest Service (Forest Service) and its cooperators resurveyed the same streams ~50 years later to determine changes in channel conditions (Sedell and Everest 1991). All streams are dynamic and channel change is a natural process, but overall trends may reflect large-scale responses to human activities. Frequencies of very large pools (based on criteria of >1.8 m deep and >42 m^2 surface area) in 658 km of stream in 13 basins in Washington and Oregon decreased by an average of 58%, ranging from a loss of 94% in the Coweeman River basin to a gain of 10% in the Wind River basin (McIntosh et al. 1993). The gain in pool habitat in the Wind River was a result of channel restoration efforts that followed the Yacolt burn and subsequent log drives in the 1910s, which had reduced the amount of large wood in the Wind River prior to the original survey. Decreases in large pool habitat on private forest lands in coastal Oregon averaged >80%. Pool habitat in largely unmanaged sub-basins of the Wenatchee River, Washington, and the Willamette River, Oregon, over the same period increased 212% and 400%, respectively (J. Sedell and B. McIntosh, USDA Forest Service, Corvallis, Oregon, pers. comm.). On the basis of habitat surveys from 1934 to 1946, McIntosh et al. (1993) concluded that the frequency of large pools in watersheds with forest management in eastern Oregon and Washington declined by an average of 31%, while pools in unmanaged basins increased by 200%. These changes have occurred since 1934, which followed more than 80 years of extensive habitat alteration in all of the surveyed basins.

Loss of large-pool habitat has been caused by various forest management-related factors, including the removal of large wood and large boulders, an increase in the amount of fine sediment (sand and gravel) deposited in pool bottoms, and in some instances, by channelization

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(FEMAT 1993). Large pools do not provide the full range of habitat conditions needed by all adult and juvenile salmonids, but they are important holding areas for adults migrating upstream and serve as rearing sites for the juveniles of certain species (Hicks et al. 1991b). Loss of large pools reduces the availability of holding areas for adult salmon. This may be particularly important in streams where large pools with inflowing groundwater provide cold-water refuges during adult migrations in summer months (Berman and Quinn 1991). Additionally, large pools often provide cover for both juvenile and adult salmonids from terrestrial predators. The observation that >50% of the large pools have been lost from many streams over the last half century reveals the extent of physical habitat alteration, especially given that many of these streams had already been changed by human activities when the original pool surveys were initiated.

A study of streams in old growth forests, forests with moderate harvest (<50% harvested within the last 40 years), and forests with intensive harvest (>50% harvested within the last 40 years) in western Washington documented significant changes in pool habitat and amounts of large wood (Ralph et al. 1994). Pool areas and depths were significantly lower in streams in old-growth forests than in harvested basins, and pools >1 m in depth were almost eliminated in harvested basins. A reduction in the abundance of large pieces of wood was also related to logging.

Studies of the effects of past timber harvest over the last several decades frequently are criticized because forest practices have changed during the interim. Unfortunately, the landscape is filled with lands changed by historical practices that no longer occur, and anadromous salmon return to habitats that reflect very little of the improvement in recent forest practices. In Oregon, the majority of private forest lands were harvested at least once prior to the development of the Forest Practices Act (Oregon Department of Forestry 1988). Current habitat conditions on forest land in the Pacific Northwest have been shaped by roughly 150 years of timber harvest, and recent land-use regulations are designed to allow some degree of recovery in the future.

Channel Structure

One of the most profound changes in habitat related to forest practices is alteration of channel structure. Channel structure may be affected directly by sedimentation, mass failure, changes in rooting and vegetative cover, and direct channel modification by heavy equipment (Cederholm et al. 1981, Chamberlin et al. 1991). Changes in hydrologic regimes and loss of in-channel wood may cause indirect, long-term modification of channel structure. Channel changes frequently are evaluated at the scale of a stream reach, but the most important scale for analysis of land-use practices on channel structure is the drainage basin (Sullivan et al. 1987, Ryan and Grant 1991). Channels may respond differently to physical change depending on geology, climate, sediment loading, vegetation, slope, and basin position (Montgomery and Buffington 1993). Decreased heterogeneity of channel units and loss of pool habitat are common responses to forest practices in the Pacific Northwest (McIntosh et al. 1993), but fisheries managers must be cautious about basing management efforts on simplistic assumptions of channel dynamics (Sullivan et al. 1987, Montgomery and Buffington 1993).

The 1970s marked the first well-documented recognition of the role of wood in stream ecosystems (Swanson and Lienkaemper 1978, Bilby and Likens 1980, Harmon et al. 1986, Bisson et al. 1987). Numerous studies have demonstrated that clearcutting, often in combination with stream clean-up, have dramatically reduced the volumes and types of wood in streams throughout the region (Harmon et al. 1986, Andrus et al. 1988, Bilby and Ward 1991). Removal of mature trees along streams reduces natural loading rates for centuries (McDade et al. 1990, Van Sickle and Gregory 1990). Loss of wood from channels directly influences the distribution and abundance of fish populations and is one of the longest lasting effects of forest harvest on anadromous salmonids (Murphy and Koski 1989, Hicks et al. 1991b).

The wide array of changes in channel structure (e.g., loss of pools, reduction in wood, sedimentation, decreased heterogeneity) influences all freshwater stages of anadromous salmonid life histories (Hicks et al. 1991b). Responses of fish populations and other members of the aquatic community are complex; many different responses have been noted in streams throughout the region (Murphy et al. 1981, Hawkins et al. 1983, Murphy et al. 1986, Hartman and Scrivener 1990, Nickelson et al. 1991, Bisson et al. 1992). Forestry operations may also lead to reduced macroinvertebrate populations, which serve as the food base for anadromous salmonids (Newbold et al. 1980, Hawkins et al. 1982, Culp 1988), although under certain circumstances the organisms that feed on algae may benefit from increased autotrophic production associated with removal of forest canopy (Erman et al. 1977, Bilby and Bisson 1992).

Floodplains are fundamental and often overlooked components of stream channels and alluvial valleys (Gregory et al. 1991). Secondary channels provide important refugia in moderate- to high-gradient streams during floods (Seegrist and Gard 1972, Tschaplinski and Hartman 1983). Seasonally flooded channels and riverine ponds support a major component of the populations of coho salmon and other fish species during winter months (Peterson 1982, Peterson and Reid 1984, Brown and Hartman 1988). Loss of floodplain habitats in both montane and lowland riparian forests has been one of the most pervasive and unregulated forms of habitat loss in the Pacific Northwest (NRC 1996).

Stream Cleaning

Recent policies for maintaining and enhancing large wood have caused considerable frustration for those who recall the period in the 1950–70s when fishery agencies required removal of logging-related woody debris from streams. Contradictions between earlier recommendations and more recent policies actually are not as contradictory as they first appear. Practices that led to degraded habitat conditions in the late 1950s often caused the introduction of large volumes of sediment directly into stream channels. Roads were located immediately adjacent to streams, road fill was side-cast directly into channels, logs were yarded along stream corridors, and trees were felled directly into the channel. Tremendous volumes of sediment and slash were left in streams at the end of logging operations. These practices resulted in unstable conditions during subsequent winter floods, high demand for oxygen by the decomposing debris, stagnant pools, and increased direct solar radiation on the channel, which led to high temperatures, low oxygen, unstable channels, poor quality spawning gravel, and apparent blocks to migration (Bisson et al. 1987).

Fishery biologists noted the mortality of fish and called for preventing erosion of sediment and slash into streams, as well as for removing slash deposits; however, the recommendations acknowledged the need to retain wood in the streambed that existed at the site prior to logging (Hall and Lantz 1969). Even earlier efforts to remove debris accumulations also recognized potential adverse effects of wood removal. In 1949, the Oregon Fish Commission removed 170 log jams and 32 beaver dams in 27 miles of the Clatskanie River, but Merrell (1951) noted:

> Some criticism has been made of the clearing in this particular area, it having been suggested that overclearing ruined the stream by eliminating pools and exposing the gravel to shifting and scouring.

In many efforts to remove excess slash and debris, almost all wood was removed in an attempt to clear the stream for fish passage and reduce the demands on oxygen supply in the water. Stream cleaning practices often became overly zealous in that it was assumed that if some removal was good, total removal was better.

Research in the 1970s in the Fraser Experimental Forest of Colorado (Heede 1972), H.J. Andrews Experimental Forest in Oregon (Swanson and Lienkaemper 1978), and Hubbard Brook Experimental Forest in New Hampshire (Bilby and Likens 1980) identified the physical and ecological functions of large wood in streams. Aquatic scientists were soon calling for maintaining large wood and even restoring large wood to historical levels. This was not so much a contradiction of earlier policies as a recognition that proper management required maintaining natural channel functions and avoiding the types of practices that caused excessive loading of logging debris and sediment. By the 1980s, understanding of the role of large wood in ecosystems rapidly expanded to both terrestrial and aquatic ecosystems and their interfaces (Swanson et al. 1982, Harmon et al. 1986).

Habitat Loss Associated with Agriculture and Livestock Grazing

Agricultural lands (including croplands and pastures) make up ~20% of the land base of the region, and rangelands account for >30% of the land. In combination, these lands used for production of crops or livestock account for ~50% of the northwestern states (Pease 1993). These lands are located in the lower portions of the river basins where stream gradients are low and valleys are formed primarily by alluvial deposition. Agricultural and range lands usually contain more species of fish than steeper headwater streams in forests (Hughes and Gammon 1987) and often some of the more productive aquatic habitat within the basin (Li et al. 1987). These lands also contain the mainstem reaches that are essential for migration of anadromous salmonids.

Land-use practices on agricultural and range lands have greatly reduced the availability and quality of salmonid habitat (Platts 1991), and analysis of habitat conditions and development of legislation or Best Management Practices (BMPs) on private agricultural lands have been notably lacking. Agricultural lands generally occur in lowland valleys that historically contained the majority of floodplains and wetlands within the region (Sedell and Froggatt 1984). Most of these aquatic habitats were eliminated by channelization, draining, road building, and filling operations prior to World War II, and many of these changes occurred before 1900 (Bowen 1978, Boag 1992). Fishery biologists have no quantitative measures of the degree to which the elimination of lowland aquatic systems affected salmon, but recent evidence indicates that these were some of the most productive habitats within the landscape. Studies of effects of livestock grazing on aquatic ecosystems and salmonids generally have observed responses consistent with studies of habitat relationships on forest lands (Chapman and Knudsen 1980, Kauffman and Krueger 1984, Platts 1991). Where riparian vegetation is heavily grazed and channel structure is changed, populations of some fish species decline, the balance of species is altered, and stream flows are negatively affected (Elmore and Beschta 1987, Beschta 1991, Elmore 1992).

In contrast to policies for forests, land-use regulations pertaining to streams for agricultural and range lands are less protective. The few that do exist apply to a small fraction of the lands and do not explicitly identify BMPs (Kauffman 1988). Many state and federal programs have relied on voluntary compliance (Oregon Agricultural Practices - ORS 568.900-933), and there is little evaluation of attempts to protect or restore aquatic habitat. The lack of consistency in development of environmental management issues or guidelines for land-use practices is a major obstacle to managing freshwater habitats in the Pacific Northwest.

Habitat Loss Associated with Urbanization

Urban lands make up only 2% of the land base of the Pacific Northwest (Pease 1993), but they exert disproportionate influences on salmonid production because urban areas are frequently located in important salmonid migration corridors and wintering sites. In spite of their relatively small area, >70% of the population of the region lives in cities and towns (76%, 70%, 57%, 93% for Washington, Oregon, Idaho, and California, respectively [American Almanac: Statistical Abstracts of the United States 1994]). Regional resource management is dictated primarily by the urban sector, but constraints on land use are borne almost entirely by the rural sector. Increases in the proportion of the urban population will only create greater conflicts between interests of the general public, private landowners, and natural resource agencies that manage the majority of the land base.

Though total urban area may be small, cities and towns are located at critical positions on major rivers, tributary junctions, and estuaries. The confluences of major rivers in the Pacific Northwest (the Willamette and Columbia rivers, Puget Sound and its tributaries) are centers of major regional metropolitan areas (Lucchetti and Fuerstenberg 1993, Nolan 1993). Aquatic habitats in urban areas are more highly altered than in any other land-use type in the Pacific Northwest, and the proportion of the streams within the urban areas that are degraded is greater than the proportion of highly altered streams on agricultural, range, or forested lands (Booth 1991).

Most urban areas are located on historical wetlands, but drainage requirements for residences and urban centers have eliminated ≥90% of these productive aquatic habitats in some drainage systems (Boulé and Bierly 1987). Water quality and habitat conditions in these critical migration pathways within river networks potentially restrict movement of salmonid smolts from their natal streams, survival in winter rearing areas, or return of adult salmon to the headwaters. In addition, habitat degradation and direct effects on invertebrate communities reduce food supplies for fish assemblages (Hachmoller et al. 1991, Borchardt 1993). Lossess of wetlands, tidal sloughs, and estuaries in heavily urbanized or industrialized river basins have been extensive; in some areas of Puget Sound, >95% of estuarine and coastal wetland habitats have been eliminated since the 19th century (Sherwood et al. 1990, Simenstad et al. 1992). Though forest practices and, to a much lesser degree, agricultural practices have drawn intense scrutiny resulting in more protective land-use regulations, urbanization and industrial development tend to cause the most extensive alteration of aquatic ecosystems. Future population increases in the Pacific Northwest will expand the spatial extent of this source of habitat loss.

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Legal History and Role of Habitat Regulation

Public attention and legislative regulation have been focused primarily on management of aquatic habitat in forests on both public and private lands. Timber harvest practices were not regulated in riparian zones until the 1970s; thus, there were >120 years of human activity and ~50–70 years of intensive harvest on public lands prior to mandated consideration of streamside protection. Some logging of federal forests occurred during the first half of the 20th century, but timber harvest accelerated dramatically after World War II—an era with little or no riparian protection. From 1940 to 1960, federal lands accounted for 19% of the total forest harvest in Oregon, but from 1960 to 1990, federal forest provided 52% of the total harvest (Dave Steere, Oregon Dep. Forestry, Salem, Oregon, pers. comm.). Even during the recent development of the Northwest Forest Plan, the federal forests accounted for 35% of the harvest in Oregon in 1992. The current debate over regional forest management has raised concerns about the abrupt shift in the proportions of federal and non-federal harvest, but previous shifts in harvest levels within the forest industry in the two decades after World War II rival those of today. Much of the logging in the Pacific Northwest currently occurs on private forest lands, which have less stringent regulations for streamside protection.

Environmental guidelines for forest practices first called for riparian protection on federal lands in the late 1960s and early 1970s. Riparian management was addressed directly in the forest planning process of the National Forest Management Act of 1976, but National Forests were encouraged to develop individual standards and guidelines, which were not coordinated and differed substantially from forest to forest (Gregory and Ashkenas 1990). In 1971, Oregon was the first state to enact a Forest Practices Act (FPA) for private forest lands. Initial legislation was aimed primarily at maintaining shade over the streams, decreasing erosion and sediment inputs, and providing for replanting after logging. The original FPA provided relatively little riparian protection around small streams and allowed for essentially complete removal of merchantable timber. Recent revisions develop more protective measures for maintaining ecological functions of aquatic ecosystems. Similar changes have occurred in Washington, Idaho, and California, but substantial differences exist in the protection requirements of neighboring states. The state of Washington has developed a watershed analysis approach that offers the potential to develop watershed-specific guidelines based on local resources and watershed conditions (Washington Forest Practices Board 1993).

Floodplains are not directly addressed in any of the statutes of the Pacific Northwest states except for protection of streamside wetlands. One-hundred-year floodplains are not recognized in the protection requirements for private commercial or state forestlands. Floodplain conditions are examined under Washington's watershed assessment approach, but no specific regulations or guidelines require management actions. Lack of consideration of floodplains in regional forest management of state and private lands reveals a fundamental weakness in the regulations, given the certainty of floods and the land-water interactions that occur during such events.

Recently, some National Forests in the Pacific Northwest have begun to implement a new aquatic conservation strategy based on a set of recommendations called PACFISH (Sedell et al. 1994). This strategy involves interim guidelines requiring functional riparian protection with no timber harvest within the streamside management zone, full floodplain protection, and even protection of small ephemeral channels that do not contain fish. The strategy also formally establishes key watersheds (drainages with at-risk species and other important aquatic resources) where protection of fish habitat is given top priority, and it encourages the development of regional conservation strategies based on thorough watershed assessment. Modification of forest management policies by the federal government in 1993 under the development of FEMAT (1993) incorporated substantially greater riparian protection than had been previously required and addressed floodplains on federal forestlands.

In general, society has called for high standards of environmental protection on public and private forest lands, but management activities in public forests are restricted to a greater extent than in private forests (Robinson 1987). Approximately 80% of the anadromous salmonid stocks identified by Nehlsen et al. (1991) and state agency reports as at risk of extinction spend a substantial portion of their life history on federal lands (FEMAT 1993, Thomas et al. 1993), but some stocks, particularly those inhabiting coastal lowlands, spend most of their time in freshwater on state and privately owned lands (NRC 1996). Currently, Pacific Northwest states have a fragmented and uncoordinated collection of statutes relating to different land-use types, zoning, and different resource users. Regulations for riparian protection on private non-forest lands are often minimal. Mature trees are required to be maintained along streams on lands zoned for forestry, but riparian forests along streams that pass through land zoned for agricultural, residential, or industrial use are allowed to be almost completely removed. These lowland streams historically were some of the most productive habitats in river drainages for anadromous salmonids, and only fragments of these habitats and their stocks are still in existence (Sedell and Froggatt 1984, Naiman et al. 1991). There is a need for greater consistency in the levels of environmental protection applied to different land-uses. We suggest that an integrated land-use practices act for each state would promote management practices that would not have to be identical for each type of land use or zoning but would ensure the ecological considerations that form the basis for management would be consistent.

Future Directions in Riparian Management and Habitat Protection

The future of anadromous and resident salmonids of the Pacific Northwest requires protecting existing intact, healthy aquatic ecosystems, restoring degraded systems, and developing sustainable resource management policies (Frissell 1993, Moyle and Yoshiyama 1994, Sedell et al. 1994, NRC 1996). Any discussion of habitat loss in the Pacific Northwest that did not call for these actions would be deficient, but these goals are not simple and each contains ecological and social traps that have the potential to impede rather than accelerate habitat recovery.

Protecting Existing Aquatic Ecosystems

One of the major tools in landscape management at a regional scale is development of systems of watershed reserves for aquatic ecosystems (FEMAT 1993, Frissell 1993, Pacific Rivers Council 1993, Moyle and Yoshiyama 1994). This reserve system in the Pacific Northwest is based primarily on public lands managed by the Forest Service and BLM. Recognition of watersheds as major functional elements of regional landscapes and of their role in protecting entire stocks or local populations is one of the major advances in ecosystem management in the Pacific Northwest. The approach is essential for sound ecosystem management, but it is constrained by land ownership patterns in the region. Lowland rivers and estuaries predominantly occur on private lands, and steeper mountainous terrain occupies the majority of federally owned lands. Approximately 20% of the stocks of anadromous salmon identified as at risk by the American Fisheries Society and state agencies in the Pacific Northwest do not occur on federal lands (FEMAT 1993). In addition, many of the stocks that occur on public lands must pass through lowland rivers during their migrations. Effective habitat management at a landscape scale requires incorporation of the entire landscape relevant to salmon life histories and integration of management policies for both public and private lands (NRC 1996). Exclusive reliance on public lands for aquatic habitat protection will jeopardize the future of many anadromous stocks and accelerate the loss of major large-river and floodplain habitats in the lower portions of river basins.

Restoring Degraded Systems

The most critical questions related to aquatic habitat restoration include the following: the degree to which it can be repaired or restored, priorities for locations where restoration efforts will be beneficial, and ecologically sound approaches for habitat restoration. As with sustainability, restoration is a term that finds almost unanimous acceptance, but misguided or ineffective restoration programs can undermine public confidence and even cause additional ecological damage (NRC 1992, Hilborn and Winton 1993). The goal of restoration is to reestablish an ecosystem's ability to maintain its function and organization without continued human intervention. It does not mandate returning to some arbitrary prior state. Any restoration program should be nested within a larger program of landscape management that protects, maintains, and restores ecosystem structure and function (Wissmar and Swanson 1990, Sedell et al. 1991, Moyle and Yoshiyama 1994). Resource analysis should precede any restoration effort, starting at the scale of entire river basins, focusing down to specific watersheds, and finally addressing local reach characteristics.

Ecosystems are dynamic and changing; thus, restoration to a previous condition often is impossible or even ecologically undesirable. Ecosystem restoration is based on restoring systems to the point that they can provide the natural materials and ecological functions that create habitat. Artificially constructing habitats does not constitute ecological restoration. Many practices commonly are mentioned within the context of restoration and often are used interchangeably with the term restoration, but their differences are important. Rehabilitation involves the reestablishment of specific components or processes to some degree of their previous state, but not complete recovery of ecological function. The term "habitat improvement" is widely used, but it has the misleading connotation that habitats are increasing in quality or function. In most cases, the habitat has been severely degraded and only a small fraction of its potential function has been restored. Ecological repair is more limited and may focus on a few limited characteristics of the ecosystem and reestablish relatively few of historical conditions. Mitigation is a substitution of systems, habitats, artificial processes, or simple economic value for the loss of natural habitat or ecological functions.

Stream restoration practices often attempt to reestablish specific geomorphic features or channel structure (Reeves et al. 1991a, Gregory and Wildman 1994) or increase densities of selected species (House and Boehne 1986, Nickelson et al. 1992). Delivery of geomorphic elements that are locally missing or deficient, facilitating natural hydrologic processes, or reestablishment of riparian plant communities can accelerate the rate of recovery of ecological processes or communities (Reeves et al. 1991b). Inaccurate assessment of physical processes, riparian plant ecology, causes of habitat degradation, or factors that limit populations or communities can result in either ineffective restoration efforts or habitat degradation or ecological damage (Frissell and Nawa 1992). Design of restoration requires thorough ecological and landscape analysis. Appropriate criteria for evaluation of the performance of restoration efforts are based on achieving the overall goals in a dynamic environment rather than simple persistence in the original location.

Several principles guide future restoration efforts from a habitat viewpoint. Choices exist between restoring areas that have been severely altered versus areas that have been only slightly changed and would recover quickly with less input of material and effort (Pacific Rivers Council 1993). Potential for recovery is greatly diminished where proportionately more natural processes, structures, and aquatic communities have been lost. However, even these severely altered habitats become appropriate candidates for restoration where there are important resources, critical habitats, or unique opportunities. Sound ecological restoration considers landscape pattern and connectivity. Setting priorities involves not just a matter of locating good or poor habitat, but considering how these areas are spatially arrayed. Restoration of river basins should be built upon nodes of high quality habitat that serve as refuges and provide sources of biotic colonists to rebuild connectivity throughout the basin. Efforts must extend into estuaries to include habitats that are critical for several life-history stages of salmonids (Shreffler et al. 1990).

One of the most important challenges of restoration is to change practices that altered habitat in the first place (Beschta et al. 1991). If environmental degradation continues, restoration efforts will be impeded or ineffective. Aquatic ecosystems should be allowed to recover naturally before habitat improvements are undertaken unless heroic efforts are required to save resources from extinction or prevent catastrophic habitat change. It is difficult to wait when the need for ecological recovery is great, but the potential for restoration efforts to be ineffective or inappropriately located is far greater in rapidly changing systems (Sedell and Beschta 1991).

Habitat restoration or rehabilitation commonly utilizes engineering approaches to erect permanent structures in streams (NRC 1992). In addition, administration of projects by agencies frequently identifies habitat targets so that funds can be allocated efficiently and project performance can be evaluated (Frissell and Nawa 1992). Unfortunately, natural processes and long-term dynamics of stream channels and communities are largely ignored, and rehabilitation projects may provide little or no benefit and may cause ecological damage (Sedell and Beschta 1991). Sound restoration of aquatic ecosystems is based on a solid foundation of ecological principles and a clear recognition of the dynamic nature of streams, rivers, wetlands, lakes, and riparian forests (Naiman et al. 1993).

Ecological restoration facilitates the reestablishment of natural physical and ecological processes that occur in the local area. Use of native species and locally adapted stocks maintains the integrity of the genetic characteristics of local populations. Some of the most important components of habitat restoration include protection or restoration of floodplains and riparian plant communities. The agents of habitat change (identified previously in Table 1) are also the basis for ecological recovery (Table 3). Environmental and biological uncertainty should be recognized and management options should emphasize alternatives that offer flexibility and opportunities to learn. Knowledge of the behavior of the environment will always be limited, and the range of possible outcomes of management actions in aquatic ecosystems introduces a large degree of uncertainty (Ludwig et al. 1993). Given the uncertainty inherent in ecosystem management and restoration, actions should be reversible either by natural processes or by human correction, if possible.

Restoration of riparian forests may be accelerated by silvicultural practices (Bilby and Bisson 1991). The goal of silvicultural management in riparian management zones should be to provide the natural ecological functions of riparian vegetation where previous practices have diminished the diversity of riparian plant communities. Riparian silviculture should encourage natural patterns of succession and create diverse and structurally complex riparian plant communities (Agee 1988). Reestablishment of shade over stream channels can be accelerated by protecting remaining streamside vegetation, especially young trees. However, in areas dominated by shrub cover, underburning may encourage regeneration of desired tree species (Agee 1993). In riparian areas where short-term canopy recovery is required for temperature protection, hardwood species may be used to rapidly reestablish vegetative cover. In many riparian zones of the Pacific Northwest, conifers are needed for long-term shading and inputs of large wood. More research is needed to determine the most effective techniques of restoring conifers to hardwood or shrub-dominated riparian zones. Pre-commercial thinning of small trees from upslope forests can provide material for placing directly into streams for short-term improvements, particularly in small streams lacking large wood.

The time frame for ecosystem restoration is constrained by the processes that shape stream channels, riparian plant communities, and aquatic communities (Table 3). In almost all cases, ecological recovery will require decades before natural systems can maintain themselves without human intervention, and centuries will be required for complete restoration of certain ecosystem components or processes. Resource management agencies should explicitly describe the time frame for restoration and clearly identify anticipated patterns of recovery.

The major agent of aquatic ecosystem restoration in the Pacific Northwest is periodic natural disturbance. Natural disturbances create and maintain the structural and ecological characteristics of riparian areas (Resh et al. 1988, Aumen et al. 1990, Bayley 1995). Disturbances in riparian areas include floods, windthrow, fire, insect outbreaks, and disease, which in combination create complex habitats and diverse plant and animal communities (Reice et al. 1990, Gregory et al. 1991, Reice 1994). Floods are essential for the sustained productivity of rivers. Streams are shaped by floods, and many rivers throughout the world are more productive after flooding (Junk et al. 1989). Flooding is a renewal process that creates pools, cleans gravel, and delivers dissolved and particulate nutrients (Elwood and Waters 1969, Bayley 1995). Fish and invertebrate communities in streams are resilient and often respond rapidly to disturbance, but the availability of refuges accelerates recovery of invertebrate community structure (Lamberti et al. 1991, Anderson 1992) and fish populations (Bisson et al. 1988, Sedell et al. 1990, Lamberti et al. 1991). Small-scale refuges during floods include deep pools, debris dams, boulders and logs, off-channel habitats on floodplains, and stems and roots of streamside forests. Floodplain habitats, large wood, and pool habitats have declined substantially in recent years and are among the major habitat losses related to the decline of Pacific salmon (Sedell et al. 1991).

Table 3. Sources of habitat modification, active restoration approaches, and estimated time scales for recovery. All of these responses vary according to the degree of landscape and stream alteration, natural disturbance events, and the magnitude of restoration efforts.

Ecosystem feature	Alteration characteristics	Ecosystem processes that restore structure or function	Recovery period (yr)
Channel structure	Floodplains	Reconnect floodplain to main channel. Silvicultural planting revegetates floodplain surface.	10–100
	Pools and riffles	Pools can be dug and riffles can be deposited, but new bedforms will not be stable if inconsistent with natural channel structure and hydrologic regimes.	1–10
	Large wood	Large wood can be placed in streams. Attention to natural dynamics and distributions is necessary to prevent further habitat degradation through the restoration effort. Natural succession may require centuries to restore inputs of wood.	5–25
	Substrate	Sediments can be placed in stream reaches if deficient. Artificial flushing of excessive sediment loads is largely ineffective.	5–20
	Hyporheic zones	Processes that reestablish bedforms and bed composition create new distribution of subsurface flow. Reestablishment of hydrologic sources may restore subsurface flow.	5–20
Hydrology	Discharge	If silvicultural acceleration of upslope and riparian vegetation is possible, recovery of evapotranspiration rates will accompany forest recovery. Dams prevent recovery of natural discharge patterns.	10–50
	Low flows	If silvicultural acceleration of conifer regeneration vegetation is possible, replacement of second-growth deciduous vegetation reduces evapotranspiration rates.	25–50
	Rapid fluctuations	After cessation, colonization by aquatic organisms and revegetation would require decades.	1–10
Sediment	Surface erosion	Revegetation of the watershed and riparian areas will diminish inputs of soil from surface erosion.	10–50
	Mass failures and landslides	Mass failures will diminish if road systems are reduced or upgraded, but failure rates will remain elevated as long as roads and culverts alter local water movements on steep slopes.	20–200
Water quality	Temperature	Reestablishment of canopy cover over streams reduces solar inputs and stream temperature.	10–40
	Dissolved oxygen	Temperature effects on oxygen will be related to shade recovery, and organic demands will be reduced as material decomposes and redistributes.	1–10

Table 3—cont.

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Table 3—cont.

Ecosystem feature	Alteration characteristics	Ecosystem processes that restore structure or function	Recovery period (yr)
Water quality—cont.	Nutrients	Revegetation of the watershed and riparian areas will retain nutrients and diminish inputs to surface waters.	10–40
Riparian forest	Production of large wood	Development of mature to old-growth riparian forest contributes new wood. Transport of wood and boulders from upstream or landslides delivers large structural elements to local reaches.	100–300
	Production of food organisms and organic matter	Development of mature to old-growth riparian forests restores natural inputs from terrestrial ecosystems.	40–80
	Shading	Reestablishment of canopy cover over streams reduces solar inputs and primary production declines to predisturbance levels. Riparian vegetation influences stream temperature.	5–20
	Rooting systems	Development of woody vegetation along streams and streambank integrity strengthens banks as root systems develop. Grasses and forbs provide similar functions along natural meadows.	20–80
	Nutrient modification	Successional development of riparian plant communities restores nutrient filtering capacity.	20–80
Exogenous material	Chemicals	Anthropogenic chemicals vary greatly in persistence in the environment.	Unknown
	Exotic organisms	Once established, exotic species likely will not be eliminated from the regional assemblage of species. Exotic plant communities may become less abundant as forests return to mature forest conditions.	Unknown

Land-use practices should be designed to maintain natural disturbance processes and to retain the beneficial effects of disturbance events to the degree possible. Analysis of the consequences of disturbances includes explicit assessment of short-term effects, local site-specific effects, long-term effects, and basin and landscape effects. At present, no resource management agency has a formal "after the disturbance" policy designed to protect beneficial changes caused by natural disturbances; too often the management response has been to fix the changes caused by the disturbance. Recognition of the role of floods and related natural disturbances in streams and riparian areas will reduce the tendency for disaster relief efforts that simply repeat previous resource management mistakes.

Habitat restoration is no substitute for appropriate environmental protection, and approaches built solely upon rehabilitation cannot maintain ecosystem health. The growth of habitat restoration programs in state and federal agencies is the most undeniable and well-documented evidence for our failure to effectively manage aquatic ecosystems of the Pacific Northwest. Our success in the future will be measured by the degree to which we are able to decrease the need for restoration programs.

Human Population

Discussion of habitat alteration and future alternatives is fundamentally a question of human population and rates of resource consumption. Salmon stocks and the ecosystems that support them have been altered so extensively that there is no question about the outcome if current land-use practices and population growth rates continue without change. Unfortunately, the time frame for response is shorter than the historical trajectory that brought us to this point. The combined population of Oregon, Washington, and Idaho was just >1 million people in 1900 and is currently >9 million (Fig. 4) (American Almanac: Statistical Abstract of the United States 1994). The population of the Pacific Northwest is projected to double to ~17 million by the year 2025 (assuming an average annual population increase of 1.9%), requiring only 30 years to attain the same absolute increase in numbers that required 90 years previously.

Projected increases in human population in the Pacific Northwest will be accompanied by increased demand not only for forest products but also for land, water, and energy. Only 2% of the Pacific Northwest is urban or residential lands, but the additional millions of people anticipated for this region in the next few decades will either live in those urban areas or will consume current forest and agricultural land to build homes and communities. Even considering a low domestic water consumption of 750 L d^{-1} per person (excluding agricultural and industrial water requirements), population growth in the Pacific Northwest will impact an additional 6 billion L d^{-1} of water in only 30 years. This consumption of water also will be reflected in the delivery of sewage and waste water to the region's streams and rivers.

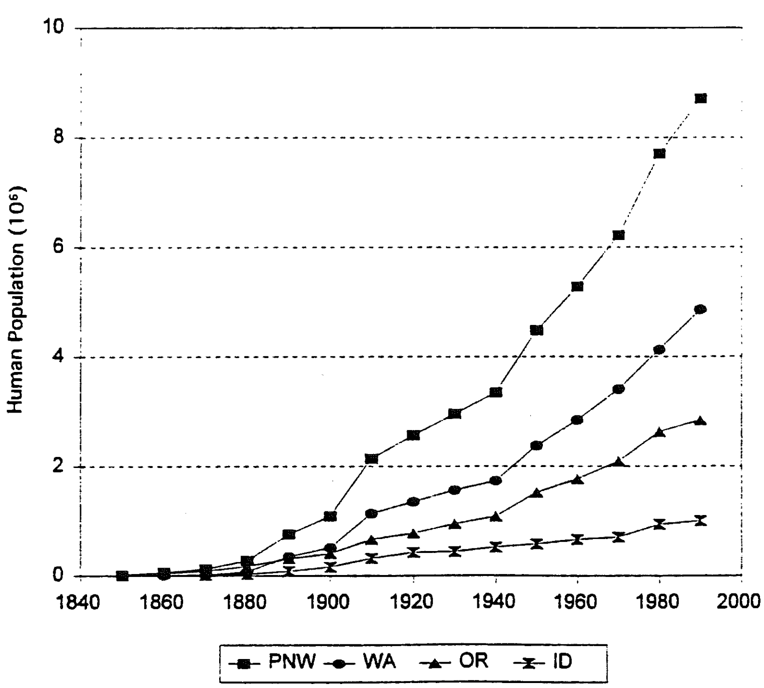

Figure 4. Trends in population of Oregon, Washington, Idaho, and the Pacific Northwest from 1850 to 1990. Source: American Almanac: Statistical Abstracts of the United States (1994).

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The major source of water for future communities of the Pacific Northwest comes from forest lands, primarily designated federal forest lands. The Forest Service has allocated ~440,000 ha of federal land in Washington and 1,112,000 ha in Oregon as designated water supplies for local municipalities (B. McCammon, Region 6, USDA Forest Service, Portland, Oregon, pers. comm.). Federal lands provide the domestic water supply for 43% of the population in Oregon and for 34% of the population of Washington. In many ways, water will be the most valuable product coming from federal lands in the near future, and public forest lands will be a critical component in the supply of water for the region in the coming century.

The people of the Pacific Northwest must evaluate the success of our efforts to manage ecosystems based on our ability to deal with ecological and institutional change rather than our static performance at any point in time. In 1902, Overton Price, the Assistant Forester for the newly formed Forest Service, noted, "It is the history of all great industries directed by private interests that the necessity for modification is not seen until the harm has been done and its results are felt." The Pacific Northwest finds itself repeating the lessons of other regions. Future management of the ecosystems of the Pacific salmon will require ecologically sound approaches for protection and restoration of aquatic habitats, effective regulations and human incentive systems, and long-term resource monitoring programs.

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