United States
Department of
Agriculture

Forest Service

Pacific Northwest
Research Station

General Technical
Report
PNW-GTR-692

February 2007

Riparian and Aquatic Habitats of the Pacific Northwest and Southeast Alaska: Ecology, Management History, and Potential Management Strategies

Fred H. Everest and Gordon H. Reeves

Authors

Fred H. Everest is an associate professor of environmental technology (retired), University of Alaska Southeast, Sitka Campus, 1332 Seward Avenue, Sitka, AK 99835; and **Gordon H. Reeves** is a research fishery biologist, U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station, Forestry Sciences Laboratory, 3200 SW Jefferson Way, Corvallis, OR 97331. Everest is currently located at P.O. Box 1444, Sitka, AK 99835.

Abstract

Everest, Fred H.; Reeves, Gordon H. 2006. Riparian and aquatic habitats of the Pacific Northwest and southeast Alaska: ecology, management history, and potential management strategies. Gen. Tech. Rep. PNW-GTR-692. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station. 130 p.

Management of riparian habitats is controversial because land use policies have historically emphasized economic values (e.g., timber production) at the expense of ecological and social values. Attempting to manage these valuable resources to attain the greatest combination of benefits has created a long-term controversy that continues to the present. Our analysis indicates that at mid to large spatial scales, healthy riparian ecosystems and land management activities are not mutually exclusive, but the degree of compatibility is determined by policy decisions based on competing demands and pressing timelines as well as available scientific knowledge. Current management schemes on federal lands in the Pacific Northwest and Alaska are appropriately addressing large spatial scales and incorporating the principles of disturbance ecology. We found no scientific evidence that either the default prescriptions or the options for watershed analysis in the Northwest Forest Plan and Tongass Land Management Plan provide more protection than necessary to meet stated riparian management goals. We believe that additional alternative riparian management strategies could be implemented and evaluated in concert to shorten the time needed to realize effective strategies that fully meet riparian management goals.

Keywords: Riparian ecosystems, management, dynamics, Northwest Forest Plan, Tongass Land Management Plan.

Preface

Management of riparian habitats, especially on forest lands west of the Cascade crest in Oregon and Washington, and in southeast Alaska, has been a subject of controversy for decades. Why the controversy? Riparian zones produce and maintain many resources of economic, ecological, and social value. Often the most valuable timber in watersheds, e.g., Port Orford cedar in the Pacific Northwest and Sitka spruce and red and yellow-cedar in southeast Alaska, grows in moist sites provided by riparian zones.[1 2] In addition, science has demonstrated that riparian habitat in western Oregon and Washington, southeast Alaska, and other locations supports higher densities and diversities of flora and fauna than other portions of the landscape.[3 4 5] The natural functions of riparian ecosystems are important contributors to the maintenance of watershed hydrology, streamflows, water quality, stream nutrients, and habitat characteristics needed to maintain the viability of native aquatic species, including many economically significant species.[6] Riparian

---

[1] Franklin, J.F.; Dyrness, C.T. 1973. Natural vegetation of Oregon and Washington. Gen. Tech. Rep. PNW-8. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station. 417 p.

[2] U.S. Department of Agriculture, Forest Service [USDA Forest Service]. 1997. Tongass land management plan revision. Final environmental impact statement Part 1: summary, chapters 1 and 2, and chapter 3 (physical and biological environment). R10-MB-338b. Washington, DC. [Irregular pagination].

[3] Crow, T.R.; Baker, M.E.; Barnes, B.V. 2000. Diversity in riparian landscapes. In: Verry, E.S.; Hornbeck, J.W.; Dolloff, C.A., eds. Riparian management in forests of the continental Eastern United States. New York: Lewis Publishers: 43-66.

[4] Oakley, A.L.; Collins, J.A.; Everson, L.B. [et al.]. 1985. Riparian zones and freshwater wetlands. In: Brown, E.R., ed. Management of wildlife and fish habitats in forests of western Oregon and Washington. Part 1–Chapter narratives. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Region: 57-80.

[5] Olson, D.H.; Chan, S.S.; Weaver, G. [et al.]. 2000. Characterizing stream, riparian, and upslope habitats and species in Oregon managed headwater forests. In: Wiggington, J.; Beschta, R., eds. Riparian ecology and management in multi-land use watersheds. AWRA Publication TPS-00-2. International conference of the American Water Resources Association. Middleburg, VA: American Water Resources Association: 83-88.

[6] Naiman, R.J.; Beechie, T.J.; Benda, L.E. [et al.]. 1992. Fundamental elements of ecologically healthy watersheds in the Pacific Northwest coastal region. In: Naiman, R.J., ed. Watershed management: balancing sustainability and environmental change. Seattle, WA: University of Washington, Center for Streamside Studies: 127-188.

zones are focal areas for recreation and have high aesthetic appeal for many outdoor activities.[7] [8] Other social and economic benefits of riparian zones accrue to fishers, hunters, farmers, loggers, resort owners, municipalities, miners, and others.[9] Unfortunately, not all benefits of riparian areas can be realized simultaneously at all times, because some are mutually exclusive at small spatial scales. However, it is possible to manage riparian ecosystems to achieve a combination of benefits at larger spatial scales, e.g., the large watershed scale. The uses of riparian ecosystems, and the question of how to achieve a socially acceptable balance among economic, ecological, and social uses, lies at the heart of the riparian debate.

Alteration of riparian habitats has been implicated as a contributor in the decline of freshwater habitat for anadromous salmonids in the Pacific Northwest. Several stocks of anadromous salmonids in the region were listed as threatened or endangered in the 1990s, and attempts to recover those populations currently address concerns with freshwater habitat, fish harvest, hydropower development, and fish hatcheries. Recovery efforts include development of new riparian management strategies that provide more protection for riparian and aquatic habitats on forest lands than previous management schemes. The new strategies have intensified the ongoing debate surrounding the appropriate goals and practices for management and protection of riparian habitats.

The controversy surrounding management of riparian areas extends to all land uses, including agriculture, urban landscapes, water development projects, forestry, and others, and to all land ownerships. However, in the Pacific Northwest and southeast Alaska, the controversy currently focuses largely on riparian management in forested watersheds. Expansion of that focus to include whole river basins and other land uses and ownerships, however, could provide a more holistic and perhaps more viable approach to management of riparian ecosystems, land management activities as a whole, and recovery of threatened and endangered species.

---

[7] Schroeder, H.W. 1996. Voices from Michigan's Black River: obtaining information on "special places" for natural resource planning. Gen. Tech. Rep. NC-184. St. Paul, MN: U.S. Department of Agriculture, Forest Service, North Central Forest Experiment Station. 26 p.

[8] Stynes, D.J. 1997. Recreation activity and tourism spending in the Lake States. In: Webster, H.H.; Vasievich, J.M., eds. Lake States regional forest resources assessment: technical papers. Gen. Tech. Rep. NC-189. St. Paul, MN: U.S. Department of Agriculture, Forest Service, North Central Forest Experiment Station: 139-164.

[9] Dwyer, J.F.; Jakes, P.J.; Barro, S.C. 2000. The human dimensions of riparian areas: implications for management and planning. In: Verry, E.S.; Hornbeck, J.W.; Dolloff, C.A., eds. Riparian management in forests of the continental Eastern United States. New York: Lewis Publishers: 193-206.

An examination of land ownership, land cover, and land uses in the Northwest and southeast Alaska provides perspective on the comparative importance of riparian lands managed by private and public landowners. Approximately 52 percent of the land base in the Northwest is privately owned forest land, rangeland, cropland, pasture, and urban and residential properties.[10] Most of the privately owned landscape consists of lowlands and valleys in downstream areas of the region's major river basins, where riparian and aquatic ecosystems historically provided important habitats for production of fish and other aquatic resources.[11 12 13 14] Dams, reservoirs, irrigation systems, cultivation, use of pesticides and fertilizers, urbanization, and transportation systems have altered many riparian and aquatic habitats in these areas, with perhaps the greatest effects associated with agriculture and hydropower production.[15 16 17] Because of intensive land use on large expanses of private land, and

---

[10] Pease, J. 1993. Land use and ownership. In: Jackson, P.; Kimerling, A., eds. Atlas of the Pacific Northwest. 8th ed. Corvallis, OR: Oregon State University Press: 31-39.

[11] Brown, T.G.; Hartman, G.F. 1988. Contribution of seasonally flooded lands and minor tributaries to the production of coho salmon in Carnation Creek, British Columbia. Transactions of the American Fisheries Society. 117: 546-551.

[12] Li, H.; Schreck, C.B.; Bond, C.E.; Rexstad, E. 1987. Factors influencing changes in fish assemblages in Pacific Northwest streams. In: Matthews, W.J.; Heins, D.C., eds. Community and evolutionary ecology of North American stream fishes. Norman, OK: University of Oklahoma Press: 193-202.

[13] Peterson, N.P.; Reid, L.M. 1984. Wall based channels: their evolution, distribution, and use by juvenile coho salmon in the Clearwater River, Washington. In: Walton, J.M.; Houston, D.B., eds. Proceedings of the Olympic Wild Fish Conference. Port Angeles, WA: Fisheries Technology Program, Peninsula College: 215-226.

[14] Sedell, J.R.; Reeves, G.H.; Hauer, F.P. [et al.]. 1990. Role of refugia in recovery from disturbance: modern fragmented and disconnected river systems. Environmental Management. 14: 711-724.

[15] Beechie, T.; Beamer, E.; Wasserman, L. 1994. Estimating coho salmon rearing habitat and smolt production losses in a large river basin, and implications for restoration. North American Journal of Fisheries Management. 14: 797-811.

[16] Bradford, J.M.; Irvine, J.R. 2000. Land use, fishing, climate change, and the decline of Thompson River, British Columbia, coho salmon. Canadian Journal of Fisheries and Aquatic Sciences. 57: 13-16.

[17] Everest, F.H.; Kakoyannis, C.; Houston, L. [et al.]. 2004. A synthesis of scientific information on emerging issues related to use and management of water resources on forested landscapes of the Pacific Northwest. Gen. Tech. Rep. PNW-GTR-595. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station. 128 p.

dams whose effective lifespans may be measured in centuries, return to the historical character of riparian and aquatic habitats is unlikely on much of this landscape.[18] Many of the changes in riparian and aquatic ecosystems resulting from agriculture and hydropower development can probably be considered irreversible, at least in the near term.

In contrast to the widespread and persistent alteration of riparian and aquatic habitats on nonforest lands, management of public forest lands generally has made fewer and less persistent changes in riparian and aquatic ecosystems. The most extensive habitat changes west of the Cascade crest in Oregon and Washington and in southeast Alaska are associated with timber harvest, but those effects, with the exception of roads, are potentially temporary and reversible.

The federal government manages nearly 48 percent of the land base in the Pacific Northwest. National forests managed by the U.S. Forest Service and rangelands managed by the Bureau of Land Management, national parks, and national wildlife refuges, account for a large percentage of Oregon (48.2 percent) and Washington (29.8 percent) (table 1). Federal lands west of the Cascade crest in Oregon and Washington total about 4.6 million ha, of which about 4.1 million ha is forested. About 59 percent of the forested landscape has been managed for production of timber and other resources. The remainder is in wilderness, or areas administratively withdrawn from forest management. Federal holdings consist largely of forests and rangelands that are generally in the higher elevation mountains of the region. Many of these areas produce large amounts of water and contain some of the best remaining habitats for native aquatic organisms (see footnote 17).[19] These lands contain numerous small streams and associated riparian ecosystems that, in combination, are largely responsible for the quantity and quality of water and aquatic habitats within the forested landscape.

More than 62 percent of Alaska is owned and managed by the federal government (table 1), but to date, management activities have resulted in limited modification of riparian and aquatic habitats on these lands. In the sparsely populated

---

[18] Gregory, S.V.; Bisson, P.A. 1997. Degradation and loss of anadromous salmonid habitat in the Pacific Northwest. In: Stouder, D.J.; Bisson, P.A.; Naiman, R.J., eds. Pacific salmon and their ecosystems. New York: Chapman and Hall: 277-314.

[19] Sedell, J.; Sharpe, M.; Dravneiks, D. [et al.]. 2000. Water and the Forest Service. FS-660. Washington, DC: U.S. Department of Agriculture, Forest Service. 26 p.

Table 1—Land ownership and land use in the Pacific Northwest and Alaska

Land use	Ownership	Oregon		Washington		Alaska	
		km²	%	*km²*	%	*km²*	%
Forests	Federal	75,680	30	38,350	22	311,610	21
Forests	Nonfederal	47,980	19	51,127	29	210,440	14
Rangeland	Federal	53,160	21	6,750	4	29,310	2
Rangeland	Nonfederal	37,040	15	22,560	13		
Cropland	Nonfederal	24,680	10	37,970	22	130	<1
Pasture	Nonfederal	7,750	3	5,750	3	2,411	<1
Urban	Nonfederal	3,810	2	6,333	4	380	<1
National parks	Federal	680	<1	7,330	4	195,460	13
Other		0		0		728,355	49
Total federal		129,520	52	52,430	30	922,670	62
Total nonfederal		121,260	48	123,737	70	554,600	38
Total combined		250,780	100	176,167	100	1,477,270	100

Sources: Pacific Northwest, Pease 1993; Alaska, Alaska DNR 2000, US GSA 2000, NPS 2005, Public Land Statistics 2000, USDA Forest Service 2000.

temperate rain forests of southeast Alaska, the federal government owns about 95 percent of the landscape: about 80 percent of federal rain forest in Alaska is in the Tongass National Forest and most of the remainder is in Glacier Bay National Park (see footnote 2). About 2.2 million ha of productive old-growth forest exists in the Tongass National Forest; about 1.7 million ha is designated wilderness or administratively withdrawn from forest management, and about 162 000 ha was harvested during the last half of the 20th century. Most streams, riparian habitats, and watersheds in the region remain largely unaffected by human activities.[20]

The conclusion to be drawn from the overview of land ownership and land use, especially in the Pacific Northwest, is that many low-elevation aquatic and riparian habitats in major river basins, mostly on private lands, have been converted from lowland and flood-plain forests to nonforested agricultural lands, reservoirs, and urban lands (see footnote 14). Riparian and aquatic ecosystems on these lands historically provided important habitats for many aquatic species. These habitats, prior to alteration, may have been the most important rearing areas for specific life-history stages of some anadromous salmonids at certain seasons of the year (see

[20] Bryant, M.D.; Everest, F.H. 1997. Management and condition of watersheds in southeast Alaska: the persistence of anadromous salmon. Northwest Science. 72(4): 249-267.

footnotes 11, 12, and 13). Many of these habitats no longer support historical indigenous aquatic communities.

Some riparian and aquatic habitats on forest lands under federal management have also been altered, but to a lesser extent than on privately owned lands. These habitats were also important historical producers of anadromous salmonids and other aquatic species and still contain some of the best remaining aquatic habitats in the region. Recovery of riparian and aquatic habitats on both forest lands and nonforest lands in western Oregon and Washington is currently being addressed by federal and state agencies and nongovernmental organizations.

Current and previous state and federal goals for riparian management are similar in that they all aim to protect water quality as well as riparian and aquatic habitats. However, policymakers have developed different strategies for achieving the goals state to state and by land ownership, fueling the debate about how to achieve management goals. Some questions in the riparian management debate are decades old and still unanswered. For example:

- Are land management activities and healthy aquatic and riparian ecosystems mutually exclusive?
- If not, how much and what type of land management can be conducted without undesirable social, economic, or ecological effects on riparian ecosystems?

Other questions are of more recent origin, for example:

- Are current riparian management schemes addressing the appropriate spatial and temporal scales?
- Have the riparian management schemes recently applied on federal lands gone too far in protecting ecological values at the expense of some social and economic values?
- Are there new or emerging options for managing riparian ecosystems that will improve multiple resource use at the watershed scale yet still maintain desired characteristics of riparian and aquatic resources?

We will explore these questions in this paper.

Executive Summary

Riparian habitats on forest lands west of the Cascade crest in Oregon and Washington and in southeast Alaska produce a variety of ecological, economic, and social values. Management of riparian habitats, however, is controversial because land use policies have historically favored some of these values (e.g., timber production) at the expense of others. The attempt to manage these valuable resources to attain the greatest combination of benefits has created a long-term controversy that continues to the present.

Some of the questions in the debate are decades old and still unanswered. For example, are land management activities and healthy aquatic and riparian ecosystems mutually exclusive? If not, how much and what type of land management can be conducted without undesirable social, economic, or ecologic effects on riparian ecosystems? Other questions are of more recent origin; for example, are current riparian management schemes addressing the appropriate spatial and temporal scales? Have the riparian management schemes recently applied on federal lands gone too far in protecting ecological values at the expense of some social and economic values? Are there new or emerging options for managing riparian ecosystems that will improve multiple resource use at the watershed scale, yet still maintain desired characteristics of riparian and aquatic resources? We attempt to answer these questions in this paper.

Our objectives focus on (1) how riparian areas can be defined and delineated; (2) a brief examination of the structure, function, and benefits of riparian ecosystems; (3) a review of the role that natural and human disturbances play in the function of riparian and aquatic ecosystems in forests of the Pacific Northwest and southeast Alaska; (4) a review of the development of forest practice rules in the Pacific Northwest and southeast Alaska; and (5) an examination of potential riparian management strategies that might increase compatibility among the different values sought from forest lands.

Riparian zones can be defined by either their physical or functional attributes, but recent definitions tend to emphasize function and, therefore, from a management perspective, increase the geographic extent of riparian ecosystems.

The structural features of riparian ecosystems are highly variable, but all share common physical elements that are controlled by environmental phenomena. Physical characteristics of riparian habitats are defined in time and space by climatic conditions, vegetation types, stream order, and geomorphic features like channel gradient, elevation, slope, aspect, and perhaps other factors. When defined physically, riparian ecosystems generally have a linear structure that may be hundreds of kilometers in length and highly variable in width. The flood plains of large rivers, for example, may contain extensive riparian habitats with widths of a kilometer or more. Conversely, riparian zones along small, incised headwater streams may be only a few meters wide.

When viewed functionally, riparian ecosystems provide a variety of important linkages and ecological functions for adjacent aquatic and upland ecosystems. Key functions include the maintenance of water quality, control of sediment delivery from uplands and sediment movement in streams, control of the movement of nutrients and contaminants, control of streambed and bank stability, and the maintenance of fish and wildlife habitats in adjacent ecosystems.

Benefits provided by riparian zones are strongly related to their structure and function. Although it is possible to think of the benefits in ecological, social, or economic terms, in most cases, the benefits blend across the three categories. Some of the benefits are strongly associated with unmanaged riparian habitats, whereas others may be derived from active riparian management. Some major benefits that accrue to society from riparian ecosystems include maintenance of water quality in streams, lakes, shallow groundwater strata, and hyporheic zones; maintenance of stream channel stability and hydrologic function in watersheds; contribution to maintenance of biodiversity in watersheds and the maintenance of viable populations of riparian, aquatic, and terrestrial species; focal sites for outdoor recreation; enhancement of the value of private residential and commercial properties; contribution to visual aesthetics in managed landscapes; maintenance of aesthetics in wild and scenic river corridors; flood control; maintenance of streamflows for human uses; high-quality potable water for domestic and industrial use; production of high-value aquatic resources (e.g., anadromous salmonids); timber production; livestock production from grazing on riparian forage; and mining for gold and other minerals. The variety of ecological, social, and economic benefits provided by riparian zones contribute to the controversy surrounding their management in Western watersheds.

Watersheds throughout the Pacific Northwest and southeast Alaska are subject to disturbances from natural events such as fire, floods, and wind and human activities such as construction of dams and reservoirs, agriculture, and timber harvest.

The type and timing of disturbances largely determine their effects on ecosystem resilience, ecological processes, and indigenous biota. Ecosystem disturbances can be classified as either "pulse" or "press" disturbances based on their temporal and spatial frequency. Pulse disturbances (e.g., wildfire) occur infrequently, and allow sufficient time between disturbances to enable ecosystems to recover to predisturbance conditions. Pulse disturbances generally allow ecosystems to remain within their normal historical range of states and conditions. Press disturbances (e.g., timber harvest), on the other hand, are characterized by frequent or continual events interspersed with insufficient recovery time to allow ecosystems to return to predisturbance conditions. Press disturbances generally reduce the resiliency of ecosystems, and may ultimately impose new regimes of variability that are outside of the natural historical range of a watershed or ecoregion. Natural and human disturbance regimes can fall into either the pulse or press category, although natural disturbances are most often associated with the former and human disturbances with the latter.

States and federal agencies have developed rules and practices to protect riparian zones from forest management. Those practices evolved over a period of more than 30 years to accommodate new scientific information and provide increased riparian protection. The culmination of forest practice rules resulted in development of the Northwest Forest Plan (NWFP) and the Tongass Land Management Plan (TLMP) for protection of riparian zones on federal lands and revised state forest practices acts for protection on state and private lands in the region. Current state-of-the-art forest practices provide extensive protection to riparian ecosystems, but they have not been fully evaluated, so their efficacy remains unknown.

In regard to the original questions we posed, first our analysis indicates that at mid to large spatial scales, healthy riparian ecosystems and land management activities are not mutually exclusive, but the degree of success in achieving compatibility is determined by policy decisions based on competing demands and pressing timelines as well as available scientific knowledge. Second, we found that current management schemes are appropriately addressing large spatial scales and incorporating the principles of disturbance ecology. Third, we found no scientific evidence that either the default prescriptions or the options for watershed analysis in the NWFP and TLMP provide more protection than necessary to meet stated riparian management goals. Finally, we found that additional alternative riparian management strategies could be implemented and evaluated in concert to shorten the time needed to realize effective strategies that fully meet riparian management goals. Emerging and future strategies for riparian management that are science-based, consider natural processes, and address large temporal and spatial scales in an interagency forum that includes all concerned stakeholders appear to hold promise for the future. Precedent has been set, for example, in organizations like the Deschutes River Basin Conservancy and the Coastal Landscape Analysis and Modeling Study in Oregon. In reality, however, the direction of riparian management will be determined, not by science, but by the normative decisions of policymakers who attempt to achieve a balance between ecosystem sustainability and the competing demands of resource users.

Contents

Introduction

Riparian ecosystems are important components of watersheds worldwide, and much of what is known about their structure and function has universal application. In the humid mountain ecosystems of the Pacific Northwest United States (PNW), southeast Alaska, and elsewhere, riparian areas are used by a rich and diverse assemblage of species (Odum 1979) and provide critical transition zones linking terrestrial and aquatic ecosystems within watersheds (Naiman et al. 1992, 2002; Oliver and Hinckley 1987). Riparian ecosystems, from a functional standpoint, also exert important controls over the characteristics of rivers and streams. Healthy riparian ecosystems contribute to natural temporal and spatial regimens of streamflow, water quality (U.S. Army Corps of Engineers 1991), nutrient supply (Clinton et al. 2002, Nakano et al. 1999), and the physical structure of aquatic habitats (Reeves et al. 1993). Also, transfer of nutrients from freshwater to terrestrial habitats provides benefits to riparian ecosystems (Collier et al. 2002; Drake et al. 2002; Helfield and Naiman 2001, 2002; Sanzone et al. 2003). Scientists and managers recognize that from a large-scale holistic perspective, it is difficult to isolate riparian ecosystems from the watershed- or river-basin-scale ecosystems in which they occur. Nevertheless, riparian ecosystems that are substantially altered by human activities can have such large effects on adjacent and downstream aquatic and terrestrial habitats that research investigations and management schemes and constraints often focus on these ecosystems.

Riparian ecosystems exert important controls over the characteristics of rivers and streams.

Forested watersheds of the United States are major sources of water and aquatic biodiversity. Forests currently cover about one-third of the Nation, but receive more than half of the total precipitation and yield more than three-fourths of the total annual runoff (Norris et al. 1991). The 77.3-million-ha National Forest System is the Nation's largest source of fresh water. In the Pacific Northwest, more than 38 percent (about 80 billion m) of the region's annual runoff of about 170 billion m flows from the area's national forests (Sedell et al. 2000). This generally water-rich forested landscape contains thousands of kilometers of streams, lakes, wetlands, and associated riparian zones that function in concert to maintain the diverse aquatic ecosystems and fish communities of the region.

Aquatic species have adapted to the natural disturbance regimes and climate cycles prevalent in forested watersheds (Reeves et al. 1995). Historically, episodic events in upland and riparian forests, such as fires, floods, mass erosion, wind, and insect outbreaks, shaped and maintained the productivity of aquatic and riparian habitats (Benda et al. 1998). Despite the effects of episodic and chronic natural disturbances and climate cycles that caused historical aquatic productivity in individual watersheds to vary with time, riparian ecosystems in forested landscapes of the West provided habitat for an abundance of terrestrial species and contributed to productive aquatic habitats that supported tens of millions of anadromous salmonids and other aquatic species (Volkman 1997).

Settlement of the West in the 19th and 20th centuries superimposed a variety of physical human disturbances atop existing climate cycles and natural disturbances. In the Pacific Northwest, deforestation for agriculture and human developments, drainage of wetlands for agriculture, activities associated with agricultural production, urbanization, and water impoundments to support agriculture, urbanization, and hydropower production are the primary human disturbances affecting riparian and aquatic habitats in lowland areas of river basins. Timber harvest and roads, however, are the dominant physical human disturbances in the forested uplands. In southeast Alaska, timber harvest and, to a lesser extent, mining are the major human disturbances affecting the landscape. In either location, human disturbances generally occur more frequently in time and space and leave different legacies than natural disturbances, and their effects are additive to natural disturbance regimes. In addition to physical changes to riparian and freshwater habitats, ecological disturbances such as fish harvest and fish hatchery production have added additional stresses to aquatic ecosystems.

Human disturbance regimes have directly and indirectly changed the characteristics of aquatic and riparian habitats in the past 150 years.

Human disturbance regimes have directly and indirectly changed the characteristics of aquatic and riparian habitats in the past 150 years. The changes have contributed to the decline of many aquatic species in the PNW (Gregory and Bisson 1997), including numerous stocks of anadromous salmonids (Nehlson et al. 1991). Although other factors (e.g., climate cycles, fishing, hunting) may also have contributed to species declines, habitat loss is considered to be the primary factor (Gregory and Bisson 1997).

The recognition that human disturbances have changed the natural spatial and temporal distribution of aquatic and riparian habitats and the species that depend on them eventually led to development and evolution of special guidelines and practices for management of riparian zones, water resources, and watersheds. The guidelines may differ by type of management activity (e.g., agriculture, urbanization, hydropower, forestry), but the common goal is to protect streamflows, water quality, or habitats of a variety of riparian and aquatic organisms, or a combination of the three, while allowing management and use of other resources. Management strategies that apply to forested watersheds differ by federal, state, and private ownership patterns, but all attempt to maintain ecological functions as well as social and economic use of resources.

The type and extent of protective measures applied to forested landscapes have been driven by these same concerns. Since the late 1960s, forest management practices have moved steadily in the direction of reducing or mitigating human disturbances to upland, riparian, and aquatic ecosystems while still allowing economic harvest of timber and providing for other resource uses (e.g., recreation) from forested watersheds. Social pressure to protect environmental assets, including riparian habitats and integrity of aquatic ecosystems, has contributed to the evolution of forest practices (Whitelaw 1992).

Changes in rules and policies for riparian management on private, state, and public forest lands have, along with many other factors, reduced timber harvests from historical levels. For example, the boundary of riparian ecosystems on federal land was greatly expanded by the Northwest Forest Plan (NWFP) (USDA and USDI 1994b). Prior to the NWFP, riparian areas were generally defined as 30 m on either side of fish-bearing streams. The boundary was extended to about 90 m on fish-bearing streams by the NWFP. Additionally, and perhaps most significantly, the riparian zone was delineated as up to 45 m on each side of non-fish-bearing streams. A similar strategy, described in the 1997 Tongass Land Management Plan (TLMP), is used on the Tongass National Forest in southeast Alaska (USDA Forest Service 1997). Recent changes in forest practices acts and rules for riparian and aquatic habitat protection in Oregon (Oregon Revised Statutes 1999), Washington (Washington State Legislature 2005), and Alaska (Alaska Division of Forestry 2001) have generally reduced the amount of extractive activity allowed in riparian zones, or required greater retention of riparian timber. These strategies have, along with other changes in management (e.g., protection of wildlife habitats and more green-tree retention in harvest areas), reduced timber harvests in both regions, but because their effectiveness has not yet been fully assessed, their implementation has heightened the debate about how to best accomplish multiple resource management and sustainable forestry on national forests.

Geographic Scope

Although riparian ecosystems universally link upland, riparian, and aquatic habitats, we will focus primarily on the relationship between riparian areas, aquatic habitats, and aquatic species as affected by management of riparian ecosystems on forested landscapes of western Oregon and Washington and southeast Alaska. In the former case, we address primarily the area encompassed by the NWFP, and in the latter, the Tongass National Forest. This focus is not meant to minimize the importance of riparian habitats on nonforested lands or other geographic regions of the Pacific Northwest or Alaska, and we will address those areas as necessary to provide context for our primary focus.

Objectives

This paper will not provide another exhaustive review of literature on the structure, function, and importance of riparian ecosystems, although we will briefly touch on those areas. Several detailed reviews of those subjects have been completed in recent years (Correll 2003, Desbonnet et al. 1994, U.S. Army Corps of Engineers 1991, Van Deventer 1992, Verry et al. 2000, Wenger 1999). Instead, we will focus on:

- How riparian areas can be defined and delineated.
- A brief review of the structure, function, and benefits of riparian ecosystems.
- The role of natural and human disturbances in the function of riparian and aquatic ecosystems in forests of the Pacific Northwest and southeast Alaska.
- The development of forest practice rules in the Pacific Northwest and southeast Alaska.
- Potential riparian management strategies that might increase compatibility among the different values sought from forest lands.

Although we have chosen not to review the ecological effects of grazing on riparian habitats in rangelands of western Oregon and Washington, some literature exists on the subject (e.g., Bolton and Monohan 2001, Chapman and Knudsen 1980).

We recognize the importance of scientific knowledge in resolving problems related to management of natural resources (Everest et al. 1997, Swanston et al. 1996), including management of aquatic and riparian habitats, but we also recognize that science is not the only factor used to arrive at decisions. Policymakers and managers use a normative process that draws upon scientific information, social and economic considerations, politics, and other factors to make such decisions (Mills et al. 1998), including those addressing management of riparian resources. We do, however, advocate that policymakers and managers use the best available science when formulating decisions relevant to management of riparian and aquatic habitats and check their final decisions for consistency with relevant scientific information (Everest et al. 1997).

Definition of Riparian Ecosystems and Delineation of Riparian Zones

Riparian ecosystems are defined by either their physical or functional attributes (Brosofske 1996, Ilhardt et al. 2000, Palone and Todd 1997). Most current **physical** definitions include a perennial or ephemeral water body, an adjacent zone dominated by hydric vegetation, and a terrestrial area where vegetation and microclimate are influenced by perennial or intermittent water tables (Obedzinski et al. 2001) (fig. 1). Physical definitions generally have a site-specific focus. Riparian zones defined and delineated by physical definitions can be highly variable in width, ranging from a few meters on small steeply incised streams to a kilometer or more on the flood plains of large rivers (fig. 2).

Functional definitions of riparian zones include the functional interactions among streams, hyporheic zones, riparian vegetation, and terrestrial vegetation at small to large watershed scales. These attributes of forested ecosystems influence water quality, temporal and spatial distribution of streamflow, and the structural characteristics of stream networks in watersheds. Riparian zones defined by functional criteria tend to be wider than those defined by physical attributes; for example, they may include source areas for recruitment of large woody debris in steep terrestrial land some distance from potential receiving streams.

More recent definitions tend to be functional and define riparian ecosystems by their flows of energy and materials at larger spatial scales.

A recent review of riparian definitions by Ilhardt et al. (2000) concluded that the way riparian ecosystems have been defined has evolved over time. Early definitions tended to focus on physical attributes, or describe the static state or physical condition of riparian areas at the site scale, whereas more recent definitions tend to be functional and define riparian ecosystems by their flows of energy and materials at larger spatial scales.

Ilhardt et al. (2000) offered the following example of a functional definition that recognizes the ecological functions of riparian areas that occur at various scales:

> Riparian areas are three-dimensional ecotones of interaction that include terrestrial and aquatic ecosystems, that extend down into

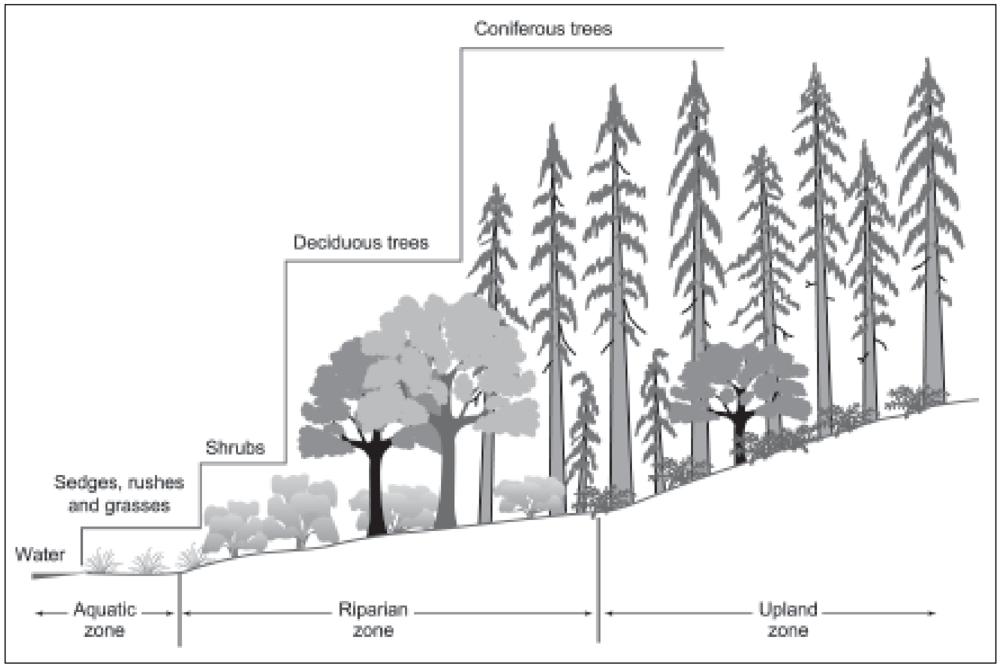
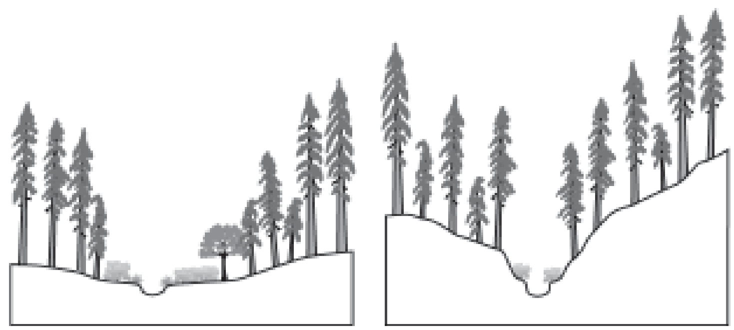


Figure 1—Riparian zones separate aquatic and terrestrial ecosystems (from Oakley et al. 1985). Widths may vary at a given site depending on whether physical (narrower) or functional (wider) definitions are used to delineate the zone.



	A. Broad, open area	B. Narrow, entrenched area
Local slopes:	30%	60%, often 80%
Location:	Well developed flood plains. Also includes lakes, wetlands, (marshes, bogs, ponds, wet meadows).	Poorly developed flood plains. Also includes small glacial or landslide lakes, small wetlands around springs or seeps.
Dominant process:	Deposition.	Active erosion and transport.
Soils:	Deep and often fine textured.	Often shallow and coarse textured.
Sunlight:	Year-round.	Often partially blocked during winter months or long periods of the day.
Winds:	Relatively open to disturbance.	Relatively sheltered.
Vegetation and structure:	Localized variations in soil type, moisture, and disturbance often create high diversity.	Often limited.

Figure 2—The effects of topography on the characteristics of riparian areas (from Oakley et al. 1985).

> the groundwater, up above the canopy, outward across the flood plain, up the near slopes that drain to the water, laterally into the terrestrial ecosystem, and along the water course at a variable width.

It is important to recognize that the way riparian ecosystems are defined affects their delineation on the ground. It is relatively easy to define the boundaries of riparian zones in forested watersheds when using only the physical characteristics of soils, water, and vegetation. Based on these ecosystem attributes, trained technicians can delineate riparian zones at the site scale in the field. It is more difficult to delineate riparian zones when using functional definitions that include near-stream terrestrial areas beyond the boundaries of water influence. In the latter case, high-resolution mapping at the watershed scale, followed by ground verification, may be necessary.

Riparian ecosystems tend to be complex and dynamic and exhibit variability within and across ecoregions (Lins 1997). For example, the vegetative characteristics of riparian habitats in water-rich areas can differ substantially from those in arid and semiarid areas, but both contribute to the health of aquatic ecosystems in the regions where they occur. Much of the variability in riparian habitats within ecoregions can be attributed to landscape disturbance regimes and topographic setting (Montgomery 1999). Topographic settings influence the type of vegetation as well as the frequency with which it is subjected to disturbance. Disturbances from natural and human sources can affect seral stages of vegetation in riparian zones and create variable mosaics of riparian habitats that wax and wane with the spatial and temporal features of disturbance.

Structure, Function, and Benefits of Riparian Zones

The structure and function of riparian ecosystems have been exhaustively studied in the United States and abroad. Literature summaries and bibliographies of thousands of individual riparian and riparian-related studies have been published in the past three to four decades (e.g., Bolton and Monohan 2001 [2,090 citations], Correll 2003 [annotated bibliography with 522 citations], University of Washington 2004 [interagency bibliography with over 8,000 riparian and riparian-related citations], U.S. Army Corps of Engineers 1991 [review and synthesis with 196 citations], Van Deventer 1992 [bibliography with 3,252 citations], Verry et al. 2000 [review and synthesis with 931 citations], Wenger 1999 [review and synthesis with 161 citations], Wenger and Fowler 2000 [review and synthesis with 72 citations]. Many of these studies have focused on an individual function of riparian zones, e.g., recruitment of large woody debris to stream channels in forested watersheds, in an attempt to determine the minimum width of riparian buffer needed to maintain a specific ecological function. Using the extensive literature base, we will briefly describe the structural features of riparian ecosystems and their primary ecological functions within the broader fabric of regional ecosystems, and direct readers to existing syntheses for more detailed treatment of the subject.

Structure

The features of riparian ecosystems are highly variable (Thomas et al. 1979), but all share common physical elements that are controlled by environmental phenomena. Physical characteristics of riparian habitats are defined in time and space by climatic conditions, vegetation types, stream order, and geomorphic features like channel gradient, elevation, slope, aspect, and perhaps other factors (see Oakley et al. 1985, Thomas et al. 1979). These factors, acting in concert with terrestrial ecosystems, contribute to the amount, intensity, timing, and frequency of high-flow events that shape both stream channel structure and riparian vegetation in flood plains.

Riparian ecosystems generally have a linear structure that may be hundreds of kilometers in length and highly variable in width.

When defined physically, riparian ecosystems generally have a linear structure that may be hundreds of kilometers in length and highly variable in width. The flood plains of large rivers may contain extensive riparian habitats with widths of a kilometer or more. Conversely, riparian zones along small, incised headwater streams may be only a few meters wide. The width of riparian habitat for a given stream size varies by climatic zone in the Northwest, with the greatest widths in the humid regions west of the Cascade Mountains and at higher elevations across the region, and progressively narrower widths in drier areas. Riparian zones in the temperate rain forests of southeast Alaska, because of high annual precipitation that creates expansive upslope fens, bogs, and forested wetlands, may extend considerable distances upslope from streams.

The elongated shape and vegetative structure of riparian zones maximizes edges internally and along adjacent aquatic and terrestrial ecosystems. Depending on structure of the vegetative community, three to five distinct edges between water, grasses, forbs, deciduous, and coniferous vegetation may occur within a single riparian zone. The high density of edges contributes to habitat and species diversity, and the productivity, of riparian ecosystems.

Topographic features of the landscape strongly affect the characteristics of riparian ecosystems (fig. 2). Streams in areas with gentle topography (<30 percent slope) may have wide flood plains subject to frequent sediment deposition, deep soils, low gradients, and little channel entrenchment. Riparian zones along such streams may be wide, vegetatively diverse, exposed to sunlight at all seasons, and subject to natural disturbances primarily from wind and floods. Streams of equivalent size in areas with steep topography (>60 percent slope) may have narrow flood plains subject to active erosional processes, shallow soils, steep gradients, and deeply incised channels. Riparian zones along these streams are usually narrow, have limited vegetative structure, may be topographically shaded during summer or winter, and are subject to natural disturbances primarily from fire, floods, and mass erosion events.

The combination of natural disturbances affecting riparian zones varies at the regional scale across the Northwest and southeast Alaska, but the frequency and magnitude of local disturbances shapes and maintains the temporal and spatial characteristics of riparian habitats at the watershed scale. Riparian zones, in general, occur in geologically unstable areas subject to erosion, deposition, and a variety of other natural disturbances (Leopold et al. 1964). These disturbances may also contribute to diversity of riparian vegetation and associated habitats used by a suite of aquatic and terrestrial organisms.

Riparian ecosystems provide a variety of important linkages and ecological functions for adjacent aquatic and upland ecosystems.

Function

Riparian ecosystems provide a variety of important linkages and ecological functions for adjacent aquatic and upland ecosystems. Key functions include the maintenance of surface and ground water quality in aquatic ecosystems; (especially hyporheic zones: the area of penetration of surface water into flood-plain gravels) maintenance of streambank and streambed stability; maintenance and protection of habitat structure for fish, wildlife, and vegetation; and maintenance of favorable microclimates for riparian-dependent species. All of these functions operate in concert in the near-stream environment. It is possible to review the individual functions of riparian ecosystems in isolation based on the results of individual studies, as we do in the following pages. However, management strategies developed from studies of individual functional aspects of riparian zones (e.g., contribution of large wood to stream channels) have often failed to meet riparian management goals (IMST 1999, Murphy 1995, USDA Forest Service 1995). Management strategies that consider ecosystem-level scientific information of riparian functions in concert are more likely to achieve stated riparian management goals (IMST 1999, Murphy 1995).

Functions related to water quality—

Riparian zones exert controls over the temperature of adjacent surface waters, the movement of suspended sediment, dissolved and particulate organic matter, nutrients, pesticides, and heavy metals from upslope areas to downslope water bodies, and streambed and bank stability. Healthy riparian ecosystems help to maintain high-quality water and structural habitat elements for aquatic biota in adjacent aquatic ecosystems.

Water temperature—

Riparian vegetation is one of the most important factors controlling water temperature in streams (U.S. Army Corps of Engineers 1991), especially during summer when solar radiation peaks and sun angle is at its seasonal zenith. In small streams, aspect and degree of incision may provide some topographic shading, although vegetation usually remains the primary source of shade. Water temperature greatly influences metabolism, development, and activity of fish and other stream organisms (Naiman et al. 1992), as well as recreational use and the value for domestic water supplies (Hornbeck and Kochenderfer 2000). Streamside vegetation controls the amount of solar radiation striking the water surface in summer, thus reducing potential heating of surface waters. In winter, riparian vegetation tends to maintain warmer water temperatures, especially in high-latitude and high-elevation streams where vegetation both insulates and blocks radiative cooling (Beschta et al. 1987). Warmer winter water temperatures reduce the potential for formation of shelf, frazil, and anchor ice.

The effect of riparian vegetation on stream temperature varies by stream size and season of the year. Riparian vegetation exerts the greatest temperature control on small streams (U.S. Army Corp of Engineers 1991). Small, forested streams that are heavily shaded by riparian vegetation typically receive only about 1 to 3 percent of total available solar radiation (Naiman 1983, Naiman and Sedell 1980). Consequently, their daily water temperatures are relatively cool and stable (Naiman et al. 1992), and their fauna are adapted to low light and cool temperatures (Naiman and Sedell 1980). Loss of riparian vegetation along small streams can cause large increases in water temperature (>10 °C) and changes in energy flux, resulting in the disruption of indigenous aquatic communities.

Riparian vegetation also influences the water temperature of mid-size streams and rivers but to a lesser degree than in small streams. Gaps in the riparian canopy along mid-size streams allow 10 to 25 percent of total available solar radiation to reach the stream surface, allowing wide variations in diel and seasonal temperatures (Naiman et al. 1992). Manipulation or loss of riparian vegetation along mid-size streams, however, can still cause increases in summer water temperatures of several degrees and affect energy flow and the health of aquatic communities.

The water temperature of large rivers is less affected by riparian vegetation. Most available solar radiation reaches the surface of large streams, but diel temperature variations are minimized by stream depth and volume of flow. Changes in the density of riparian vegetation along large rivers have less effect on aquatic biota than along small or mid-size streams. Most benefits of shading by streamside vegetation are derived within about 30 m of streams (fig. 3) (Brazier and Brown 1973, FEMAT 1993, Steinblums et al. 1984) although distance varies by stream size and topographic features.

In addition to direct shading, the microclimate surrounding streams and riparian zones also may affect stream temperatures and the suitability of riparian habitats for vertebrates. Specific features of microclimate (e.g., soil moisture, solar radiation, soil temperature, air temperature, windspeed, and relative humidity) are influenced by near-stream vegetation (Chen 1991, Chen et al. 1995) and may

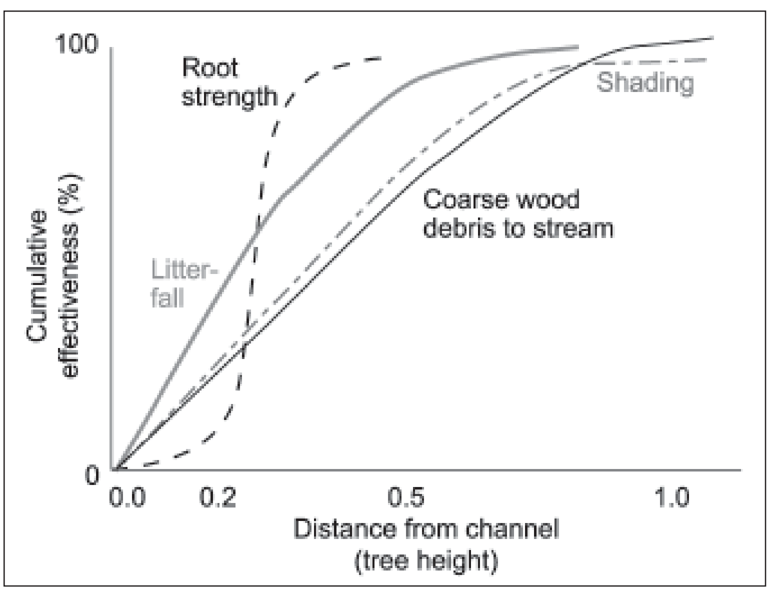


Figure 3—Generalized curves indicating percentage of riparian ecological functions and processes occurring within varying distances from the edge of a forest stand (from FEMAT 1993).

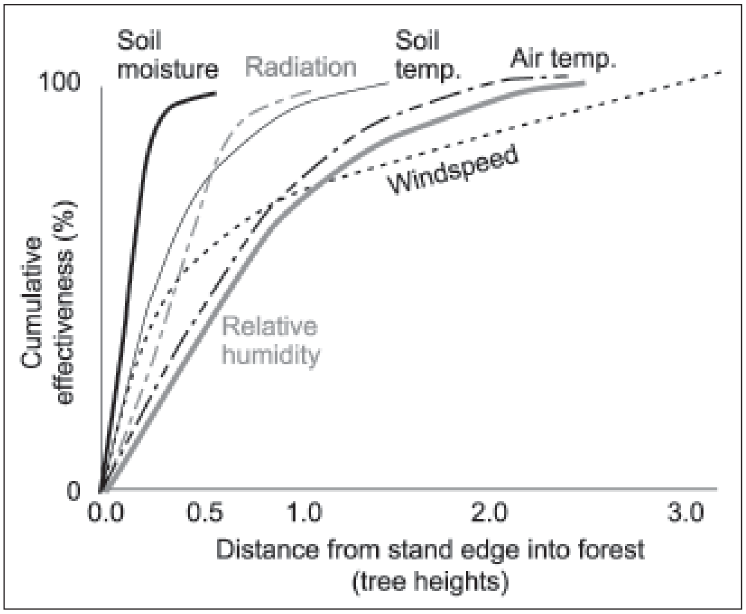


Figure 4—Generalized curves indicating percentage of microclimate attributes occurring within varying distances of the edge of a riparian forest stand (Chen 1991) (from FEMAT 1993).

indirectly affect water temperature. Chen (1991) estimated the widths of riparian vegetation needed to maintain 100 percent of microclimate effects near streams (fig. 4). Maintenance of air temperature and windspeed, factors that can influence stream temperatures, may require a vegetated corridor up to 125 m wide.

Sediment—

Sediment is the Nation's most common contaminant of surface waters by weight and volume and has been identified by the U.S. Environmental Protection Agency as the number one problem threatening America's waterways (Koltun et al. 1997). Suspended and bedload sediments are natural components of flowing waters. Watersheds that are unmanaged have a natural range of sediment production and delivery to stream channels, and streams have a natural capacity to process and transport sediment downstream. Surface and mass erosion in unmanaged watersheds vary widely in time and space owing to large infrequent natural events.

If sediment delivery from human actions significantly exceeds natural levels, alterations in natural system functions occur.

Many human activities in watersheds, including timber harvest and road-building and use, accelerate soil erosion and sedimentation in receiving waters by exposing mineral soil to erosive forces. If sediment delivery from human actions significantly exceeds natural levels, alterations in natural system functions occur (Platts and Megahan 1975), resulting in sediment deposition, channel instability, and high levels of turbidity (Everest et al. 1987, Nehlson et al. 1991). Elevated concentrations of inorganic sediments in streams may impair many biological functions. For example, elevated levels of sediments can reduce the family richness and abundance of invertebrate drift and reduce growth of trout in affected streams (Shaw and Richardson 2001).

Riparian vegetation can reduce sedimentation and its effects on stream and lake habitats in the following ways (see U.S. Army Corps of Engineers 1991, Wenger 1999):

- Vegetative cover reduces erosion in riparian zones (U.S. Army Corps of Engineers 1991).
- Vegetation and organic litter in riparian zones filter and trap sediment moving downslope in surface waters (Karr and Schlosser 1977).
- Roots of riparian vegetation reduce erosion of streambanks (Beeson and Doyle 1995).
- Large woody debris originating from riparian zones traps and retains sediment moving in stream channels (Bisson et al. 1987) and keeps it from accumulating downstream.
- Large riparian areas in flood plains reduce erosion by moderating streamflow and scour during flood events (Gregory et al. 1991, Naiman et al. 1988).

All of these riparian functions effectively reduce sedimentation in streams and lakes, although their effectiveness may change seasonally. Riparian vegetation may be less effective in controlling sedimentation in winter than in summer when vegetative growth is at its maximum (Schwer and Clausen 1989). Widths of riparian vegetation needed to filter and retain sediment in transport from source areas to streams are generally reported to be <50 m (e.g., U.S. Army Corps of Engineers 1991).

Nutrients and contaminants—

Pathways of nutrient flow between riparian and aquatic ecosystems have received considerable study, especially in recent years. Energy flow is complex, moving both downslope from riparian ecosystems to streams and upslope from streams to riparian ecosystems. Allochthonous contributions of small and large organic debris from riparian vegetation provide an important energy source to hyporheic (Clinton et al. 2002) and stream waters (Vannote et al. 1980, Verry et al. 2000), and terrestrial invertebrates contribute to the food web of aquatic systems (Nakano et al. 1999).

Nutrient energy also flows from aquatic to riparian systems. In the Pacific Northwest and Alaska, anadromous salmonids bring large quantities of nutrients from the sea to freshwater streams where decomposing carcasses provide fertilizer to riparian vegetation (Drake et al. 2002; Helfield and Naiman 2001, 2002; Naiman et al. 2002). The net result can be positive feedback to salmonid spawning and rearing habitats (Helfield and Naiman 2001) through enhanced growth of riparian vegetation that affects shade, sediment and nutrient filtration, and quantities of invertebrates and large woody debris in stream channels. Aquatic arthropods also transfer energy from aquatic systems to terrestrial predators (Collier et al. 2002, Sanzone et al. 2003).

Riparian vegetation and subsurface processes in riparian zones have the capability of trapping, binding, storing, and detoxifying many types of pesticides, heavy metals, and other contaminants (see Desbonnet et al. 1994, U.S. Army Corps of Engineers 1991**,** Wenger 1999). In the PNW, many of these functions are more important in agricultural and urban areas that are more subject to the polluting effects of human activities than are forested watersheds (e.g., Rienhold and Witt 1992, Rinella and Janet 1998). Essentially no agricultural pesticides or fertilizers are used in southeast Alaska.

Current application of chemical pesticides, herbicides, and fertilizers is minimal on private and federal forest lands of the Pacific Northwest. Only about 1 percent of the commercial forest land in the region and 0.2 percent of the federal land[1] receives some form of forest chemical treatment each year. Nitrogen- and phosphorus-based fertilizers are used occasionally in forestry to enhance tree growth on private forest lands in the Pacific Northwest. Use of fertilizer is rare on federal forest lands in the Pacific Northwest, and is usually limited to nurseries and seed orchards. Use on private forest lands is more common but still limited in extent. Water quality sampling programs in the Willamette River basin indicate that nitrogen and phosphorus concentrations in waters flowing from forested watersheds are similar to those at national benchmark sites on streams minimally disturbed by human activities (Wentz et al. 1998).

Healthy riparian zones can strongly affect the movement of pesticides and nutrients from terrestrial to aquatic ecosystems in forested, agricultural, and urban landscapes (see U.S. Army Corps of Engineers 1991, Wenger 1999). Some of the most important riparian functions include:

---

[1] Smith, G. 2000. Personal communication. Silviculturist, U.S. Department of Agriculture, Forest Service, Pacific Northwest Region, Portland, OR 97208.

- Trapping of a high percentage of phosphorus bound to sediments (the most common phosphorus transport mechanism [Karr and Schlosser 1977]).
- Uptake by vegetation and denitrification of a high percentage of nitrate nitrogen moving through the root zone and anaerobic zones of riparian areas (e.g., Fennessy and Cronk 1997, Gilliam 1994).
- Trapping and detoxification of pesticides bound to sediments (e.g., Frick et al. 1998).
- Intercepting aerosol drift of aerially applied pesticides (e.g, Wenger 1999).

All of these functions are generally provided by riparian corridors ≥50 m wide (e.g., Desbonnet et al. 1994, U.S. Army Corps of Engineers 1991, Wenger 1999), although riparian vegetation is more effective at retaining sediment-bound nutrients than soluble nutrients. Aerosol sprays may require riparian buffer strips up to 100 m wide to prevent stream contamination (Nriagu and Lakshminarayana 1989).

Streambank and streambed stability—
Riparian vegetation functions as a stabilizer of streambanks and streambeds, and thus helps to maintain water quality and the natural structural elements of stream channels. Streams can be classified by channel type (e.g., Paustian 1992) based on channel entrenchment, width-to-depth ratio, and sinuosity. Human or natural disturbances can cause a stream to shift from one type to another, with a corresponding change in channel geometry. Such shifts may result in a long period of channel instability, as the channel tends to re-establish its original type or reach stability in a new type.

Riparian vegetation is one of several important factors that influence the stability of streambeds and banks. Between disturbance events, riparian vegetation contributes to the maintenance or re-establishment of channel stability in the following ways:

- Reduces streambank erosion.
- Helps maintain established stream channel geometry within historical norms.
- Slows flood flows and dissipates stream energy.
- Reduces streambed erosion.

Riparian corridors >15 m wide have been shown to control streambank erosion in small Eastern U.S. streams (Wipple et al. 1981), and 30-m corridors maintained streambank stability in low-order streams in northern California (Erman et al. 1977).

Riparian vegetation plays an important role in maintenance of regional biodiversity.

Functions related to wildlife habitat—

At the landscape scale in the Pacific Northwest, riparian vegetation plays an important role in maintenance of regional biodiversity (Naiman et al. 1993) and provides disproportionately important habitat for many wildlife species (Gregory and Ashkenas 1990, Kelsey and West 1998). Of the 414 wildlife species in western Oregon and Washington, 359 use riparian zones or wetland habitats during some seasons of the year, or some parts of their life cycle (Oakley et al. 1985). Wildlife benefit from several key functions of riparian ecosystems that provide:

- Reliable sources or water, food, and cover in areas where water is scarce (Thomas et al. 1979).
- Maximum habitat diversity and edges for wildlife species because of the elongated shape of riparian zones (Patton 1975).
- Specific microclimates (Brosofske et al. 1997) that are desired by some species of wildlife, or required at some seasons.
- Preferred foraging, breeding, rearing, hiding, and resting habitats, and thermal cover for particular species at certain times of the year (Oakley et al. 1985).
- Travel corridors and migration routes between habitat types or summer and winter ranges (Noss 1983).

Overall, the temporal and spatial needs of riparian and terrestrial vertebrates for specific seral stages and stand conditions in riparian habitats are poorly known, and more research is needed. Small generalists may need only a few meters of a variety of vegetated riparian conditions to meet their needs (e.g., Raphael et al. 2002), whereas large mammals may need >150 m of late-successional riparian habitats to meet specific needs (Buskirk et al. 1989, Raphael and Jones 1997, USDA Forest Service 1997). After reviewing the relationship between riparian areas and the habitat needs of wildlife, Wenger (1999) concluded that narrow buffers provide habitat benefits for many species, but protecting diverse riparian wildlife communities requires some buffers at least 100 m wide.

Functions related to habitat for fish and other aquatic life—

The condition of aquatic ecosystems at the watershed scale is strongly tied to the condition of riparian vegetation within a watershed (Welsch 1991). The structure and productivity of habitats for fish and other aquatic organisms are controlled to a large extent by adjacent and upstream riparian vegetation. Some of the functional interactions between riparian and aquatic ecosystems, such as control of water quality issues like temperature, sediment, nutrients, and contaminants and streambed and bank stability, have already been discussed. Additional critical functions of riparian vegetation for development and maintenance of habitat for fish and other aquatic species include:

- Contribution of large woody debris that provides habitat structure for salmonids and a variety of other aquatic organisms (Bisson et al. 1987, Sullivan et al. 1987).
- Contribution of leaves and particulate organic matter, the primary energy source for aquatic food webs in most small and mid-size streams (Minshall et al. 1985, Wipfli and Gregovich 2002).

Widths of riparian corridors needed to maintain these functions generally are ≤70 m (fig. 3) (FEMAT 1993).

Conclusions on riparian functions from the scientific literature—
Most studies on the functions of riparian ecosystems have addressed single functions at site scales with the intent of determining the width of riparian zone needed to maintain the individual function under study. Much valuable information has resulted from such studies, but caution is needed in their interpretation, and especially in their application to riparian management plans. Focusing on single functions (e.g., large woody debris or water temperature) simplifies delineation of riparian zones but fails to account for the three-dimensional (width, length, depth at the watershed scale) complexity and multiple functions inherent in riparian ecosystems. The key point is that complex riparian ecosystems and their functions can only be understood at large temporal and spatial scales. The multiple functions of riparian ecosystems operate in concert, with differing widths of unmanaged near-stream vegetation needed to maintain different functions (table 2). Attempts to protect or maintain a single function, based even on well-designed scientific studies, may result in damage or loss of other functions. If managers choose to protect the most vulnerable functions of riparian ecosystems, i.e., the ones requiring the widest strips of unmanaged vegetation in the near-stream environment, then all riparian functions are likely to be retained.

If managers choose to protect the most vulnerable functions of riparian ecosystems, …then all riparian functions are likely to be retained.

Benefits

Ecosystems at the watershed scale provide many ecological, social, and economic benefits to society. Although the potential to realize all of the benefits at some level is present in major watersheds (about 7th order and larger), despite decades

Table 2—Estimated widths of unmanaged near-stream vegetation in forested watersheds needed to maintain various functions of riparian ecosystems

Riparian function	Width unmanaged vegetation required	References
Maintain water temperature	~50 m	Brazier and Brown 1973, FEMAT 1993, Steinblums et al. 1984
Maintain microclimate	~125 m*	Chen 1991, FEMAT 1993
Control sediment	~50 m	For example, U.S. Army Corps of Engineers 1991
Control nutrients/contaminants	~100 m±*	Desbonnet et al. 1994, Nriagu and Lakshminarayana 1989, Wenger 1999
Maintain streambed/banks	~30 m*	Erman et al. 1977
Maintain wildlife habitats	~150 m±*	Schoen 1977, USDA Forest Service 1997
Maintain fish habitats	>70 m*	Bisson et al. 1987, FEMAT 1993

Note: Widths were derived from site-scale studies but correctly apply to riparian networks at watershed scales.
* = Requires late-successional or old-growth forest vegetation.

of research and study, it remains unclear as to whether all of the benefits can be derived simultaneously at desired levels as defined by society, especially at small scales. The principal benefits derived from riparian areas in ephemeral headwater catchments may differ from those associated with mid-sized perennial streams, which in turn may differ from benefits of riparian zones along major rivers. However, at all scales, questions remain about interactions between potential benefits, and whether some are mutually exclusive of others.

Some benefits are strongly associated with unmanaged riparian habitats, whereas others may be derived from active riparian management.

Benefits provided by riparian zones are strongly related to their structure and function. Although it is possible to think of the benefits in ecological, social, or economic terms, in most cases the benefits blend across the three categories. Some of the benefits are strongly associated with unmanaged riparian habitats, whereas others may be derived from active riparian management. Some major benefits that accrue to society include:

- Maintenance of water quality in streams, lakes, shallow ground-water strata, and hyporheic zones.
- Maintenance of stream channel stability and hydrologic function in watersheds.
- Contribution to maintenance of biodiversity in watersheds and the maintenance of viable populations of riparian, aquatic, and terrestrial species.

- Focal sites for outdoor recreation.
- Contribution to the value of private residential and commercial properties.
- Contribution to visual aesthetics in managed landscapes.
- Maintenance of aesthetics in wild and scenic river corridors.
- Flood control.
- Maintenance of streamflows for human uses.
- High-quality potable water for domestic and industrial use.
- Production of high-value aquatic resources, for example, anadromous salmonids.
- Timber production.
- Livestock production from riparian forage.
- Mining for gold and other minerals.

The variety of ecological, social, and economic benefits provided by riparian zones contributes to the controversy surrounding their management in Western watersheds.

Effects of Watershed Disturbances on Riparian Structure and Function

Watersheds throughout the Northwest and southeast Alaska are subject to disturbances from natural events and human activities. The type and timing of disturbances largely determines their effects on ecosystem resilience, ecological processes, and indigenous biota. Ecosystem disturbances can be classified as either "pulse" or "press" disturbances based on their temporal and spatial frequency. Yount and Niemi (1990) referred to disturbance regimes that maintain the resiliency of ecosystems as pulse disturbances. Pulse disturbances occur infrequently, and there is sufficient time between disturbances to enable ecosystems to recover to predisturbance conditions. Pulse disturbances generally allow ecosystems to remain within their normal historical range of states and conditions.

Watersheds throughout the Northwest and southeast Alaska are subject to disturbances from natural events and human activities.

Press disturbances, on the other hand, are characterized by frequent events interspersed with insufficient recovery time to allow ecosystems to return to predisturbance conditions. Press disturbances generally reduce the resiliency of ecosystems and may ultimately impose new regimes of variability that are outside of the natural historical range of a watershed or ecoregion. Natural and human disturbance regimes can fall into either the pulse or press category, although natural disturbances are most often associated with the former and human disturbances with the latter.

Natural Disturbances

Natural disturbances in Northwest watersheds are generally classified as pulse disturbances because they are cyclic or episodic in nature, usually widely scattered in time and space, and stem from a variety of physical and biological sources. The effects of natural disturbances are often asynchronous, so adjacent watersheds have decoupled disturbance patterns resulting in different levels of disturbance at any given time (Naiman et al. 1992). The result is an incremental, regional-scale process of ecosystem change and renewal that is an essential part of maintaining ecosystem productivity in the long term. Changes associated with natural disturbances are generally gradual enough for indigenous biota to cope with and adapt to at regional or province scales. Effects of natural habitat disturbances (e.g., stand-replacement fires) may cause temporary extirpation of species at small spatial scales, but adjacent populations in favorable habitats are likely to rapidly recolonize recovering habitats.

Natural disturbances provide a baseline from which to interpret the effects of human disturbances, or the significance of cumulative effects from natural and human impacts.

Natural disturbances provide a baseline from which to interpret the effects of human disturbances, or the significance of cumulative effects from natural and human impacts (Benda et al. 1998). Natural physical disturbances include climate cycles and their associated effects on terrestrial, riparian, freshwater, and marine ecosystems, and natural events (often climate induced) such as drought, fire, floods, mass erosion, wind, and ice storms, whereas biological disturbances are often related to insect and disease outbreaks (Harris and Farr 1974, Rogers 1996). The frequency of climate cycles may range from a few years to millennia, and the scale of effects is generally regional. Other natural events may occur on timeframes ranging from decades to centuries and on spatial scales ranging from a few square meters to thousands of square kilometers.

The dominant natural disturbance processes that affect riparian ecosystems in forested watersheds of Oregon, Washington, and southeast Alaska vary geographically. Although all of the disturbance agents mentioned above can potentially affect any watershed, fire was the dominant agent across the Pacific Northwest (Agee 1993, Wright and Bailey 1982). Also, synergy between fire and subsequent intense rainstorms and flooding may be the sequence of disturbances with the greatest effect on riparian ecosystems in that geographic area (Benda et al. 1998). Conversely, wind may be the primary natural disturbance in forested watersheds and riparian systems in the rain-forest ecosystems of the western Olympic Peninsula, and wind has been documented as the primary agent in coastal British Columbia, and southeast Alaska (Harris 1989, Nowacki and Kramer 1998).

The cumulative effects of natural disturbances shape and maintain regional-scale terrestrial, riparian, and aquatic ecosystems of the Northwest and southeast Alaska. The flora and fauna of these regions have evolved with, and adapted to, the temporal and spatial landscape mosaic of natural disturbances (e.g., Reeves et al. 1995). As long as natural disturbance processes operate within historical levels of variability at the regional scale, it is likely that productive habitats for the region's flora and fauna will exist in the long term. However, substantive changes in the spatial and temporal distribution of disturbance regimes increase the risk of permanent habitat changes, challenge species adaptability, and could lead to extirpations and extinctions.

Climate cycles—

The climate of the Pacific Northwest is naturally variable and cyclic. Maritime, continental, and arctic influences, each modified by the orographic effects of major mountain ranges, contribute to high geographic variability in precipitation, runoff (Everest et al. 2004), and the characteristics of riparian ecosystems across the region (Oakley et al. 1985, Thomas et al. 1979). The natural spatial variability of riparian and aquatic habitats is further complicated by temporal climatic cycles of variable duration and predictability. The most obvious temporal cycle is the annual cycle of seasons that drives three types of hydrographs dominated by rain in the coastal zone and valleys west of the Cascade Mountains, rain-on-snow in the transition snow zone of the Coast Range and Cascade Mountains, and snow in the high-elevation mountains of the region. But, other longer term climatic events strongly contribute to the natural range of variability in the riparian and aquatic ecosystems of the region.

El Niño Southern Oscillation (ENSO) affects precipitation and runoff in the Northwest and contributes to short-term and long-term variability of riparian and aquatic habitats. El Niño is a recurrent interannual climatic event characterized by unusually warm ocean temperatures in the equatorial Pacific Ocean. Such ENSO events typically occur every 2 to 7 years and generally last 12 to 18 months (Hare et al. 1999). Receding El Niños are often followed by the opposite extreme, La Niña, which is characterized by unusually cold ocean temperatures in the equatorial Pacific. The two events have opposite, but significant effects on global weather patterns. El Niños cause winters warmer and drier than average in the Pacific Northwest whereas La Niñas produce winter conditions that tend to be cooler and wetter than normal, although the effects of individual events can be highly variable.

La Niñas that occurred between 1895 and 1989 generally produced cooler temperatures in coastal climate zones of the Pacific Northwest and in some areas of the western Cascades of Oregon, while much of the region experienced higher than normal precipitation and favorable conditions for riparian and aquatic habitats. Drought conditions caused by El Niños can stress riparian ecosystems, cause below-normal summer streamflows, and reduce production of aquatic biota.

The Pacific Decadal Oscillation (PDO) also affects riparian and aquatic habitats in the Pacific Northwest and southeast Alaska but in a less predictable way than ENSO. The PDO is an interdecadal Pacific climate pattern with profound effects on the North Pacific Ocean and terrestrial environments of the Pacific Northwest (Mantua et al. 1997). Two main characteristics distinguish the PDO from ENSO. First, PDO events in the 20^{th} century have persisted for two to three decades, and second, the effects are most visible in the North Pacific Ocean and the North American continent (Hare 1998). The PDO also has warm and cool regimes that affect temperature, precipitation, runoff patterns, and riparian and aquatic ecosystems in western North America and affect the productivity of anadromous salmonid rearing areas in the North Pacific Ocean. For example, during the cool PDO regimes of 1925-1946 and 1977 to at least 1995, salmonid production was favored in the northern areas and was at low ebb in the PNW and California. Production of anadromous salmonids was highest in the PNW and California during the 1890-1924 and 1947-1976 periods when Alaska's production was low. During cool phases of the PDO, storm activity and precipitation increase in the Alaska region, and weather is calmer, warmer, and drier in the Pacific Northwest. The reverse is true during warm PDO phases. The major effect of the PDO is on water temperature and streamflow, but persistent drought during warm phases can affect the health of riparian vegetation in the PNW.

Global climate change is a third factor that may complicate management of riparian ecosystems in the Pacific Northwest and Alaska. However, the exact nature of the impact of global warming in these regions and world has not been determined. Some predict (e.g., Aber et al. 2001, Climate Impacts Group 2004) that warmer and drier summers will yield less water for the maintenance of summer instream flows, riparian habitats, and fish populations in the PNW. Also, predicted wetter winters will likely enhance growth of vegetation, and predicted warmer, drier summers will likely increase the potential for wildfires (McKenzie et al. 2004). Because predictions differ considerably from model to model, the net result for riparian health is unclear.

Predicted results of global warming in Alaska (e.g., US EPA 1998, Rupp et al. 2000) include increased precipitation, runoff, and streambank erosion; advance of the northern extent of forested areas including riparian vegetation; increased wildfire with consequent transition to younger forest stands in the interior; and increased susceptibility to insect pests in certain forest biomes. The net effect of these predictions on riparian health is also uncertain.

The science community is currently investigating key aspects of global warming, including the potential severity and likely climatic and environmental consequences. The scientific evidence indicates that the Earth is in a gradual warming phase, and climate change models predict temperature increases in the Pacific Northwest of about 1.3 °C by 2020 and about 1.9 °C by 2040 (Climate Impacts Group 2004). Temperatures in Alaska could increase by 2.4 °C in spring, summer, and fall, and 4.8 °C in winter by 2100 (US EPA 1998).

The natural climate cycles of the Northwest have created variable and complex intrawatershed precipitation and runoff patterns that produce natural landscape events such as floods, droughts, fire, and landslides, and influence the distribution of flora and fauna at the watershed scale. Human use of land and water in the region has often failed to adequately consider these events in resource plans, or the way in which human activities can alter the frequency and magnitude of these events.

Fire—

Fire is a dominant natural disturbance process in the Pacific Northwest and strongly influences the age distribution of riparian (Bendix 1994) and upland forests (Agee 1993). Variation in climate, topography, fuels, lightning strikes, and the actions of aboriginal and modern humans control the frequency, intensity, and size of fires in the region (Schoonmaker et al. 1997).

Wildfire can affect riparian and aquatic ecosystems in at least the following ways:

- Increased sediment delivery to channels
- Increased woody debris delivery to channels
- Loss of riparian vegetation and streamside cover
- Decreased litterfall
- Increased streamflow
- Increased nutrient levels in streams

The effects of fire, which generally operate in concert, can temporarily destroy the structure and function of riparian ecosystems in burned areas and cause a short-term reduction in the productivity of aquatic systems (Bisson et al. 2003; Minshall et al. 1997, 2001; Rinne 1996). Fire frequency (rotation) can affect wood recruitment and wood volume in streams (Benda and Sias 2002), with shorter rotations having a higher probability of causing low instream volume of large woody debris. After an initial decline following fire, riparian and aquatic species may experience renewed vigor as aquatic ecosystems process sediments and large woody debris added to channels via subsequent storm runoff, and watersheds and riparian habitats revegetate (Minshall et al. 2001, Reeves et al. 1995).

The frequency of fire in the period predating European settlement ranged from about 21 years in the temperate rain forests of the Olympic Mountains of Washington (Wetzel and Fonda 2000) to about 16 years in the eastern Siskiyou Mountains of Oregon (Agee 1991). In all cases, fire-return intervals were scale related, and many of the fires at the frequencies noted above were small, low-intensity blazes that more strongly affected understory than overstory vegetation. Low-intensity fires probably had local and minimal impacts on riparian vegetation adjacent to streams in cool, damp valley bottoms (Agee 1993).

Stand-replacing fires (Agee 1993) of high intensity occurred at lower frequency across the region. As summarized by Benda et al. (1998), the average stand-replacing fire interval in the Pacific ecoregion is about 400 years on the Olympic Peninsula (Agee 1993), about 200 to 300 years in the central Oregon Coast Range (Long 1995, Teensma et al. 1991), about 150 to 200 years in the western Cascade Mountains of Oregon and Washington (Morrison and Swanson 1990, Teensma 1987), and about 80 to 100 years in southwestern Oregon (Gara et al. 1985). High-intensity fires were capable of resetting succession in riparian zones at intervals of from less than one to several centuries.

Stand-replacing fires interacted synergistically with other natural disturbances, especially floods and mass erosion, to cause additional long-term effects in riparian and aquatic habitats. Severe rainstorms following large stand-resetting fires can trigger mass erosion events, extreme surface erosion from burned areas (Klock and Helvey 1976), accelerated runoff, and increased flooding. The combined short-term effects can bury stream channels with sediment, delay re-establishment of riparian vegetation in disturbed areas, and reset the age of riparian vegetation in downstream areas (Benda et al. 1998). The long-term effects can be positive as more complex and productive riparian and aquatic habitats emerge in the decades and centuries following stand-resetting fires.

The effects of fire on riparian and aquatic systems, and recovery rates following fire, are related to previous management history in watersheds.

The effects of fire on riparian and aquatic systems, and recovery rates following fire, are related to previous management history in watersheds. For example, Minshall (2003) indicated that fire in watersheds already affected by extensive human disturbances such as logging and road construction can be expected to produce more severe effects than fire in largely intact watersheds. Also, observations by Minshall (2003) indicated that stream ecosystem recovery following wildfire is more dependent on riparian vegetation and flood-plain conditions than on the condition of upland portions of watersheds. Therefore, added human disturbances such as salvage logging and road construction in riparian areas following fire can greatly extend the time required for ecosystem recovery.

Floods—
Floods are common natural events in western Oregon and Washington and southeast Alaska. The most common effects of floods on riparian and aquatic systems include:

- Bank erosion and undercutting of riparian trees.
- Sediment inundation of riparian vegetation.
- Increased movement of sediment and transport of woody debris in channels.
- Redistribution and clumping of woody debris in channels.
- Channel scour that widens channels and redistributes coarse sediments.
- Flushing and deposition of fine sediments in channels.

Floods caused by rapid spring snowmelt and regional floods caused by intense precipitation from large Pacific storms affect riparian habitats in western Oregon and Washington. Both types of events can cause overbank flows that alter riparian ecosystems and stream channels. Effects of floods as listed above usually occur in concert, but the severity may vary by stream size, gradient, and valley configuration.

The magnitude and frequency of floods is highly variable. Floods caused by rapid snowmelt are the least common events in the region. The only major flood in western Oregon and Washington attributed to this source occurred in 1948 (NOAA 2001). The event, which lasted 45 days, caused widespread flooding along hundreds of kilometers of the Columbia River, scoured stream channels and riparian zones, and caused extensive damage to cities along the lower Columbia River.

Large regional floods have more extensive effects on riparian habitats and stream channels than other types of events. Numerous regional-scale floods have occurred in Oregon and Washington in the last century (table 3). In addition to causing extensive property damage and significant loss of human life, the events altered riparian vegetation and stream channels over thousands of kilometers of

Table 3—Frequency and location of major floods in Oregon and Washington, 1860-2000

Date	Oregon	Washington
1861	Coastal, Willamette River	
1890	Coastal, Willamette River	
1923	Coastal, Willamette River	
1943	Coastal, Willamette River	
1948	Columbia River	Eastern, Columbia River
1964	Statewide	Southern
1990		Statewide
1995	North central	
1996	Statewide	Western, southeast

Source: NOAA 2001, National Weather Service 1999a.

streams in the area. Recurrence intervals for major floods in individual river basins may range from years to decades and may vary regionally with the greatest frequency in coastal zones. Major floods are habitat resetting events for riparian and aquatic systems, often removing large tracts of riparian vegetation and changing the locations of stream channels. Flooding is a long-term natural process that regulates productivity and facilitates renewal of riparian and aquatic ecosystems.

Floods in sparsely settled southeast Alaska are less documented than those in the Pacific Northwest. The Alexander Archipelago of southeast Alaska is composed of more than 2,000 islands and a narrow strip of mainland. Hundreds of short streams and rivers in the area are characterized by steep gradients in the headwaters, and low-gradient mainstems in glacial valleys. Much of the area receives more than 250 cm of rainfall per year, but the terrain is covered primarily with old-growth spruce-hemlock rain forests that provide controlled runoff. Few rivers in southeast Alaska are gauged, so records of unusually high streamflow and river stage are rare.

The effects of floods can be accentuated by fire, volcanism, and mass erosion. High-intensity precipitation and floods following wildfire can magnify the effects of flooding on stream channels and riparian vegetation in downstream areas. Lahars associated with volcanic eruptions, e.g., Mount St. Helens in 1980, are a unique type of flood event that can bury stream channels with mud and destroy riparian vegetation in affected areas. Mass erosion events that occur simultaneously with flooding can also compound the effects of floods on riparian and aquatic habitats.

Mass erosion—

Mass erosion events such as slumps, earthflows, debris avalanches, and debris torrents are common in the steep and unstable terrain of the Pacific Northwest and southeast Alaska (Swanston 1969, 1971). The characteristics of these events and the mechanics of slope failure in forested terrain are well documented in the literature (Swanson et al. 1987, Swanston 1974, Swanston and Swanson 1976). Mass erosion is episodic in time and space in unmanaged forests, but the effects can change stream channels and riparian habitats in affected stream reaches. The common effects are:

- Bank erosion and undercutting of riparian vegetation.
- Channel scour and destruction of vegetation in riparian zones.
- Inundation of riparian zones with sediment.
- Increased woody debris and redistribution of woody debris in channels.
- Damming and obstruction of channels.
- Sedimentation and shifts in channel configuration.

The frequency of occurrence of mass erosion varies by the type of event. Earthflows in deep soils in steep terrain, although relatively rare, may be active annually during the wet season for decades. Debris avalanches and debris torrents are more common, and at the landscape scale are initiated by intense storms with return intervals of about 7 years in the Northwest (Swanston and Swanson 1976) and 5 years in southeast Alaska (Swanston 1969). The recurrence interval for a given site, however, is usually more than a millennium (Benda 1988).

Wind—

Windstorms are common natural disturbances in the Pacific Northwest (Benda et al. 1998, Sinton et al. 2000) and southeast Alaska (Deal et al. 1991, Lawford et al. 1996). Ecological effects of wind are scale-related (Nowacki and Kramer 1998, Ulanova 2000), ranging from small-scale canopy disturbances (gap dynamics associated with blowdown of a single tree or small group of trees) to large-scale stand-resetting events in which most trees on hundreds or thousands of hectares of land are blown down by a single storm.

Windthrow can fell individual trees or whole stands in riparian areas and affect adjacent and downstream aquatic habitats in several ways. Extensive windthrow of riparian vegetation can cause:

- Increased sediment delivery to channels.
- Decreased litterfall.

- Increased large woody debris in channels.
- Loss of shade (elevated stream temperatures).
- Shift from allochthonous (offstream) to autochthonous (instream) energy sources in small streams.
- Maintenance of soil productivity in riparian zones through mixing.

Although windstorms are among the most frequent natural disturbances occurring in the Pacific Northwest and southeast Alaska, forested areas of the landscape are affected differentially based primarily on aspect, topography (Harris 1989, Kramer 1997), climate, stand age, tree height and diameter, and tree species present (Canham et al. 2001, Larson and Waldron 2000, Lohmander and Helles 1987, Ruel 2000). At the regional scale, recurrence intervals of events that cause substantive blowdown of timber occur on a decadal basis or even more frequently (table 4), but smaller individual units of the landscape may be unaffected for centuries. Wind often interacts synergistically with human disturbances (e.g., clearcut logging) to increase timber blowdown, especially along the edges of clearcuts (Sinton et al. 2000), power lines (Ruel and Pin 1993), and riparian buffer strips (Hairston-Strang and Adams 1998, Ruel et al. 2001).

Small-scale wind disturbances create gaps in forest canopies through stem snap and uprooting of individual trees. Ott (1997) found that 76 percent of gaps created by wind in southeast Alaska forests were the result of stem snap, usually involving one to three trees. Gaps created had a median size of 35 to 55 m^2. Heart rot contributed to stem snap by weakening or killing trees in old-growth forests (Hennon 1995). Although little research has been done on gap dynamics in riparian buffer strips, it seems reasonable to assume that both stem snap of weakened trees and uprooting of healthy trees from saturated soils are normal disturbance processes in riparian ecosystems. Gaps created by wind in riparian zones contribute large woody debris to aquatic habitats, but probably have minimal effects on summer and winter water temperatures, energy inputs, or nutrient cycling.

Catastrophic blowdown events that affect large areas of the landscape occur infrequently in the Pacific Northwest and southeast Alaska, but they can have major ecological effects. In a review of historical windstorms in Oregon, the National Weather Service (2000), listed 13 major events between 1880 and 1995 (table 4), an average of more than one per decade. A retrospective analysis of windthrow on northeast Chichagof Island in southeast Alaska indicated that between 1710 and 1996, significant windthrow events occurred in 16 of the 30 decades covered by the study (Nowacki and Kramer 1998). The frequency of major windstorms prevented

Table 4—Historical windstorms in Oregon that caused major windthrow of timber resources

Date	Location	Prevailing wind	Maximum speed
			Kilometers per hour
01/09/1880	Western	South	130
01/20/1921	Western	Southwest	210
04/21-22/1931	Northern	Northeast	125
11/10-11/1951	Statewide	Southwest	130
12/04/1951	Western	Southwest	160
12/21-23/1955	Statewide	Southwest	145
11/03/1958	Western	Southwest	120
10/12/1962	Statewide	Southwest	220
03/27/1963	Western	Southwest	160
10/02/1967	West, northeast	Southwest	185
03/25-26/1971	Statewide	Southwest	135
11/13-14/1981	Statewide	South	160
12/12/1995	Western	Southwest	190

the establishment of old-growth timber stands on mountainous terrain exposed to prevailing southeast storms. In this geographic area, valley bottoms and riparian areas were the least frequently disturbed locations.

Stand resetting events of this type can improve timber site productivity through tree uprooting that churns soils, increasing permeability and nutrient cycling (Bormann et al. 1995), but the effects on riparian and aquatic habitats are mixed. Long reaches of riparian timber in undisturbed stands and in buffer strips adjacent to clearcuts can be blown into streams, increasing woody structure for aquatic organisms (Bisson et al. 1987, Swanson and Lienkaemper 1978). But the resulting loss of streamside canopy can change water temperature (Beschta et al. 1987), energy inputs (Hicks et al. 1991, Murphy and Hall 1981), and nutrient cycling in affected riparian areas for at least several years (Bormann et al. 1995).

Certain areas of the landscape are more vulnerable to windthrow than others. Harris (1989) and Kramer (1997) found blowdown in southeast Alaska concentrated on hilltops and ridge noses on south-facing slopes directly exposed to prevailing southeast storms, and on east- and west-facing slopes where winds accelerate as they bend around mountain flanks. Sinton et al. (2000) found that windthrow in the Bull Run watershed of Oregon, prior to timber harvest in the watershed, was confined primarily to topographic features exposed to prevailing east and northeast gales from the Columbia Gorge. Timber in wide valleys with gentle side slopes is also vulnerable to windthrow (Nowacki and Kramer 1998, Ruel et al. 2001), especially when prevailing winds flow parallel to the long axis of valleys (National Weather Service 2000). In the latter case, riparian timber in open valleys running parallel to prevailing storm tracks may be vulnerable to periodic windthrow.

Ice and snowstorms—

Ice, snowstorms, and ice formation and transport in streams of southeast Alaska, as well as at high elevation across the Pacific Northwest, are normal annual events. However, ice formation in streams during unusually cold weather, and abnormally severe ice and snowstorms, can have infrequent but significant effects on riparian and aquatic habitats. The most common effects of ice and snowstorms, or ice flows in streams are:

- Ice gouging of streambed, banks, and destruction of near-stream riparian vegetation.
- Stream damming, flooding, and scour of riparian vegetation.
- Transport of sediment attached to anchor ice.
- Limbing, stem snap, and felling of riparian trees because of weight of ice formation from freezing rain.
- Increased woody debris in streams and redistribution of woody debris.

Severe ice and snow damage to riparian vegetation usually occurs at the local or subregional scale and at infrequent intervals.

At least two notable events occurred in the Pacific Northwest in the 20th century (National Weather Service 1999a, 1999b). Western Washington received the maximum snowfalls on record in January and February of 1916. Areas around Puget Sound received up to 1.2 m of snow, and winds created snowdrifts in excess of 1.5 m. Trees across the area, even at sea level, were felled and damaged by accumulations of heavy wet snow. Another record snowstorm occurred in 1950, affecting western Oregon, the Columbia Gorge, and southwestern Washington. Heavy snow, followed by sleet and freezing rain severely damaged riparian and upland vegetation across the area. Events of this type occur a few times per century at the scale of the Pacific Northwest, but recurrence at a given location may take centuries to millennia.

Insects and disease—
Forests of the Pacific Northwest and southeast Alaska are subject to chronic and episodic mortality from insects and disease. Damage from boring and defoliating insects is usually episodic and can weaken or kill trees across tens of thousands of hectares in a single outbreak. Forests under stress from drought or other climatic factors are most vulnerable to attack. Disease kills fewer trees (USDA Forest Service 1977) than do insects, but root rots and heart rots occur frequently enough in old forests to contribute to mortality and increase the vulnerability of individual trees to windthrow.

Insect and disease outbreaks may affect riparian and aquatic habitats in the following ways:

- Decreased litterfall
- Increased large woody debris in channels
- Loss of shade (elevated stream temperatures)
- Shift from allochthonous (instream) to autochthonous (offstream) energy sources in small streams

The effects, even of episodic outbreaks, are usually of short duration and widely scattered in time and space. Several outbreaks of spruce budworm and Douglas-fir tussock moth occurred in the Northwest in the 20th century (Mason et al. 1998, Stipe 1987, Stoszek and Mica 1978). The effects on riparian zones are poorly documented, and were probably minimal at all scales.

Summary of Natural Disturbances

We have discussed natural disturbances and their effects on riparian and aquatic habitats as individual phenomena, but at the regional scale, these events operate simultaneously. In any given year, a combination of fire, floods, wind, unusual storms, mass erosion, ice, insects, and disease are likely to affect portions of some watersheds in the Pacific Northwest and southeast Alaska. At the landscape scale, however, there is likely to be a natural spatial and temporal heterogeneity of disturbances among watersheds.

Some events can occur sequentially and operate synergistically. For example, some of the greatest changes in riparian and aquatic systems in mountainous areas of the Northwest occur when wildfire is followed by intense winter storms that trigger floods, surface erosion, slope failures, and widespread mass erosion events (Benda et al. 1998). The synergistic combination of tree diseases, saturated soils

Natural disturbances historically affected relatively small areas of the landscape at any given time (e.g., subwatershed scale), although their cumulative effects can be important processes in ecosystem change and renewal.

from intense precipitation, and windstorms can also magnify the effects of natural disturbances on riparian and aquatic habitats in southeast Alaska (Nowacki and Kramer 1998).

Considered together at the regional scale, natural disturbances historically affected relatively small areas of the landscape at any given time (e.g., subwatershed scale), although their cumulative effects can be important processes in ecosystem change and renewal. These events may remove riparian stands at the site to subwatershed scales, replenish large woody debris and sediments in stream channels, and cause riparian and aquatic species to wax and wane in response (Reeves et al. 1995). The recurrence intervals of disturbances at a given location, however, are often measured in centuries or millennia.

Cumulative effects of natural disturbances can control the vegetative structure of the landscape. For example, a study modeling the fire history in western Oregon (Wimberly et al. 2000) indicated that over the past 3,000 years, a shifting mosaic of late-successional forests in the Coast Range historically occupied between about 49 and 91 percent of the landscape at the province scale. One can assume that riparian zones in the region had at least a similar proportion of late-successional forest, and probably more because trees in normally damp riparian habitats were less subject to fire mortality than timber on dry upper slopes (Agee 1993). Based on this study, a shifting pattern of 49 to 91 percent late-successional forest could be considered the normal range to which riparian, terrestrial, and aquatic species in the Coast Range have adapted in at least the past three millennia. Regional shifts in abundance of late-successional forest habitats outside this range could increase the risk of extinction of some species, or cause changes in the community structure of indigenous biota.

Moderate site-specific disturbances can lead to temporary shifts in community structure during the process of habitat renewal. Severe environmental changes at a site scale can lead to extirpation of species, but since natural disturbances are usually limited in time and space, populations in adjacent undisturbed habitats are able to quickly recolonize affected areas as habitats return to predisturbance conditions (Reeves et al. 1995).

In summary, we emphasize again that the effects of natural disturbances (pre-European settlement) are not only scale-related, but represent the baseline against which human disturbances (by European settlers), and the cumulative effects of natural and human disturbances, are measured and evaluated. Although the pulse of natural disturbances can cause severe changes in riparian and aquatic ecosystems at site scales, the effects are less severe at regional scales. At the scale of the

Northwest, the mosaic of natural events is integrated into the structure and function of regional ecosystems and represents the disturbance regime to which indigenous species historically adapted.

Human disturbances in watersheds of the Pacific Northwest and southeast Alaska are often profoundly different in temporal and spatial distribution than natural disturbances.

Human Disturbances

Human disturbances in watersheds of the Pacific Northwest and southeast Alaska are often profoundly different in temporal and spatial distribution than natural disturbances. Disturbances from a complex array of human actions generally tend to fit the press disturbance category, because they occur more frequently in time and space, affect larger areas of the landscape, and leave different legacies, and many are more permanent than natural disturbances (Ebersole et al. 1997, Reeves et al. 1995). Most human disturbances that affect riparian ecosystems are related primarily to land use activities such as agriculture, forestry, urbanization, and dams and reservoirs that store and use water resources for a variety of purposes. These activities, which can have universal effects on riparian vegetation in watersheds, are exacerbated by increasing human populations in the Northwest and, to a lesser degree, in southeast Alaska.

Human populations are increasing rapidly in Oregon, Washington, and Idaho. Oregon and Washington were the 10th and 7th fastest growing states, respectively, in the Nation in the 1990s, and census projections indicate that the populations of all three states will grow between 31 and 43 percent in the next quarter century (U.S. Bureau of the Census 1997). The projected increase in population, from both internal growth and immigration, will place additional demands on the region's natural resources in the near future. Although human populations are increasing more slowly in southeast Alaska, growing populations of the Nation and world also will place additional demands on Alaska resources. Without some moderation of population growth, human disturbances on the landscape are likely to accelerate and further alter riparian and aquatic habitats of the regions.

Dams and reservoirs—

Dams and reservoirs located on rivers and streams in the Pacific Northwest have caused persistent alterations of thousands of kilometers of riparian habitats. About 2,050 dams at least 3 m in height and storing at least 12 300 m of water were built in Oregon and Washington by the end of the 20th century (ASDSO 2006, Washington State Department of Ecology 2003). Most of the dams and the preponderance of storage capacity were developed after 1940 (fig. 5). Low-cost hydropower has facilitated many aspects of regional development, but the generating

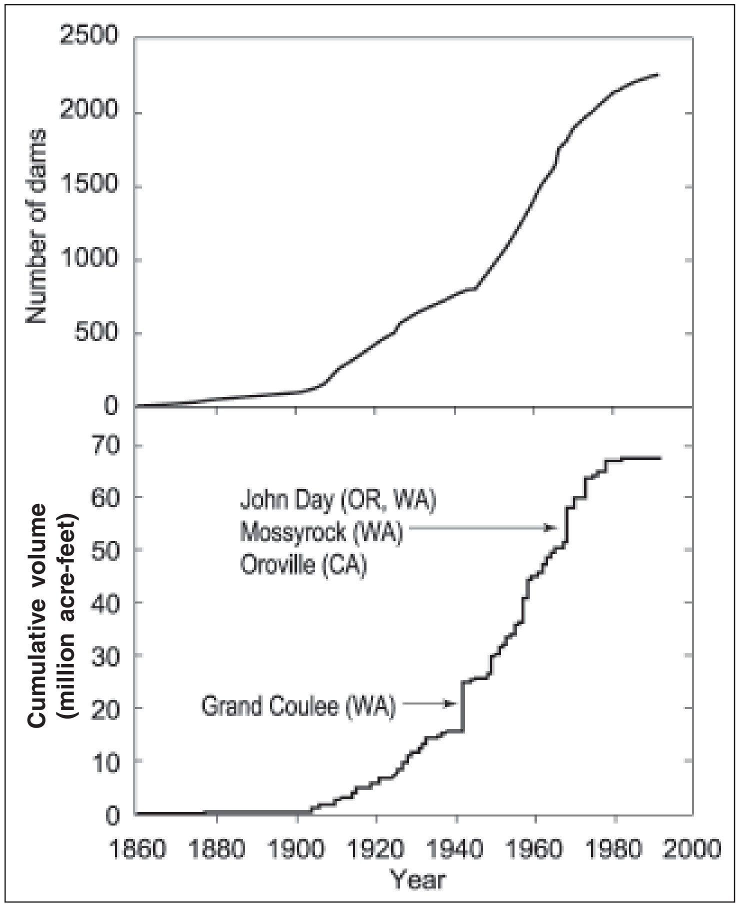


Figure 5—Cumulative number of federal and nonfederal dams (a), and cumulative volume of storage (b), in the Pacific Northwest (Idaho, Oregon, Washington, and northern California) from 1860 to 1990 (from Lee et al. 1997).

facilities have substantially changed the natural physical and ecological characteristics, including the riparian ecosystems, of the rivers on which they occur.

Reservoirs impounded by the dams inundate and destroy riparian habitats that formerly bordered streams within reservoir boundaries. New riparian systems, often with different characteristics, may develop along reservoir shorelines, but fluctuating reservoir levels may prevent re-establishment of riparian ecosystems. Reservoirs also tend to delay the downstream movement of storm flows and thus reduce both the height and duration of peak flow for a given storm (Ziemer and Lisle 1998). Riparian communities bordering downstream waters may respond by changing community structure, density, and proximity to stream channels. Many major river systems in western Oregon and Washington are notably affected by reservoir storage (e.g., the Rogue, Willamette, Santiam, Lewis, and Skagit Rivers).

A unique class of dams called "splash dams" facilitated log drives on Pacific Northwest streams in the 1870 to 1920 period (Sedell et al. 1991). Use of splash dams for log transportation was extensive in western Washington and Oregon at the turn of the 20th century. Over 150 such dams existed in coastal Washington rivers, and over 160 splash dams were used on coastal streams and Columbia River tributaries in Oregon (Sedell et al. 1991). Boulders and woody debris were removed from channels of these streams for decades to facilitate downstream movement of logs. The frequent, near-instantaneous release of water (man-made flash floods) to transport logs resulted in scour and removal of near-stream riparian vegetation and persistent simplification of channel structure along thousands of kilometers of streams in the Northwest. Man-made "flash floods" of this type and frequency have no natural analogs. The greatest effects occurred in small and mid-sized basins. Splash dams altered riparian ecosystems and stream and river channels to the extent that they have not yet returned to predisturbance conditions in many systems (Sedell et al. 1991). But, unlike storage reservoirs and run-of-the-river hydropower generating facilities, the effects of splash dams are less persistent, although long recovery times from splash dam disturbances may be required.

Splash dams altered riparian ecosystems and stream and river channels to the extent that they have not yet returned to predisturbance conditions in many systems.

Agriculture—
Agriculture has also made major persistent changes in riparian and aquatic habitats in the Pacific Northwest (see bibliography, Bolton and Monohan 2001, that contains more than 2,000 literature citations). Agricultural activity in western valleys and on historical flood plains has modified native vegetation and the physical drainage features of the landscape on many major rivers. Agriculture has caused loss of native vegetation and large woody debris, streambank instability, and loss of flood-plain function (Spence et al. 1996); altered flow regimes; increased sedimentation; increased water temperature; changed nutrient supply (Rinella and Janet 1998, Wentz et al. 1998); increased chemical pollution (Rienhold and Witt 1992, Wentz et al. 1998); modified and consolidated stream channels (Sedell and Froggatt 1984); and simplified aquatic and riparian habitats (Spence et al. 1996).

Riparian and aquatic habitats are more highly altered in urban landscapes than in any other land use types in the Pacific Northwest.

Urbanization—
Urban areas, although affecting only about 2 percent of the Northwest landscape (Pease 1993), are usually located along major waterways, at the confluence of rivers, or on estuaries (Gregory and Bisson 1997). Riparian and aquatic habitats are more highly altered in urban landscapes than in any other land use types in the Pacific Northwest, and streams within urban areas are more degraded than in

agricultural, range, or forest lands (Booth 1991). Stream channels and riparian habitats within urban areas are often altered to facilitate flood control and rapid routing of water away from developed areas. Small streams are often consolidated and piped through cities, and larger streams are realigned and confined to concrete-lined channels.

Urban areas have expanded in the late 20th century into lowland forests and agricultural lands to accommodate the growing population of the Northwest. Consequently, some privately owned forest lands, and their associated streams and riparian habitats, have been converted to urban lands (Kline and Alig 2001). Nationwide, urban and developed areas expanded by more than 285 percent between 1945 and 1992 (USDA Economic Research Service 1995). Forests, the largest source of land for development in the Northwest, can be converted to urban areas or fragmented by land developments (Alig et al. 2000). The human population of the Pacific Northwest is projected to increase by approximately 4 million people by 2050, resulting in further reductions in private forest areas and more than a 20-percent increase in urban areas (Kline and Alig 2001), with commensurate changes in riparian, aquatic, and terrestrial habitats.

Timber harvest and roads—

Timber harvest and roads have made extensive changes in watershed hydrology and riparian vegetation (Jones et al. 2000) and aquatic communities (Trombulak and Frissell 2000) in the Pacific Northwest and, to a lesser degree, in southeast Alaska. In the past four decades, commercial timber has been removed from thousands of kilometers of riparian zones by clearcutting and selective harvesting, resulting in long-term changes in the structure and function of riparian ecosystems. The National Forest System alone contains about 200 000 km of roads in upland and riparian ecosystems in Oregon and Washington and about 8000 km in Alaska (Coghlan and Sowa 1998). Roads were built in and along flood plains and through riparian zones of many fish-bearing streams to provide access for timber harvest operations and other purposes (Oakley et al. 1985). Construction and maintenance of roads altered riparian function over much of the area with long-lasting effects on riparian zones (Thomas et al. 1979).

Timber harvest has changed riparian vegetation in at least two ways. First, harvest of commercial timber on private, state, and federal lands was conducted near streams until the enactment of forest practices acts in the 1970s. Although vegetated buffer strips of variable configurations have been left along most perennial fish-bearing streams since that time, riparian timber beyond designated buffer strips was often clearcut along with upslope stands and the logging slash burned before reforestation of the area. Second, even within buffer strips that were left along perennial streams, some or most commercial timber was regularly removed by selective harvest techniques. The result was widespread thinning in near-stream forest canopies, loss of large standing timber near streams, and disturbance of litter, soil, and hydrologic function in riparian habitats. Changes in riparian zones from these sources rapidly translated to changes in aquatic ecosystems. Major changes to aquatic systems resulting from alteration of riparian habitats include:

- Increased stream temperatures in summer and increased or reduced stream temperatures in winter depending on geographic location.
- Changes in stream energy sources: reduced particulate organic inputs and increased solar radiation in streams.
- Increased sedimentation.
- Reduced streambank and stream channel stability.
- Long-term reduction in large woody debris.

Many of these changes degraded habitats for aquatic and riparian-dependent species and contributed to Endangered Species Act (ESA) listings of salmonid populations and other organisms.

Water temperature—

Loss of riparian vegetation through a variety of land management activities (principally timber harvest and roads in western Oregon and Washington) allows more solar radiation to reach stream surfaces in summer, increasing water temperature and light available for photosynthesis (Brown and Krygier 1971). Loss of forest canopy can also increase winter temperatures in low-elevation coastal drainages (Beschta et al. 1987), but in northern latitudes and at higher elevations, a reduction in winter temperatures may occur owing to loss of vegetative insulation and an increase in radiative cooling of stream waters (Hicks et al. 1991).

Significant biological consequences may result from moderate alteration of water temperature that results from disturbance of riparian areas.

Significant biological consequences may result from moderate alteration of water temperature that results from disturbance of riparian areas. Changes in water temperature can alter the structure and composition of fish communities by changing the outcome of interaction among potential competitors (Baltz et al. 1987, Dambacher 1991, Hillman 1991, Reeves et al. 1987). Changes in the temperature of surface waters can also affect the temperature and biota of hyporheic zones (NRC 1999). Hyporheic zones and their biota, because of their subsurface location, are naturally resistant to environmental change and are therefore rather nonresilient when changes do occur. Disturbances that cause changes in water quality within hyporheic zones may affect bioproduction and threaten endemic groundwater biota within the channels of gravel-bed streams (Notenboom et al. 1994) and alter the distribution and abundance of riparian vegetation throughout river corridors (Stanford and Ward 1993). Elevated temperatures can also affect migration timing and patterns of fish and exacerbate outbreaks of disease (Spence et al. 1996).

Elevated water temperatures first caused concerns about timber harvesting near forest streams in the 1960s and 1970s, and passage of the federal Clean Water Act in 1977 resulted in revised forest practice rules designed to maintain or restore stream temperatures to prelogging levels. Current forest practice rules throughout the Northwest contain regulations for maintenance of water quality, including water temperature. Nevertheless, elevated water temperatures resulting from logging remain in some watersheds. For example, elevated water temperature is listed as the primary source of impairment in national forest lands listed in Oregon's 303(d) impaired water bodies under the Clean Water Act. (Lee et al. 1997).

Stream energy sources—
Timber harvest and other alterations in riparian vegetation can alter the energy dynamics of small streams. Removing the vegetative canopy over streams can shift heterotrophic systems driven by inputs of organic litter to autotrophic systems whose primary energy source is sunlight (Allan 1995). Such changes can also shift the peak time of energy input from fall for heterotrophic systems to summer for autotrophic systems (Schlosser and Karr 1981). Changes in riparian vegetation not only reduce the source of organic litter that can provide 75 percent or more of the organic food base in small streams, but also reduce the capacity of riparian zones to retain nutrients for slow release to streams (Welsch 1991). Changes in energy dynamics can affect salmonid food supplies by reducing input of terrestrial insects from forest canopies and altering the structure of aquatic insect communities within channels (Wipfli and Gregovich 2002).

Small non-fish-bearing streams can also be important sources of energy for fish.

Small non-fish-bearing streams can also be important sources of energy for fish. Recent work by Wipfli and Gregovich (2002) estimated that a small, headwater stream in southeast Alaska exported enough macroinvertebrates and detritus to support 100 to 2,000 young-of-the-year salmonids per kilometer in fish-bearing streams. Modification of vegetation along these small streams by timber harvest can alter this pathway. Altering riparian forest canopy will reduce input of detritus and organisms from outside the channel and likely increase primary production (Wipfli and Gregovich 2002). The extent of change depends, in part, on the degree to which the vegetation is altered. Complete removal could decrease productivity by shifting to predominately primary production. Intermediate levels of vegetation removal may elevate headwater productivity and downstream transport of materials because of increased amounts of solar radiation reaching the streams while there continues to be the input of materials from remaining trees and understory vegetation (Wipfli and Gregovich 2002). The latter result is dependent on the extent to which physical conditions remain intact.

Sediment inputs from roads—

Interactions between roads, riparian health, and sedimentation are strongly linked throughout the Pacific Northwest and southeast Alaska. Road densities in managed forests average about 1.15 km/km^2 and 0.12 km/km^2, in the Northwest and southeast Alaska, respectively. Forest roads affect the health of riparian ecosystems in two primary ways. First, roads frequently represent the primary source of accelerated sediment production from human activities in steep forested watersheds (Haupt 1959, Reid and Dunne 1984, Swanston and Swanson 1976). Roads are responsible for large increases in both surface erosion and mass erosion (Furniss et al. 1991) that both affect, and are affected by, riparian vegetation. In western Oregon, roads in mid- to upper-slope areas of watersheds were found to accelerate debris torrents by factors of 30 to 300 times that observed in undisturbed forest (Morrison 1975, Sidle et al. 1985, Swanston and Swanson 1976).

Large volumes of sediment also are delivered to streams from surface erosion. Surface erosion originates from unpaved road surfaces, drainage ditches, and cut and fill surfaces, regardless of their locations in watersheds (Brown and Krygier 1971, Burns 1972, Larse 1971, Weaver et al. 1987). Sediments from surface erosion traverse riparian zones enroute to receiving channels. Intact riparian vegetation may capture and store large portions of the sediment, but riparian vegetation disturbed by roads, logging, or other activities may allow most of the sediment to pass through to stream channels where it affects the health of stream biota and compromises the quality of salmonid spawning habitats (Everest et al. 1987).

Second, roads parallel streams in many forested river valleys on public and private land (Oakley et al. 1985), encroaching on stream channels (Everest et al. 1985) and occupying portions of the former sites of riparian gallery forests (Furniss et al. 1991). Encroachment and loss of riparian vegetation in areas occupied by roads causes persistent changes in the character and function of riparian areas and corresponding changes in the productivity of associated aquatic habitats.

Roads in riparian areas become sediment sources in areas that were sediment sinks in their undisturbed states. Road encroachment on riparian zones and stream channels is so common and so persistent in the United States that some forest practice guidelines increase the prescribed width of riparian buffers by the width of riparian habitats occupied by roads (U.S. Army Corps of Engineers 1991).

The sediment entering stream channels from mass erosion (slumps and earthflows, debris avalanches, debris flows, and debris torrents) affects riparian vegetation in several ways. Earthflows and landslides may remove all riparian vegetation at their points of entry into stream channels. Debris flows and torrents may also scour all riparian vegetation from the banks of small delivery streams and also for some distance downstream in the larger receiving channels (Swanston 1991). The pulse of sediment entering streams can cause channel scour, long-term instability, and loss of riparian vegetation through scour and sediment deposition (Sullivan et al. 1987).

Riparian vegetation can mitigate the effects of mass erosion if the events are not overwhelmingly large. Sediment from small mass erosion events may be trapped and stored in riparian zones (Welsch 1991), and large woody debris transported by mass erosion and deposited in channels may help protect streambanks and channel and habitat complexity and accelerate sediment processing from affected areas (Bisson et al 1987).

Historical timber harvest, salvage of windthrown timber from stream channels, road construction, and water transportation of logs in forested watersheds has decreased standing timber in riparian zones and large woody debris in stream channels throughout the Northwest and in parts of southeast Alaska.

Woody debris—

Historical timber harvest, salvage of windthrown timber from stream channels, road construction, and water transportation of logs in forested watersheds has decreased standing timber in riparian zones and large woody debris in stream channels throughout the Northwest and in parts of southeast Alaska. Windthrow and subsequent salvage of riparian timber is one area where synergism occurs between natural wind disturbance and logging. Logging of timber stands, especially clearcutting, creates openings in large contiguous blocks of timber and enhances the potential for windthrow along exposed edges. In an analysis of windthrow in the Bull Run watershed in Oregon, Sinton et al. (2000) reported that 10 percent of the basin had been affected by windthrow since 1890, but only 2 percent was affected prior to forest harvest in 1958. A strong windstorm in 1983 caused extensive blowdown in the basin, and 80 percent of windthrown trees came from recently exposed clearcut edges. Ruel et al. (2001) also noted that high levels of windthrow were associated with riparian buffers in wide valleys where winds blew perpendicular to the long axis of the valley. Wherever narrow buffer strips of riparian timber are left to protect aquatic habitats, the exposed edges of the buffers are vulnerable to accelerated windthrow. Windthrow adds woody debris to stream channels, but historical salvage operations quickly removed most of the large material. Today, windthrown timber is often left in stream channels for fish habitat, although simplified stream channels resulting from the historical salvage of riparian windthrow remain widely distributed across the landscape of the Pacific Northwest.

Current amounts of large woody debris in coastal streams of Oregon and Washington are a fraction of historical levels (Bilby and Ward 1991, Bisson et al. 1987, NRC 1992). Much of the loss is the result of timber harvest that predates the establishment of forest practices acts and federal regulations regarding timber harvest. Additional losses resulted from stream cleaning policies of the 1970s and 1980s when large woody debris was intentionally removed from channels to protect capital investments (e.g., bridges) and improve fish habitat. Stream surveys by private timber companies and federal land management agencies in the Northwest reveal an overall loss of stream habitat quality (FEMAT 1993, Kaczynski and Palmisano 1993, Wissmar et al. 1994) that is strongly related to changes in riparian vegetation, especially harvest of merchantable riparian timber. For example, the Bureau of Land Management (BLM) estimated that 65 percent of riparian areas on their lands in Oregon and Washington did not meet management objectives in the late 1980s (USDI Bureau of Land Management 1991).

Reductions in large standing timber in riparian zones and large woody debris in streams have:

- Changed channel hydraulics and morphology by reducing roughness elements in streams (Bisson and Sedell 1984, Martin et al. 1998), consolidating channels (Sedell and Froggatt 1984), increasing stream gradients (Bilby 1979), decreasing channel stability (Bilby 1984), and generally accelerating streamflows.
- Simplified aquatic habitats by reducing pools, side channels, and resting and hiding cover for aquatic species (Cherry and Beschta 1989, Reeves et al. 1993).
- Reduced the retention time of organic matter and inorganic sediments in stream channels (Sedell et al. 1988).

Most of these changes have reduced the quality and productivity of rearing and spawning habitats for salmonids and other aquatic species. The changes are likely to persist for a century or more until riparian conifers grow to sufficient size to again provide large woody debris recruitment to streams.

Human disturbances in river basins of the Pacific Northwest and southeast Alaska occur more frequently in time and space and often are more persistent than natural disturbances.

Summary of Human Disturbances

Human disturbances in river basins of the Pacific Northwest and southeast Alaska occur more frequently in time and space and often are more persistent than natural disturbances. Dams, reservoirs, agriculture, and urban areas have caused extensive long-term changes in the structure and function of riparian systems and the species that depend upon them (Everest et al. 2004). Thousands of kilometers of riparian and aquatic habitats on major rivers have been converted to slack-water reservoirs, meandering and braided streams in river valleys have been consolidated into single, realigned channels with loss of riparian and side channel aquatic habitats (NRC 1996), and riparian forests in many valleys have been cleared to provide arable land for agriculture (Miller et al. 1999).

Timber harvest and associated roads, typically press disturbances as applied in the Northwest, have reduced late-successional forests in the Oregon Coast Range province by more than 80 percent from the historical preharvesting average (Wimberly et al. 2000). Smaller changes have occurred in southeast Alaska where about 2.5 percent of late-successional forest has been harvested in the last century (Everest et al. 1997). Timber on some portions of the Northwest landscape, especially on private lands on the Olympic Peninsula and in the Puget Sound area, has been harvested two or three times in the past 150 years. Timber rotation age commonly ranges from 40 to 60 years over most of the private forest lands in the region, and between 100 and 200 years on the federal landscape. Although only about 20 percent of federal forest lands within the area of the NWFP in Oregon and Washington are currently dedicated to timber production, the overall rate of harvest for the region still assures that forest succession over more than half of the forested landscape will be reinitiated at least once a century. Such frequent cutting over large areas can prevent development of ecologically important seral stages, such as late-successional and old-growth timber stands (Hall et al. 1985).

As previously noted, Wimberly et al. (2000) reported that late-successional forests (ages 80 to 200 years) in the Oregon Coast Range historically occupied between about 49 and 91 percent of the landscape at the provincial scale (fig. 6). Following decades of intensive timber harvest in the Coast Range, the remaining late-successional forest currently totals about 11 percent—well outside the historical range. One would also expect that 11 percent or less of riparian habitats in the region retain late-successional characteristics, because for decades large timber was removed from most riparian areas when upslope harvest units were cut. The change

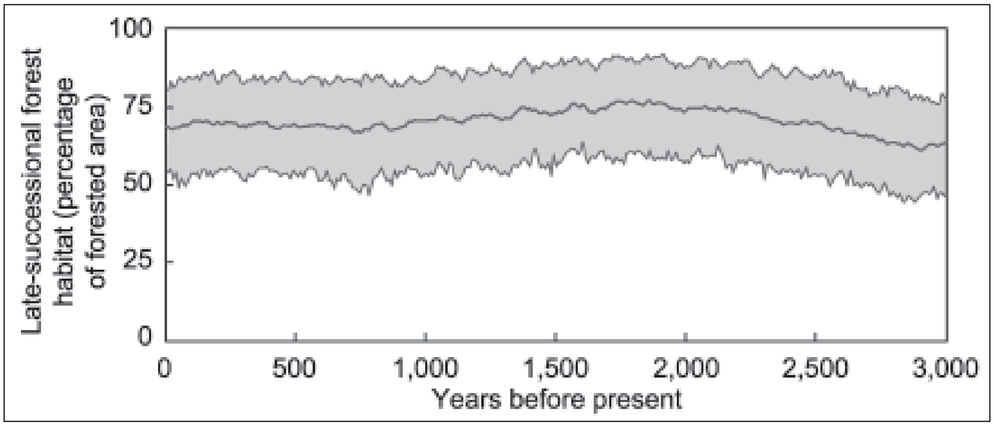


Figure 6—Simulated historical abundance of late-successional forest habitat in the Oregon Coast Range over the past 3,000 years. Heavy line represents the mean, and thinner lines are 95-percent confidence intervals. The current level is about 11 percent—well outside the historical range (from Wimberly et al. 2000).

Effects of forestry are potentially less persistent than dams, agriculture, and urbanization.

in the distribution and abundance of late-successional forest may reduce the potential for upland and riparian-dependent biota to recover unless riparian restoration is rapidly accomplished.

The effects of forestry are potentially less persistent than dams, agriculture, and urbanization. Ecological effects of forestry can be changed through laws, regulations, and silvicultural practices, and reversed through watershed restoration (Williams et al. 1997) and rehabilitation of altered habitats (Reeves et al. 1991) perhaps more easily than many other human disturbances. For example, urbanization and agriculture often cause major modifications of the extent and composition of riparian vegetation, and extensive alterations of stream channels. The altered riparian ecosystems bear little resemblance in either composition or behavior to the natural ecosystems they replaced. Because of concerns about economics and safety, there is little room to allow the altered ecosystems to revert to their unaltered state. Timber harvest, on the other hand, is a periodic disturbance and therefore has greater flexibility to allow riparian systems to be dynamic and to recover predisturbance conditions.

The spatial and temporal distribution of human disturbances in the landscapes of the Northwest and southeast Alaska, coupled with existing natural disturbance regimes, have significantly altered the structure and function of riparian and freshwater ecosystems in the two regions. Industrial forestry is only one contributor to human disturbance regimes, and one that is being addressed by forest practices acts and other laws and regulations. Other human disturbances are also being addressed at various intensities. The frequency and persistence of human disturbances in the Northwest have contributed to the extinction of more than 100 stocks of anadromous salmonids in the past century (Nehlson et al. 1991) and the listing of at least 47 other aquatic species (US FWS 2000) (table 5). Many species that were able to adapt to natural disturbances have been unable to cope with the combined disturbance regimes of human actions and natural events. These consequences of landscape disturbances are likely to be exacerbated in the future by increasing human populations in the Northwest, and to a lesser degree, in southeast Alaska.

The goal of the revised forest practices is to restore and maintain riparian and aquatic communities and still allow timber harvest and active management to achieve other goals and other uses.

Forest practice rules and regulations attempt to mitigate the consequences of disturbances caused by the effects of timber harvest, grazing, and roads, and maintain natural ecosystem functions within a fundamentally changed landscape. Practices related to timber harvest have evolved from simple site-specific rules in the 1970s to complex actions that currently address disturbance at more ecosystem-level and landscape-scale perspectives than ever before (see below). The goal of the revised forest practices is to restore and maintain riparian and aquatic communities and still allow timber harvest and active management to achieve other goals and other uses (e.g., second-growth thinning to reduce fire risk, improve wildlife habitat, and accelerate old-growth development, and improve recreation opportunities).

Evolution of Riparian Management in Oregon, Washington, and Southeast Alaska

Loss of habitat quality on forest lands coupled with land use changes on nonforested lands and other factors such as commercial fishing, contributed to the eventual ESA listing of many economically important stocks of fish and other aquatic species.

As timber harvest in the federal, state, and private forest lands of the West accelerated after World War II, the primary focus of forest managers was on harvesting high-volume stands of old-growth timber in the most economical ways. Environmental concerns associated with timber extraction, the value of forested landscapes for recreation activities, and even reforestation of cutover lands, were often not recognized. Sedimentation, increased stream temperatures, loss of riparian vegetation, and degradation of aquatic habitat quality were widely documented across forested landscapes of the Pacific Northwest (e.g., Gibbons and Salo 1973, Gregory and Bisson 1997, Hartman and Scrivener 1990, Iwamoto et al. 1978, Karr and Schlosser 1977, Krygier and Hall 1971, Meehan 1991, Naiman 1992, Peterson et al. 1992, Raedeke 1988, Salo and Cundy 1987). Loss of habitat quality on forest lands coupled with land use changes on nonforested lands and other factors such as commercial fishing, contributed to the eventual ESA listing of many economically

Table 5—Threatened (T) and endangered (E) aquatic animals in the Pacific Northwest

Status	Common name	Scientific name
Idaho:		
E	Banbury Springs limpet	*Lanx* sp.
E	Bliss Rapids snail	*Taylorconcha serpenticola*
E	Bruneau Hot Springs springsnail	*Pyrgulopsis bruneauensis*
T	Bull trout (U.S. conterminous 48 states)	*Salvelinus confluentus*
T	Chinook salmon (fall Snake R.)	*Oncorhynchus tshawytscha*
T	Chinook salmon (spring/summer Snake R.)	*Oncorhynchus tshawytscha*
E	Idaho springsnail	*Fontelicella idahoensis*
T	Snake River Basin steelhead	*Oncorhynchus mykiss*
E	Snake River snail *(physa)*	*Physa natricina*
T	Sockeye salmon (Snake R.)	*Oncorhynchus nerka*
E	Utah snail *(valvata)*	*Valvata utahensis*
E	White sturgeon	*Acipenser transmontanus*
Oregon:		
E	Borax Lake chub	*Gila boraxobius*
T	Bull trout (U.S. conterminous 48 states)	*Salvelinus confluentus*
T	Chinook salmon (fall Snake R.)	*Oncorhynchus tshawytscha*
T	Chinook salmon (lower Columbia R.)	*Oncorhynchus tshawytscha*
T	Chinook salmon (spring/summer Snake R.)	*Oncorhynchus tshawytscha*
T	Chinook salmon (upper Willamette R.)	*Oncorhynchus tshawytscha*
T	Chum salmon (Columbia R.)	*Oncorhynchus keta*
T	Coho salmon (OR, CA pop.)	*Oncorhynchus kisutch*
T	Foskett speckled dace (Foskett)	*Rhinichthys osculus* ssp.
T	Hutton tui chub (Hutton)	*Gila bicolor* ssp.
T	Lahontan cutthroat trout	*Oncorhynchus clarki henshawi*
E	Lost River sucker	*Deltistes luxatus*
E	Oregon chub	*Oregonichthys crameri*
E	Shortnose sucker	*Chasmistes brevirostris*
E	Sockeye salmon (Snake R.)	*Oncorhynchus nerka*
T	Steelhead (lower Columbia R.)	*Oncorhynchus mykiss*
T	Steelhead (middle Columbia R.)	*Oncorhynchus mykiss*
T	Steelhead (Snake R. basin)	*Oncorhynchus mykiss*
T	Steelhead (upper Willamette R.)	*Oncorhynchus mykiss*
T	Vernal pool fairy shrimp	*Branchinecta lynchi*
E	Warner sucker	*Catostomus warnerensis*

Table 5—Threatened (T) and endangered (E) aquatic animals in the Pacific Northwest (continued)

Status	Common name	Scientific name
Washington:		
T	Bull trout (U.S. conterminous 48 states)	*Salvelinus confluentus*
T	Chinook salmon (fall Snake R.)	*Oncorhynchus tshawytscha*
T	Chinook salmon (lower Columbia R.)	*Oncorhynchus tshawytscha*
T	Chinook salmon (Puget Sound)	*Oncorhynchus tshawytscha*
T	Chinook salmon (spring/summer Snake R.)	*Oncorhynchus tshawytscha*
T	Chinook salmon (spring upper Columbia R.)	*Oncorhynchus tshawytscha*
T	Chum salmon (Columbia R.)	*Oncorhynchus keta*
T	Chum salmon (summer run Hood Canal)	*Oncorhynchus keta*
T	Sockeye salmon (Ozette Lake and tribs.)	*Oncorhynchus nerka*
E	Sockeye salmon (Snake R.)	*Oncorhynchus nerka*
T	Steelhead (lower Columbia R.)	*Oncorhynchus mykiss*
T	Steelhead (Snake R. basin)	*Oncorhynchus mykiss*
E	Steelhead (upper Columbia R.)	*Oncorhynchus mykiss*
T	Steelhead (upper Willamette R.)	*Oncorhynchus mykiss*

Source: US FWS 2000.

important stocks of fish and other aquatic species. States, land management agencies, and regulatory agencies responded to changes in aquatic habitats on forested landscapes by initiating or improving regulations governing timber harvest and management on private and public forest lands.

The driving forces that shaped forest management and forest practice rules on private and public land consisted of at least the following six elements:

- Stated goals for management of timber and other resources
- Market value of timber and other resources
- Nonmarket value of resources
- Social values regarding resource use and preservation
- Scientific information
- State and federal laws

These elements, when considered in concert, created considerable complexity for decision- and policymakers who developed forest practice rules through normative decisionmaking processes. To add to the complexity, many of the elements (e.g., laws, scientific information, and especially social values) changed with time (Bliss 2000, Shindler and Cramer 1999).

Beginning in the 1970s, state legislators and forest managers in Oregon, Washington, Alaska, and other Western States formulated their initial forest practices acts. The acts were developed in response to mounting research evidence (studies conducted from 1956 to 1970) that logging increased water temperature and sedimentation in fish habitats in forested watersheds (table 6) and to public concerns that logging was damaging fish habitat (e.g., Moore 1971). Each act established goals for management of forest lands and developed a suite of general practices and guidelines for forest management operations, including timber harvest, road construction and maintenance, reforestation, and protection of riparian, aquatic, and terrestrial ecosystems. At about the same time, federal land management agencies also developed strategies and rules for harvesting timber and managing other forest resources. The initial state and federal rules were aimed primarily at maintaining stream temperatures and preventing accelerated sedimentation.

Forest management goals and the practices used to accomplish the goals differed by ownership.

Forest management goals and the practices used to accomplish the goals differed by ownership. Management of private forest lands emphasized sustained economical timber production, whereas public land managers were charged with multiple use of forest resources. Although timber management goals differed by management entity, the goals for management of other forest resources, including riparian and aquatic ecosystems, were similar for all ownerships. In general terms, all of the management entities emphasized sound management of soil, air, water, fish, wildlife, recreation, and scenic resources consistent with their timber harvest programs.

Forest practices acts for Oregon, Washington, and Alaska were passed in 1971, 1974, and 1978, respectively. Forest practice rules in the initial acts (generally called "best management practices" or BMPs) often depended on voluntary compliance to meet stated goals for riparian and aquatic ecosystems. Nearly three decades later, after many major revisions of the rules to achieve the original riparian management goals, the rule sets are still referred to as BMPs.

Forest management goals and practices for protection of riparian and aquatic habitats on Forest Service and BLM lands were also initiated in the 1970s. Specific goals for management of riparian and aquatic habitats emphasized maintenance and improvement of water quality and aquatic habitat characteristics. Federal forest practice rules progressed through three decades of evolutionary change during which management practices provided incrementally more protection of riparian and aquatic habitats to achieve stated management goals. The NWFP and the TLMP are the current strategies employed for protection of riparian and aquatic habitats on national forests and forested BLM lands west of the Cascade crest in

Table 6—Selected studies (1970 and earlier) that contributed to formulation of state forest practices acts and federal regulations for protection of riparian and aquatic habitats in managed forests of Oregon, Washington, and Alaska

Study date	Authors	Effects of forest management	Area
1956	Cordone, A.J.	Increased sediment	CA, OR, WA, AK
1957	Packer, P.E.	Increased sediment/roads	AK
1962	Chapman, D.W.	On fish resources	CA, OR, WA
1963	Calhoun, A.; Seeley, C.	Increased ”logging damage” to streams	CA
1964	Bishop, D.M.; Stevens, M.E.	More landslides	AK
1964	Packer, P.E.; Christensen, G.F.	Increased sediment/roads	OR, WA, AK
1965	Dyrness, T.C.	Increased sediment	OR
1967	Dyrness, T.C.	Increased mass erosion	OR
1967	Levno, A.; Rothacher, J.	Increased stream temperature	OR
1968	Meehan, W.R.	Increased stream temperature	AK
1968	DeWitt, J.W.	Less riparian vegetation	CA, OR, WA, AK
1968	Sheridan, W.L.; McNeil, W.J.	On salmon streams	AK
1969	Meehan, W.R. et al.	On salmon habitat	AK
1969	Hall, J.D; Lantz, R.L.	On coho, cutthroat	OR
1970	Anderson, H.W.	Increased sediment	CA, OR, WA, ID
1970a	Brown, G.W.; Krygier, J.T.	Increased sediment	OR
1970b	Brown, G.W.; Krygier, J.T.	Increased stream temperature	OR
1970	Fredriksen, R.L.	Increased sediment	OR
1970	Ringler, N.	On spawning habitat	OR
1970	Sadler, R.R.	Less riparian vegetation	OR

the Pacific Northwest and the Tongass National Forest in southeast Alaska, respectively. Subsequently, the federal government developed a unified federal policy for management of watersheds on federal lands (Federal Register 2000). The goal of the unified federal policy is to standardize watershed protection and management nationwide by eight federal agencies that administer large federal land holdings.

Initially, when each state formulated forest management goals and adopted management practices to achieve the goals, little recognition was given to the potential cumulative effects of practices or the geomorphic or physiographic variability within forested watersheds of the state. Since the 1970s, forest practices have evolved in response to new information on environmental effects of timber harvest, recognition that the original management goals for riparian and aquatic habitats were not being met, and changing laws and social values (NWIFC 2001, ODF 2002, Oregon State Archives 2002). Management strategies and their associated forest practice rules for state and private lands generally contain the following common themes, although priorities differ by ownership:

- Emphasis on timber production from forest lands.
- Protection of water quality, riparian and aquatic habitats, and other forest resources consistent with the goal of timber production.
- A set of forest practice rules (that differ by state) to achieve stated goals through application of standard-width buffer strips along perennial streams and control of disturbances from felling, yarding, and roads to maintain water quality.

Strategies for forest management on federal forest lands of the Pacific Northwest and southeast Alaska changed substantially in the 1990s. Current management strategies and their associated forest practice rules contain the following common themes:

- Emphasis on multiple resource use.
- Strategies that emphasize watershed reserves, watershed restoration, and use of default buffers or watershed analysis to meet management goals.
- Maintenance of water quality, riparian and aquatic habitats, and species viability consistent with some timber production.
- Strategies that address watershed, provincial, and regional scales.
- Harvest at extended timber rotation ages (long temporal scale for disturbance).
- Human disturbance regimes that remain within the natural historical range of disturbance for specific provinces.

The current federal rules, like those of Washington state, contain provisions for watershed analysis that allow managers flexibility to develop and apply strategies tailored to the particular vegetative, geomorphic, and climatic characteristics of watersheds where human disturbances are proposed. Watershed analysis includes the following components for future planning efforts:

- Watershed-scale planning.
- Planning at long temporal scales.
- Adapting plans to the unique biogeophysical features of watersheds.
- Planning in harmony with natural disturbance regimes.

Forest practices have evolved in response to new information on environmental effects of timber harvest, recognition that the original management goals for riparian and aquatic habitats were not being met, and changing laws and social values.

- Planning to protect source areas and processes that form and maintain riparian and aquatic habitats.
- Considering the effects of management of nonforested lands in the watershed.

These criteria provide managers with a more holistic view of the watersheds they manage and provide the necessary flexibility to achieve management goals.

Establishment and Evolution of Forest Practice Rules

Oregon—

The Oregon state legislature authored and approved the Nation's first comprehensive state Forest Practices Act in 1971 (ODF 1995). The goal of the policy is to

> encourage economically efficient forest practices that ensure the continuous growing and harvesting of forest tree species and the maintenance of forestland for such purposes as the leading use on privately owned land, consistent with sound management of soil, air, water, fish and wildlife resources and scenic resources within visually sensitive corridors as provided in ORS 527.755 and to ensure the continuous benefits of those resources for future generations of Oregonians.

The law became effective on July 1, 1972, and implementation began immediately following adoption of the first set of forest practice rules, referred to collectively as "best management practices." The initial rules made modest changes in the way timber harvest and regeneration was accomplished on state and private forest lands in response to increasing concerns by resource managers and the public that timber harvest was degrading aquatic ecosystems and fish and wildlife habitats. The first rule set was largely site specific and focused on standards for reforestation, road construction and maintenance, and streamside buffer strips. Although many of the initial rules were advisory in nature, some were quantitative enough to be enforceable.

The 1972 forest practice rules divided streams into two classes, fish-bearing streams (class I) and non-fish-bearing streams (class II). Treatment of riparian vegetation along class I and II streams was aimed at maintaining state water quality standards in fish-bearing waters. The original rules called for maintenance of 75 percent of the original shade cover on streams, which could be accomplished by leaving nonmerchantable tree species, or in cases where nonmerchantable vegetation was insufficient, leaving a fringe of merchantable trees. It was possible to waive the latter requirement, however, if other means of maintaining stream temperatures were available. Management of vegetation along class II streams required retention or re-establishment of undergrowth sufficient to maintain water quality in class I waters downstream. No specific width of buffer strip was mandated for either class of stream. The original rules, which incorporated some of the available scientific knowledge of the day, addressed neither the effects of forest management at a watershed scale, nor the structural aspects of fish habitat and stream channel morphology.

The original set of forest practice rules evolved significantly over the approximately 30-year history of the act.

The original set of forest practice rules evolved significantly over the approximately 30-year history of the act. Many of the major revisions incrementally increased protection for riparian areas, water quality, and other fish and wildlife habitat requirements. In 1974 and 1975, new rules were adopted for tractor skidding and mechanical clearing, and water quality protection from surface mining activities. In 1978, in response to Section 208 of the federal Clean Water Act, rules regarding water quality were clarified and “prior approvals” by the Department of Forestry were required for several practices that could directly affect water quality. In the same year, new rules were added to address “filling and removal” of material from stream channels, other stream channel alterations, and the use of herbicides (ODF 1995).

Major changes also occurred in the 1980s. Following severe storms and mass erosion in western Oregon in 1981 and 1982, new rules requiring written plans for operations in areas with high risk of mass erosion were adopted. A major amendment to the act in 1987 required site-specific protection for state and federally listed threatened and endangered species, and in 1988, written plans for forestry operations within about 30 m of class I streams and within about 90 m of sites of threatened or endangered species, wetlands, and several other sensitive sites were required (ODF 1995).

Additional significant changes occurred in the 1990s. In 1991, Senate bill 1125 instructed the Board of Forestry to revise stream protection rules to provide equal protection for fish present in all Oregon waters (ODF 1999). Subsequently, in 1992, new interim stream protection rules were adopted. In 1993, rules were adopted for listing biological sites that are scientifically and ecologically significant, and in 1994, new final rules were adopted for classification and protection of waters of the state with the objective of reaching a desired future condition of mature streamside timber stands. These rules acknowledged the need to maintain stream structure through perennial addition of large woody debris. The rule set

Despite the advances made in 1995, the new rule set was still criticized for not providing adequate riparian and aquatic habitat protection.

provided protection for streams based on their size and beneficial uses, as well as protective measures for lakes, wetlands, and other water bodies. The rules also provided incentives for stream enhancement and conversion of hardwood riparian areas to conifers as needed (ODF 1995).

Despite the advances made in 1995, the new rule set was still criticized for not providing adequate riparian and aquatic habitat protection. In a report for the Oregon Department of Forestry, Botkin et al. (1995) reviewed the forest practice rules and concluded that they would effectively maintain integrity of intact and pristine riparian ecosystems (relatively rare in the 21^{st} century), but that they were unlikely to restore degraded riparian zones on state and private lands in Oregon.

Oregon’s current forest practice rules, adopted in 1999 (Oregon Revised Statutes 1999), bear little resemblance to the initial set developed in 1972. The current rules provide more comprehensive protection for aquatic and riparian habitats than any previous set, but several years of monitoring and evaluation will be needed to fully test their effectiveness. The Governor of Oregon commissioned an Independent Multidisciplinary Science Team (IMST 1999) to assess the effectiveness of the current forest practice rules for protecting salmonid habitats. Based on the professional judgment of the scientists on the IMST, the 1999 rules for riparian protection, large wood management, and sedimentation control are unlikely to contribute to the recovery of habitat of depressed populations of anadromous salmonids.

The overall goal of current water protection rules is “to provide resource protection during operations adjacent to and within streams, lakes, wetlands, and riparian management areas so that, while continuing to grow and harvest trees, the protection goals for fish, wildlife, and water quality are met.” The protection goal for water quality is “to ensure through the described forest practices that, to the maximum extent practicable, non-point discharges of pollutants resulting from forest operations do not impair the achievement and maintenance of water quality standards.” The protection goal for fish habitat is “to establish and retain vegetation consistent with the vegetation retention objectives for streams and lakes that will maintain water quality and provide aquatic habitat components and functions such as shade, large woody debris, and nutrients.”

To achieve the current goals for aquatic and riparian ecosystems, streams are classified into three categories: type F, fish bearing, or fish bearing and source of domestic water; type D, source of domestic water but without fish use; and, type N, other streams. Streams are further classified into three categories by volume of flow. Small streams have average annual flows of <0.03 m /s, medium streams have average annual flows of ≥0.03 and <0.28 m /s, and large streams have average annual flows of ≥0.28 m /s. Forest operations within about 30 m of type F and D streams, within about 90 m of significant wetlands, and within about 30 m of large lakes require a written plan by the operator and written approval by the state forester.

Widths of riparian management areas (defined as slope distance from the streambank) are specified for each category of stream (table 7). Operators may vary the width of riparian management areas depending on topography, operational requirements, vegetation, fish and wildlife resources, and water quality protection as long as vegetation retention requirements are met. However, the average width of a riparian management area within an operation must equal or exceed the required width. Additional provisions protect side channels, wetlands, and unstable stream-adjacent slopes that extend beyond the widths of designated riparian management areas.

Additional protection for aquatic and riparian systems is provided by rules governing timber felling and yarding. The rules focus on minimizing ground disturbance on steep slopes, control of sediment entering streams, and minimizing disturbance to riparian vegetation and stream channels during yarding operations. Felling operations are required, wherever possible, to keep trees out of streams and avoid damage to retained riparian vegetation, and promptly remove any logging slash that enters stream channels.

Rules related to road construction and maintenance are designed to maintain forest productivity, water quality, and fish and wildlife habitat. Specific rules govern road location, design, crossing structures, and fish passage. Crossing structures must be designed to pass peak streamflows with a recurrence interval of 50

Table 7—Riparian management area widths (slope distance) for streams of various sizes and beneficial uses as required by Oregon Department of Forestry administrative rules

Stream size	Type F	Type D	Type N
		Feet	
Large	100	70	70
Medium	70	50	50
Small	50	20	Apply specific water protection measures

Note: Type F = fish bearing, or fish bearing and source of domestic water; type D = source of domestic water but without fish use; type N = other streams.

Source: Oregon Revised Statutes 1999.

years and to allow passage of adult and juvenile fish upstream and downstream during periods when migration normally occurs.

Overall, Oregon forest practice rules have evolved over the past 30 years from a simple initial rule set to current rules that address most of the ecological issues related to protection of the state's aquatic and riparian habitats. Despite all of the advances for protection of riparian and aquatic ecosystems, the current rules still emphasize uniform buffer strip widths according to the size and human uses of streams, and site-specific, small-scale application of rules. The true effectiveness of the current set of rules, however, remains unknown because insufficient time has elapsed to implement, monitor, and evaluate their effects.

Washington—

The current Washington Forest Practices Act was enacted in 1974 (Holter 2001) and has been amended numerous times in its nearly 28-year history. The initial set of forest practice rules, adopted in 1976, focused on road construction and maintenance, timber harvesting, reforestation, and use of forest chemicals. In 1979, a special committee identified 14 issues related to forest practice impacts on the environment, including a number of riparian-related issues such as unstable soils, watersheds, fish habitat, slide areas, and forest chemicals. Study groups were established to analyze the issues and determine which ones were likely to result in significant future adverse impacts. Based on the studies, new rule changes on threatened and endangered species, chemical applications, forest roads, timber harvest, slash and debris disposal, and other issues were adopted in 1982. Additional studies on cumulative effects and riparian habitat were commissioned in 1984, and in the same year, the State Environmental Policy Act (SEPA) required state agencies to adopt SEPA rules.

Additional major amendments to the rules related to riparian issues were adopted in 1987, 1988, 1992, and 2001. In 1986, a group of stakeholders (Timber, Fish, Wildlife Group [TFW]) that included state agencies, industrial and small forest landowners, tribes, counties, and environmental groups developed a consensus process for rule proposals that could be recommended to the Forest Practices Board. A new and robust TFW rules package that included specific rules for riparian management zones (RMZs), adaptive management, and other issues was adopted in November 1987.

Another major set of rule changes for management of wetlands, cumulative effects, stream temperatures, clearcut sizes and timing, and several other issues including watershed analysis for harvest operations, was adopted in 1992. The ESA listing of a number of salmonids in 1997, 1998, and 1999 resulted in adoption in 2000 of an emergency set of rules for water typing, RMZs, unstable slopes, roads, and wetlands and SEPA guidance for watershed analysis. A revised permanent rule set for these issues was adopted in 2001.

The current rules are complex, designed to fit different stream sizes, timber site characteristics, and physiographic regions of the state; to use watershed analysis as needed or desired; and to provide for present and future riparian and aquatic habitat needs. The two goals of riparian management are to (1) protect aquatic and related habitats to achieve restoration of riparian function and (2) maintain these resources once they are restored. The rules are comprehensive and only key excerpts are mentioned here. For complete reference to the current rules, refer to Washington Administrative Code (WAC) 222 (Washington State Legislature 2005). The current rules use a four-level water typing system with specified management practices for each type of water. Type S waters include all inventoried "shorelines of the state" (streams with mean annual flow ≥0.57 m /s and lakes ≥8 ha with associated wetlands and shore lands). Type F waters are segments of natural streams (other than type S); lakes >0.2 ha that contain fish habitat or are used for domestic water, fish hatcheries, or campgrounds; and off-channel habitats used by fish at some time of the year. Type Np waters are segments of natural waters with perennial flow but not used by fish. Type Ns waters are seasonal, non-fish-bearing streams in which surface flow is not present during at least some portion of the year.

The current rules are complex, designed to fit different stream sizes, timber site characteristics, and physiographic regions of the state; to use watershed analysis as needed or desired; and to provide for present and future riparian and aquatic habitat needs.

The rules for RMZs associated with the water types are designed to protect aquatic resources and related habitat to achieve restoration of riparian function, and the maintenance of these resources once they are restored. Separate rule sets apply to RMZs in western and eastern Washington, but both sets divide RMZs into three components for type S and type F streams: a core zone,[2] an inner zone,[3] and an outer zone.[4] The combined RMZ in western Washington is managed for a desired future stand condition with basal areas that differ by site class (a measure of the productivity of forest sites for growing timber—fastest potential growth on site I and slowest on site IV lands). When the stand is 140 years old, the basal area requirements range from 55.4 m^2/ha for site I to 51.4 m^2/ha for site IV (table 8).

[2] Designated zone immediately adjacent to a stream.

[3] Designated area adjacent to, but upslope from, the core zone.

[4] Designated area adjacent to, but upslope from, the inner zone.

Table 8—Basal area targets for western Washington riparian management zones for type S and F waters

Site class	Desired future condition target basal area (at 140 years)
	Square meters per hectare
I	55.4
II	53.4
III	50.1
IV	51.4

Note: Type S = all inventoried "shorelines of the state"; type F = segments of natural streams (other than type S); lakes >0.2 ha that contain fish habitat or are used for domestic water, fish hatcheries, or campgrounds; and off-channel habitats used by fish at some time of the year.

When existing riparian stands along type S and F waters in the combined core and inner zones do not meet stand requirements, no harvest is permitted in the inner zone. When no harvest is permitted in the inner zone or the landowner chooses not to enter the inner zone, the width of core, inner, and outer zones are defined according to site class and stream size (table 9). Harvest may still occur in the outer zone, but 49 riparian leave trees/ha, either clumped or dispersed, must remain after harvest (table 10). A third strategy allows landowners to place large woody debris in streams in lieu of leaving riparian leave trees in the outer zone.

Trees can be harvested and removed from the inner zone when surplus basal area, consistent with stand requirements, is present. When this situation occurs, there are two strategies for harvest and removal. The first is a thinning option in which the smallest diameter trees are removed first, the proportion of conifers in the stand is not decreased, and at least 141 conifers/ha are left. A different set of RMZ widths applies to this strategy (table 11). The second is a complex strategy for leaving trees in the RMZ closest to the water in a way that speeds trajectory toward the desired future condition of basal area. Another set of RMZ widths applies to this strategy (table 12).

Perennial non-fish-bearing waters (Np) also receive no-harvest buffer strips of 15-m width and variable length depending on the length of Np water extending above the confluence of type S or F waters downstream. The length of buffer is determined by table 13 when the length of Np water is 305 m or less. If an operating area is located more than 152 m upstream from the confluence of a type S or F

Table 9—Riparian management zone (RMZ) widths for type S and F waters in western Washington when no harvest is allowed in the inner zone

Site class	RMZ width	Core zone width (Measured from outer edge of bankfull width or outer edge of channel migration zone of water)	Inner zone width (Measured from outer edge of core zone)		Outer zone width (Measured from outer edge of inner zone)	
			Stream width ≤10 ft (3.1 meters)	Stream width >10 ft (3.1 meters)	Stream width ≤10 ft (3.1 meters)	Stream width >10 ft (3.1 meters)
		Meters				
I	61.0	15.2	25.3	30.4	20.4	15.5
II	51.8	15.2	19.2	23.8	17.4	12.8
III	42.7	15.2	13.1	16.8	14.3	10.7
IV	33.5	15.2	7.0	10.1	11.3	8.2
V	27.4	15.2	3.1	5.5	9.3	6.7

Note: Type S = all inventoried “shorelines of the state.” Type F = segments of natural streams (other than type S); lakes >0.2 ha that contain fish habitat or are used for domestic water, fish hatcheries, or campgrounds; and off-channel habitats used by fish at some time of the year.

Table 10—Riparian management zone outer zone leave tree requirements for type S and F waters in western Washington

Application	Leave-tree spacing	Tree species	Minimum d.b.h. required
			Centimeters
Outer zone	Dispersed	Conifer	30.5
Outer zone	Clumped	Conifer	30.5
Protection of sensitive features	Clumped	Trees representative of the overstory including both hardwood and conifer	20.3

Note: d.b.h. = diameter at breast height. Type S = all inventoried “shorelines of the state.” Type F = segments of natural streams (other than type S); lakes >0.2 ha that contain fish habitat or are used for domestic water, fish hatcheries, or campgrounds; and off-channel habitats used by fish at some time of the year.

Table 11—Riparian management zone (RMZ) widths for type S and F waters in western Washington when using the thinning strategy to reduce time needed to meet large wood, fish habitat, and water quality needs

Site class	RMZ width	Core zone width (Measured from outer edge of bankfull width or outer edge of channel migration zone of water)	Inner zone width (Measured from outer edge of core zone): Stream width ≤10 ft (3.1 meters)	Inner zone width: Stream width >10 ft (3.1 meters)	Outer zone width (Measured from outer edge of inner zone): Stream width ≤10 ft (3.1 meters)	Outer zone width: Stream width >10 ft (3.1 meters)
			Meters			
I	61.0	15.2	25.3	30.4	20.4	15.5
II	51.8	15.2	19.2	23.8	17.4	12.8
III	42.7	15.2	13.1	16.8	14.3	10.7
IV	33.5	15.2	7.0	10.1	11.3	8.2
V	27.4	15.2	3.1	5.5	9.3	6.7

Note: Type S = all inventoried "shorelines of the state." Type F = segments of natural streams (other than type S); lakes >0.2 ha that contain fish habitat or are used for domestic water, fish hatcheries, or campgrounds; and off-channel habitats used by fish at some time of the year.

Table 12—Riparian management zone (RMZ) widths for type S and F waters in western Washington when using the management strategy for leaving reserve trees closest to the water to reduce time needed to meet large wood, fish habitat, and water quality needs

Site class	RMZ width	Core zone width (Measured from outer edge of bankfull width or outer edge of channel migration zone of water)	Inner zone width: Stream width ≤3.1 meters (Measured from outer edge of core zone)	Inner zone width: Stream width ≤3.1 meters: Minimum floor distance (Measured from outer edge of core zone)	Inner zone width: Stream width >3.1 meters (Measured from outer edge of core zone)	Inner zone width: Stream width >3.1 meters: Minimum floor distance (Measured from outer edge of core zone)	Outer zone width (Measured from outer edge of inner zone): Stream width ≤10 ft (3.1 meters)	Outer zone width: Stream width >10 ft (3.1 meters)
				Meters				
I	61.0	15.2	25.6	9.1	25.6	15.2	20.1	20.1
II	51.8	15.2	19.5	9.1	21.3	15.2	17.1	15.2
III	42.7	15.2	13.4	9.1	**	**	14.0	**

Note: Type S = all inventoried "shorelines of the state." Type F = segments of natural streams (other than type S); lakes >0.2 ha that contain fish habitat or are used for domestic water, fish hatcheries, or campgrounds; and off-channel habitats used by fish at some time of the year.

Table 13—Required no-harvest, 15.2-meter (50-foot) buffers on type Np waters in western Washington

Length of type Np water from the confluence of type S or F water	Length of 15.2-meter buffer required on type Np water (starting at the confluence of the type Np and connecting water)
Greater than 305 meters	152.4 meters
Greater than 91.4 meters but less than 305 meters	Distance of the greater of 91.4 meters or 50 percent of the entire length of the type Np water
Less than or equal to 91.4 meters	The entire length of type Np water

Note: Type Np = segments of natural waters with perennial flow but not used by fish. Type S = all inventoried "shorelines of the state." Type F = segments of natural streams (other than type S); lakes >0.2 ha that contain fish habitat or are used for domestic water, fish hatcheries, or campgrounds; and off-channel habitats used by fish at some time of the year.

water and the type Np water is more than 305 m in length, then a buffer of 15.2 m on each side of the stream is determined by using table 14. In addition, a 9-m-wide equipment limitation zone is enforced along all type Np and Ns streams and sensitive sites such as seeps. Alluvial fans also receive 15.2-m buffers.

The current forest practice rules also provide detailed guidance for road construction and maintenance, timber felling and bucking, cable and ground yarding operations, slash disposal, and use of forest chemicals in riparian zones and wetlands (see WAC 222 for details). Rules associated with these activities are aimed at maintaining and restoring desired riparian functions and conditions.

The current Washington forest practice rules use a variety of practices and strategies to protect aquatic and riparian ecosystems in both the east and west physiographic regions of the state. The 10-year direction for Washington forest practices calls for:

- Transition from an individual forest practice-based program to one that is landscape based (provides for watershed analysis, or varies prescriptions by stream size and timber site class) and that recognizes cumulative effects on public resources.
- Refocuses forest practice rules on outcomes rather than process or action.
- Continuation of an active role in the Timber/Fish/Wildlife process and coordination with all stakeholders.

Because the current set of rules was adopted in 2001, implementation and monitoring of their effects has just begun. Consequently, it remains unknown

Table 14—Minimum percentage of length of type Np waters to be buffered when more than 500 (152.4 meters) feet upstream from the confluence of a type S or F water

Total length of a type Np water upstream type S or F water	Percentage of length of type Np water that must be protected with a 50-foot (15.2 meter) no-harvest buffer more than 500 feet (152.4 meters) upstream from the confluence of a type S or F water
Meters	*Percent*
305.0 or less	Refer to table in subsection i of Oregon forest practice rules
305.1 to 396.0	19
396.1 to 490.0	27
490.1 to 610.0	33
610.1 to 762.0	38
762.1 to 1067.0	42
1067.1 to 1524.0	44
Greater than 1524.0	45

Note: Type Np = segments of natural waters with perennial flow but not used by fish. Type S = all inventoried "shorelines of the state." Type F = segments of natural streams (other than type S); lakes >0.2 ha that contain fish habitat or are used for domestic water, fish hatcheries, or campgrounds; and off-channel habitats used by fish at some time of the year.

whether the current rules will restore and maintain aquatic and riparian ecosystems at historical norms and sustainable levels.

Alaska—

Standards for riparian management and reforestation differ by region and land ownership.

The Alaska Forest Resources and Practices Act was enacted in 1978 (Alaska Division of Forestry 2001). The original act was designed to protect fish habitat and water quality and to ensure prompt reforestation of forest lands. The act divides the state into three forest practices regions, coastal spruce-hemlock (Region I), interior spruce-hardwood south of the Alaska Range (Region II), and interior spruce hardwood north of the Alaska Range (Region III). Standards for riparian management and reforestation differ by region and land ownership. The original act did not provide comprehensive rules coverage for all land ownerships. Major revisions were adopted in Region I in 1990 in response to the Tongass Timber Reform Act (TTRA) to address riparian management on private, state, and federal lands, improve notification procedures for timber operations, and establish enforcement procedures. Additional changes to the stream classification system and riparian management standards for coastal forests (Region I) were adopted in 1999.

The Alaska forest practice rules divide water bodies into four classes. Type A water bodies must meet one of the following criteria: (1) have anadromous fish and streams with gradients of <8 percent and with particulate substrates, (2) have wetlands and lakes including their outlets, and (3) have estuarine areas delimited by salt-tolerant vegetation. Type B water bodies are used by anadromous fish, but otherwise fail to meet the criteria for type A water bodies. Type C waters are not used by anadromous fish, are tributary to type A and B waters, and have gradients of <12 percent. Type D waters have the same criteria as type C waters, except that gradients are >12 percent.

Forest practice regions, land ownerships, and water types are used to stratify forest practice rules for riparian management in Alaska (table 15). On state and other public lands, in the coastal spruce-hemlock region, no-harvest buffer strips of 30 m along the water body and partial harvest between 30 m and 91 m from the water body consistent with maintenance of fish and wildlife habitat are required along anadromous fish streams and high-value resident fish streams. Slope stability standards also apply within the buffer strips (table 15).

Forest practice rules for private lands in the spruce-hemlock region also require 20-m-wide buffer strips on type A waters, either 20-m buffers or a buffer to the slope break, whichever is smaller, on type B waters, and 8-m buffers with specific criteria for type C and D waters. Slope stability standards also apply on private lands.

Forest practice rules for the interior spruce-hardwood region south of the Alaska Range are similar to those of the coastal region, except that no designated buffer strip widths apply to private lands. Timber harvest on private land within 30 m of anadromous and high-value resident fish waters must be designed to protect fish habitat and water quality (table 15).

Forest practice rules for riparian management in the interior spruce-hardwood region north of the Alaska Range require smaller buffer strips on public lands as compared to the other forest practice regions in Alaska. Slope stability standards also apply to public lands. No buffer strips are required on private lands, but management conducted within 30 m of any waters containing anadromous fish must be consistent with the goal of maintaining adequate fish habitat protection.

Forest practice rules for Alaska have evolved to address many critical ecological issues related to protection of aquatic and riparian habitats and have been tailored to meet the needs of different physiographic regions of the state. As in the

Table 15—Current Alaska Forest Resources and Practices Act riparian management standards by region, land ownerships, and water types

Region	Landowner and authority	Standard
I: Coastal spruce-hemlock	State AS 41.17.118(a)(2)	Harvest of timber may not be undertaken within 30.5 meters immediately adjacent to an anadromous or high-value resident fish water body.
		Between 30.5 and 91.5 meters from the water body, timber harvest may occur but must be consistent with the maintenance of important fish and wildlife habitat.
		Slope stability standards apply within 30.5 meters from the water body on anadromous and high-value resident fish waters and tributaries to these waters with <12 percent gradient, and within 15.2 meters of other tributaries to anadromous and high-value resident fish waters.
	Other public AS 41.17.119(1)	Harvest of timber may not occur within 30.5 meters from the shore or bank on anadromous or high-value resident fish waters located south of the Alaska Range.
		Slope stability standards apply within 30.5 meters from the water body on anadromous and high-value resident fish waters and tributaries to these waters with <12 percent gradient, and within 15.2 meters of other tributaries to anadromous and high-value resident fish waters.
	Private AS 41.17.116(a)	Along a type A water body, harvest of timber may not be undertaken within 20.1 meters of the water body.
		Along a type B water body, harvest of timber may not be undertaken within 20.1 meters of the water body or to the break of the slope, whichever area is smaller.
		Along a type C water body, the operator shall, where prudent, retain low-value timber within 7.6 meters of the stream or to the limit of the riparian area, whichever is greater (slope break or 30.5 meters) where the width of the water body is >4.0 meters at the ordinary high-water mark (OHWM) or >2.4 meters at OHWM if the channel is incised.
		Along a type D water body, the operator shall, where prudent, retain low-value timber within 7.6 meters of the stream or to the limit of the riparian area, whichever is greater (slope break or 50 feet) where the width of the water body is >4.0 meters at OHWM or >2.4 meters at OHWM if the channel is incised.
		Slope stability standards apply to 30.5 meters from the water body on types A, B, and C water bodies, and within 15.2 meters on type D water bodies.
II: Interior spruce-hardwood south of the Alaska Range	State AS 41.17.118(a)(2)	Harvest of timber may not be undertaken within 30.5 meters immediately adjacent to an anadromous or high-value resident fish water body.
		Between 30.5 and 91.5 meters from the water body, timber harvest may occur but must be consistent with the maintenance of important fish and wildlife habitat.
		Slope stability standards apply within 30.5 meters from the water body on anadromous waters, and within 15.2 meters of tributaries to anadromous waters.
	Other public AS 41.17.119(1)	Harvest of timber may not occur within 30.5 meters from the shore or bank of an anadromous or high-value resident fish water body that is located south of the Alaska Range.
		Slope stability standards apply within 30.5 meters from the water body on anadromous waters, and within 15.2 meters of tributaries to anadromous waters.
	Private 11 AAC 95.260	A timber harvest operation within 30.5 meters from the shore or bank of an anadromous or high-value resident fish water body must be located and designed primarily to protect fish habitat and surface water quality from significant adverse effects.

Table 15—Current Alaska Forest Resources and Practices Act riparian management standards by region, land ownerships, and water types (continued)

Region	Landowner and authority	Standard
III: Interior spruce-hardwood north of the Alaska Range	State AS 41.17.118(a)(1)	Harvest of timber may not be undertaken within 30.5 meters immediately adjacent to an anadromous or high-value resident fish water body unless the division determines that adequate protection remains for the fish habitat.
		Slope stability standards apply within 30.5 meters from the water body on anadromous waters, and within 15.2 meters feet of tributaries to anadromous waters.
	Other public AS 41.17.119(2)	Harvest of timber may not occur within 30.5 meters immediately adjacent to an anadromous or high-value resident fish water body north of the Alaska Range unless the commissioner determines that adequate protection remains for the fish habitat.
		Slope stability standards apply within 30.5 meters from the water body on anadromous waters, and within 15.2 meters of tributaries to anadromous waters.
	Private 11 AAC 95.260	A timber harvest operation within 30.5 meters from the shore or bank of an anadromous or high-value resident fish water body must be located and designed primarily to protect fish habitat and surface water quality from significant adverse effects.

states in the Pacific Northwest, Alaska's forest practice rules are largely site-specific and applied at small scales. Little attempt has been made to address cumulative effects of forest management at the watershed scale. An attempt has been made to monitor and assess the effectiveness of forest practice rules for protecting riparian and aquatic habitats on private lands (e.g., Martin 2001, Martin et al. 1998). However, spatial and temporal expansion of the current monitoring efforts is needed to provide definitive answers on the effectiveness of the current rules.

Alaska's forest practice rules are largely site-specific and applied at small scales. Little attempt has been made to address cumulative effects of forest management at the watershed scale.

USDA Forest Service—

The importance of riparian areas on national forest lands was recognized in the National Forest Management Act of 1976 (NFMA) 36 CFR 219.27, which states:

> Riparian areas. Special attention shall be given to land and vegetation for ~30 m from the edges of all perennial streams, lakes, and other bodies of water [note the physical rather than functional definition]. This area shall correspond to at least the recognizable area dominated by riparian vegetation. No management practices causing detrimental changes in water temperature or chemical composition, blockages of water courses, or deposits of sediment shall be permitted within these areas which seriously and adversely affect water conditions or fish habitat…

Prior to passage of the act, Forest Service regulations recognizing the importance of riparian habitats were inconsistent, as was management of riparian habitats

Chronological changes in riparian management in the USDA Forest Service in the past three decades are difficult to track because of the decentralized decisionmaking structure of the agency.

across the National Forest System. Forest planning efforts postdating the act were required to address riparian ecosystems, but subsequent management guidelines and practices remained inconsistent and changed with ensuing iterations of forest planning.

The chronological changes in riparian management in the USDA Forest Service in the past three decades are difficult to track because of the decentralized decisionmaking structure of the agency. The Forest Service Manual (FSM) provides overall direction for riparian and aquatic ecosystem management on national forest lands, but each region and national forest can supplement the FSM to provide progressively more local direction for resource management. Frequently, when sections of the manual are revised, previous sections are removed, discarded, and replaced with the new material. The result is a progressive loss of corporate memory at the local level of how management direction changed over time. The following information was gleaned from U.S. Forest Service administrative offices and archives and probably does not represent a complete history of the changes in riparian and aquatic habitat in management in the Pacific Northwest and Alaska, although some highlights of change are noted.

Pacific Northwest Region (national forests in Oregon and Washington)— Recognition of the importance of anadromous salmonids on Forest Service lands was noted in 1959 in the Pacific Northwest Region's Wildlife Management Handbook. Section 2633.3–Engineering states, "The protection of anadromous fish in streams requires special precautions in the design of roads and in the installation of stream crossing facilities." The two primary considerations were:

- Providing unrestricted passage of sea-run fish to and from spawning beds, including spawning migrations from lakes and reservoirs.
- Preventing siltation, disturbance, or destruction of spawning beds during the spawning and incubation periods.

The Forest Service Manual for the Pacific Northwest Region in 1967 also addressed the issue of woody debris removal from streams. Section 2522.11 of the Watershed Management Manual provides considerations for debris cleaning from stream channels. The section mentions that preventing debris from entering streams is a high priority. Suggestions for achieving prevention include, "Felling and yarding timber away from streams, leaving streamside 'filter' strips, special timber sale layout design, road construction and logging slash treatment on floodplains and immediate channel side slopes are examples.” The focus of the section, however, is on potential damage from debris concentrations and considerations and priorities for debris removal. Primary considerations for removal were:

- Water quality. “Debris concentrations adversely affect the quality of water for domestic, industrial, agricultural, and fishery use.”
- Physical damage. “There is much to justify the removal of concentrations of debris which can interfere with the ability of a stream channel to carry peak discharges.”
- Fish migration. “In addition to the effect of water quality on fishery resources, debris jams can limit fish movement and prevent or retard fish from reaching more suitable spawning areas.”

The first regional-level streamside management guidelines for the national forests of Oregon and Washington appeared in section 2526 of the Watershed Management Manual in 1974, following passage of the Federal Water Pollution Control Act of 1972 (P.L. 92-500). The goal of the guidelines was to prevent non-point-source pollution and protect anadromous and resident fish habitats on the region’s national forests. The first streamside management guidelines classified streams into four categories based on their importance to fish production and water quality, and certain practices were “suggested” for protecting each class of stream. Many of the suggested guidelines, however, were qualitative and difficult to measure.

Streams were defined in the following manner:

- Class I: Perennial or intermittent streams or segments thereof, used for domestic water, used by large numbers of fish for spawning, rearing, or migration, or having a major effect on the quality of downstream waters
- Class II: Perennial or intermittent streams or segments thereof, used by moderate though significant numbers of fish for spawning, rearing, or migration, or having a moderate effect on water quality in Class I streams, or a major effect on water quality of Class II streams
- Class III: All other perennial streams or segments thereof not meeting higher-class criteria
- Class IV: All other intermittent streams or segments thereof not meeting higher-class criteria

The broad goal of the guidelines was “to apply best management practices” consistent with achieving specific water quality goals and to protect the stream and adjacent area so as to maintain the aquatic resources at high natural levels. To accomplish the goals for class I and II streams, the guidelines "suggest" that timber not be felled into streams, logs not be skidded across streams, equipment and logging debris be kept out of streams, vegetation on streambanks be left undisturbed, and sufficient shade be left to meet water quality standards. Guidelines for road construction and maintenance suggested keeping sediment and debris out of streams, minimizing disturbance to stream channels, using bridges and open-bottom culverts as crossing structures when possible, and limiting construction activities to seasons of the year that would minimize damage.

Management practices for class III streams were concerned primarily with preventing mass soil movement, maintaining satisfactory downstream water temperatures, and preventing debris from moving downstream into higher class waters. Specific guidelines suggest felling timber away from streams, retaining streambank vegetation for bank stability and shade, keeping equipment and logging debris out of streams, and protecting stream channels during road construction and maintenance.

Management practices for class IV streams were concerned primarily with preventing mass soil movement and preventing debris from moving downstream into higher class waters. Specific guidelines suggest felling timber away from streams, keeping equipment and logging debris out of streams, and protecting stream channels during road construction and maintenance.

Each of the 19 national forests in the region, developed its own variation of streamside management guidelines for inclusion in forest plans.

The original set of regional forest practice guidelines for the national forests of Oregon and Washington provided regional guidance for forest management activities around water and remained in force for about a decade. In the 1970s and into the 1980s, the regional guidelines addressed sedimentation, loss of streamside shade, and improved fish passage on the region's national forests. Each of the 19 national forests in the region, however, working within the framework of regional manual direction, developed its own variation of streamside management guidelines for inclusion in forest plans. Consequently, application of the guidelines at the forest level was highly variable.

The variation in management of riparian and aquatic habitats in the region continued into the early 1990s. A Regional Fisheries Task Force, commissioned by the regional forester in 1991, reviewed the forest plans of seven national forests in Oregon and Washington. The task force examined sections of forest plans that addressed descriptions of existing fish habitat conditions, effects assessments, management direction, monitoring, and measurability of management criteria. The findings indicated that coverage of fish and riparian issues in forest plans ranged from good to poor, with an overall rating of fair (Heller et al. 1991). Weaknesses in the plans included the use of general, non-watershed-specific and nonquantitative descriptions of existing fish habitat conditions, particularly for riparian areas, vague, nonspecific discussions of effects, and standards and guidelines that were qualitative and unmeasurable (Heller et al. 1991). The task force concluded that specific habitat requirements of indigenous stocks of fish might not be met through the implementation of BMPs.

The aquatic conservation strategy, for the first time, assumed an ecosystem approach to management of riparian and aquatic habitats.

The aquatic conservation strategy of the NWFP was the next iteration of riparian and aquatic management in the region. The strategy, for the first time, assumed an ecosystem approach to management of riparian and aquatic habitats by identifying watershed reserves (at the provincial scale), interim default riparian reserves (with greater width and upstream extension than previous strategies), watershed analysis (watershed scale) to tailor management plans to the unique and variable features of watersheds, and watershed restoration (watershed scale) to deal with the legacy of past management effects.

The results from a set of scientific studies were used to develop and justify the interim riparian boundaries identified for the NWFP by the Forest Ecosystem Management Assessment Team (FEMAT) (FEMAT 1993). These studies involved the range of ecological functions and processes that occur within certain portions of riparian zones along fish-bearing as well as non-fish-bearing streams. The latter had been given little or no consideration previously. A thorough and comprehensive review and synthesis of the scientific literature was used to develop the relations between a given ecological process and the interim size of the riparian zone (figs. 3, 4). Considerations of the needs of wildlife were also incorporated into the delineation process. Fourteen scientists from a range of physical and biological disciplines integrated the findings into the delineation of the interim riparian zone boundaries.

The NWFP interim riparian reserves, the heart of the strategy, exclude most management activities within two site-potential tree heights (about 90 to 120 m) along each side of perennial streams, and one site-potential tree height (about 45 to 60 m) along intermittent streams. Depending on the degree of dissection of the forested landscape, riparian reserves along both perennial and intermittent streams may occupy between 40 and 90 percent of the landscape (Hohler et al. 2001). Interim riparian reserves of this magnitude, coupled with key watershed reserves, have provided a connected watershed-level reserve system for terrestrial, riparian, and aquatic ecosystems. The amount of forested landscape protected by these strategies has fueled the controversy regarding riparian protection and resulted in both new research to evaluate prescribed buffer widths, and a re-examination of existing scientific literature on the subject.

Alaska Region (Tongass National Forest)—
Industrial forestry began on the Tongass National Forest in southeast Alaska in the 1950s, but specific goals and guidelines for protecting riparian and aquatic habitats were not instituted until the late 1970s. The TLMP, completed in 1979, was the first national forest plan approved following passage of NFMA. The original plan stressed full protection of the biological potential of streams and rivers, with the stated goal to "preserve the biological productivity of every fish stream on the Tongass" (USDA Forest Service 1997). The plan, however, offered few guidelines or practices to achieve that goal. For example, there were no requirements to leave standing timber in buffer zones along fish-bearing streams. The plan was amended in 1986, and forestwide standards and guidelines for riparian management, based on the forest's Aquatic Habitat Management Handbook (USDA Forest Service 1986) and BMPs for soil and water conservation, were established. Stream channels were classified by topographic and geomorphic characteristics (Paustian 1992). All stream reaches were relegated to three classes based on the presence of anadromous fish (class I), resident fish (class II), and their effects on the quality of downstream waters (class III). Management practices were tiered to the stream and channel classifications. Commercial timber harvest, however, was still allowed in riparian buffers because the forest's highest value spruce, hemlock, and cedar occurred there (USDA Forest Service 1989).

Despite improving riparian management practices during the 1970s and 1980s, the productivity of freshwater habitats on the forest showed declines between 1950 and 1986 (Tongass National Forest Interdisciplinary Team 1990). Losses of productivity were significant within disturbed watersheds where large areas had been clearcut, but were minimal at the forest scale. Heightened concerns for the area's world-class anadromous fisheries stimulated additional changes in riparian management.

The Tongass Timber Reform Act (TTRA) was passed by Congress in 1990 with additional direction for management of riparian and aquatic habitats on the forest. The act required 30-m no-cut buffers along all class I streams (anadromous fish streams) and on class II streams (resident fish streams) flowing directly into class I streams. The TTRA again increased protection of riparian and aquatic habitats, but problems with consistent application were noted. A riparian activity review conducted on the forest in 1991 to assess application of the requirement of TTRA (USDA Forest Service 1991) found that TTRA was inconsistently interpreted and applied on the forest.

The next attempt to increase protection for riparian and aquatic habitats on the Tongass was associated with a federal management program in the Pacific Northwest called, "Interim Strategies for Managing Anadromous Fish-Producing Watersheds in Eastern Oregon and Washington, Idaho, and Portions of California," also known as PACFISH (USDA and USDI 1994a) in 1994. The PACFISH strategy was developed in response to compelling evidence that salmonid habitats on Forest Service and BLM lands in the Northwest had been severely degraded and that the trend was likely to continue under current USFS and BLM land and resource management plans (USDA and USDI 1994a). The PACFISH strategy was intended to guide management of riparian and aquatic habitats until a new round of forest planning was completed. The strategy included the same four components included in the NWFP, i.e., key watershed reserves, riparian habitat conservation areas, watershed analysis, and watershed restoration.

When the Forest Service and BLM developed the PACFISH strategy, the intention was to apply it to all national forest lands used by Pacific anadromous salmonids, including the Tongass and Chugach National Forests in Alaska. The strategy provided conservative default protection for riparian zones, until watershed analysis was conducted to adapt plans to the local conditions of specific watersheds. A directive from Congress in the Conference Committee Report to the Fiscal Year 1994 Appropriation Act for the Interior and Related Agencies forbade application of PACFISH to Alaska forests. In the directive, the Alaska Region was instructed to: "proceed with stream analyses and studies and review procedures related to the PACFISH strategy in 1994 in order to study the effectiveness of current procedures [for protecting the habitat of anadromous salmonids], and determine if any additional protection [for anadromous fish habitat] is needed."

In response to the directive, an assessment (Anadromous Fish Habitat Assessment) of current forest management practices and the condition of fish habitats was made on the forest (USDA Forest Service 1995). The core of the review consisted of three components. First, a comprehensive literature review was conducted of Pacific salmon and steelhead habitat characteristics, processes, uses, and management interactions in Alaska. More than 1,500 relevant publications were located and reviewed. Second, a team of scientists from Alaska and the Pacific Northwest conducted a field review of current management practices for protecting riparian and aquatic habitats on the Tongass National Forest. Finally, watershed analyses were conducted on three Tongass watersheds to compare past management activities with postwatershed analysis management plans. Findings from these activities (USDA Forest Service 1995) indicated that fish habitats on the forest were declining and that current practices for managing riparian and fish habitats were inadequate to protect habitat quality and the freshwater portion of the anadromous fish life cycle.

Numerous recommendations were made for improving management and essentially all were incorporated into the 1997 TLMP revision (USDA Forest Service 1997). The final strategy for protection of riparian and aquatic habitats in the 1997 TLMP revision is remarkably similar to the PACFISH strategy in that it contains watershed reserves, default prescriptions for riparian habitat conservation areas on four stream classes and all stream channel types on the Tongass, the option to use watershed analysis to change default prescriptions, and watershed restoration to repair degraded habitats.

Bureau of Land Management—

Initial riparian management guidelines for forested BLM lands in the Pacific Northwest were linked with the Oregon Forest Practices Act (see page 47). In 1972 agency direction mandated that forestry activities either meet or exceed the BMPs required for timber harvest and road construction in the state Forest Practices Act. Later, in 1975, when BLM resource management plans were developed for districts in the region, standard buffers of about 23 m applied to anadromous fish habitats west of the Cascades, and buffers of 15-m width applied to fish-bearing streams east of the mountains.

Despite use of these guidelines and BMPs, widespread degradation of anadromous fish habitats on BLM lands was mentioned as part of the need to apply the PACFISH strategy to BLM lands in the Pacific Northwest (USDA and USDI 1994a). Subsequently, riparian and aquatic habitat management on BLM lands in the Northwest was included under the PACFISH umbrella in 1994. The result was application of a consistent management strategy for riparian habitats across the region by the major federal land management agencies.

The unified federal policy—

Despite the unprecedented move in 1994 to develop a consistent umbrella strategy for management of riparian and aquatic habitats on Forest Service and BLM lands in the Northwest, past inconsistencies within and among watershed management strategies of federal agencies in the United States prompted Congressional development of a unified federal policy in 2000. The policy was developed to ensure a consistent nationwide watershed management approach to federal land and resource management (Federal Register 2000). The U.S. Departments of Agriculture, Interior, Commerce, Defense, and Energy, and the Environmental Protection Agency, the U.S. Army Corps of Engineers, and the Tennessee Valley Authority are participating in implementation of the policy on >320 million ha of federal land. The policy, which is part of the Clean Water Action Plan for restoring and protecting America's waters, has two goals: (1) use a watershed approach to prevent and reduce pollution of surface and ground waters resulting from federal land and resource management activities and (2) accomplish this in a unified and cost-effective manner.

The following guiding principles were used to develop the policy:

- Use a consistent and scientific approach to manage federal lands and resources and to assess, protect, and restore watersheds.
- Identify specific watersheds in which to focus funding and personnel and accelerate improvements in water quality, aquatic habitat, and watershed conditions.
- Use the results of watershed assessments to guide planning and management activities in accordance with applicable authorities and procedures.
- Work closely with states, tribes, local governments, private landowners, and stakeholders to implement the policy.
- Meet the requirements of the Clean Water Act to comply with applicable federal, state, tribal, interstate, and local water quality requirements to the same extent as nongovernmental entities.
- Take steps to help ensure that federal land and resource management actions are consistent with applicable federal, state, tribal, and local government water quality management programs.

Although implementation is underway, it is expected to take some time to achieve consistent goals and strategies in watershed management among the departments and agencies involved in the policy. Implementation of the policy might encourage agencies to pool funds and staff effort to focus on priority management needs.

It is expected to take some time to achieve consistent goals and strategies in watershed management among the departments and agencies involved in the policy.

Commonalities in Development of Forest Practice Rules

Rules and practices for accomplishing riparian protection goals, are variable and are based on the normative decisions of policymakers within each management jurisdiction.

The goals for management and protection of riparian and aquatic habitats are similar for state and federal forested lands in the Pacific Northwest and Alaska. That is, all offer a significant level of protection for riparian and aquatic habitats based on a consistent body of scientific information applicable to the region. The rules and practices for accomplishing riparian protection goals, however, are variable and are based on the normative decisions of policymakers within each management jurisdiction. In some cases, different practices apply to contiguous riparian and aquatic habitats on opposing sides of state lines, even though the goals for resource protection are similar. These variations appear not to be based on a need for flexibility in management to accommodate different physiographic or geomorphic situations but rather a difference of opinion among policymakers about how much protection of riparian ecosystems is needed to achieve stated goals.

Despite variations among state and federal forest practice rules, all share commonalities in development. For example:

- All were initiated in the 1970s.
- All shared the goals of protecting riparian and aquatic habitats.
- All employed some type of vegetative buffer strips to protect riparian vegetation and streambanks.
- All sought to find the minimum width of vegetated buffer strips that would protect riparian and aquatic values.
- All addressed timber felling and yarding practices near streams.
- All developed special rules for road construction and maintenance to minimize sedimentation and stream channel disturbance.
- All, in time, recognized that initial forest practice rules did not meet stated goals for riparian protection, and through a sequential process of evaluation and amendment provided progressively more protection for riparian and aquatic habitats over a period of two to three decades.
- Many of the strategies still focus on small-scale, relatively short-term criteria.

The progression in development of state and federal riparian and aquatic management strategies has moved from the initial 1970s focus on single functions at site scales, to the 1980s focus on multiple functions at site scales, to the 1990s focus on multiple functions at watershed scales (fig. 7). Rule development was

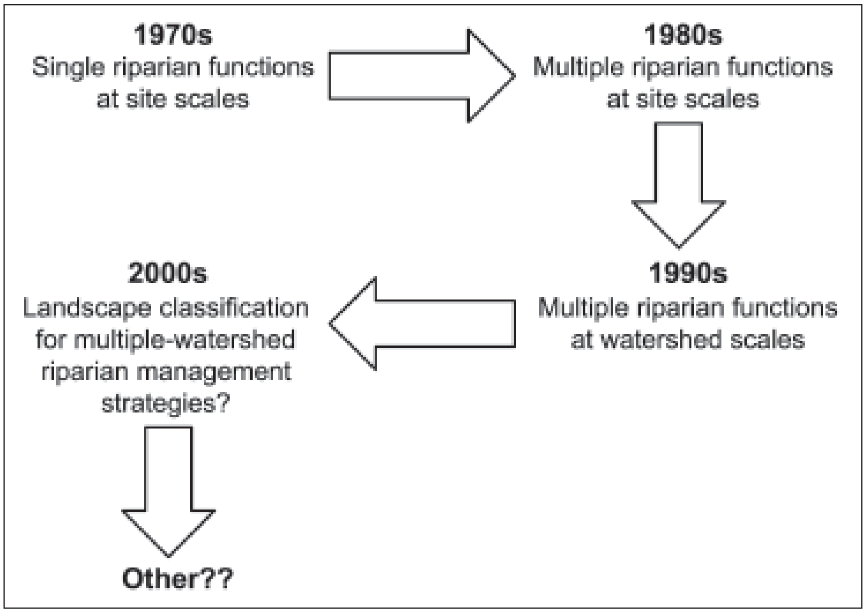


Figure 7—Temporal progression in the way state and federal riparian management strategies addressed riparian functions at various scales.

driven in part by new science and emerging legal issues (table 16). Future progression in this sequence may lead to landscape-scale classifications that aid managers in identifying and grouping similar watersheds so that watershed analyses become more efficient and perhaps apply to areas larger than individual watersheds (Benda et al. 1998, Montgomery 1999).

During each phase of development, implementation of forest practices received some degree of monitoring and evaluation (e.g., Adams and Stack 1989, Caldwell et al. 1991, Dent and Walsh 1997, Feller 1981, Moring 1975, Morman 1993, Rashin and Graber 1992, Robison et al. 1999, Runyon and Andrus 1994, USDA Forest Service 1995). Although the monitoring was generally incomplete, and often designed at inappropriate temporal and spatial scales, it did frequently provide managers with evidence that practices were not meeting riparian and aquatic protection goals for water temperature, coarse woody debris, and fish habitat structure—hence, the progressive increases in protection over time.

Current rules, with all of their commonalities and differences, protect more of the ecological processes that form and maintain riparian and aquatic ecosystems than any of their predecessors. However, monitoring and evaluation at the appropriate temporal and spatial scales are needed to evaluate the effectiveness of current

Table 16—Summary of regulations for management of riparian zones on state and federal lands in the Pacific Northwest and southeast Alaska; ecological and legal concerns and key scientific papers that influenced development of the regulations over time; and potential directions

	State lands		Federal lands				
	Fish-bearing streams	**Non-fish-bearing streams**	**Fish-bearing streams**	**Non-fish-bearing streams**	**Ecological purpose(s)**	**Legal concerns/issues**	**Key science papers**
Pre-1970s	None	None	None	None			
1970s	Best management practices (BMPs)	None	BMPs—minimal buffers that were predominately nonconifers	Limited for temperature and erosion control	Water temperature and sediment control	Clean Water Act, Sec. 208	Alsea Watershed Study (Hall and Lantz 1969, Moring and Lantz 1975), Gibbons and Salo 1973
1980s	BMPs with special rules for operating near streams	None	100 feet	Limited for temperature and erosion control	Large wood recruitment Sedimentation	Clean Water Act	Salo and Cundy 1987
1990s	To 30.4 meters—no harvest near stream and varing amounts in remaining area	Limited protection in perennial non-fish-bearing streams in WA	Defaults to 91.2 meters (2 heights of site-potential tree) until watershed analysis	Defaults to 45.6 meters (1 height of site-potential tree) until watershed analysis	Variety of ecological processes at watershed scale	Tongass Timber Reform Act Clean Water Act Endangered Species Act—fish and wildlife	Murphy and Koski 1989, McDade et al. 1990, Robinson and Beschta 1990, FEMAT 1993
2000	Same	Possibly along selected channels	Same Consideration of landscape context	Same Consideration of landscape context	Variety of ecological processes at watershed/landscape scale Maintain dynamic nature and processes of aquatic ecosystems	Clean Water Act Endangered Species Act—fish and wildlife	Reeves et al. 1995, Benda et al. 1998, Cissel et al. 1999

strategies. Therefore, each of the current rule sets only represents another step in the evolutionary process of forest practices development, and all could be changed again in the future to more, or perhaps less, restrictive rules depending on results of evaluations and changing legal, social, and science issues. Even after more than two decades of development, Murphy (1995) reported that all state forest practice rules in the Northwest and Alaska were judged to be ineffective in meeting goals for riparian management. Also, the Independent Multidisciplinary Science Team (IMST 1999) concluded that the most current Oregon forest practice rules would not recover habitat of listed stocks of salmonids. The nature and timing of future changes in forest practice rules is of vital interest to all parties concerned with management of forest resources in the West.

The forest practices associated with the NWFP and TLMP riparian and aquatic management strategies that apply to federally managed forests in western Oregon and Washington, and southeast Alaska, respectively, potentially address ecosystem management at the watershed scale (FEMAT 1993, USDA Forest Service 1997). These strategies addressed large temporal and spatial scales, used the best available science to protect features and processes that maintain riparian and aquatic ecosystems, allowed managers to use watershed analysis to design strategies that address the physical and biological features of individual watersheds, and took into account both natural and human disturbances when designing management strategies. The way in which managers actually used the strategies, however, ranged from site-specific applications to full-scale watershed analyses. Because implementation of these strategies has been underway for less than 5 years, full evaluation of their effects has not been made.

The decades-long evolution in forest practices resulted in substantial ecological cost to riparian and aquatic ecosystems in the Pacific Northwest, Alaska, and in the United States in general.

Benefits and Costs of Forest Practice Rules Development

The decades-long evolution in forest practices resulted in substantial ecological cost to riparian and aquatic ecosystems in the Pacific Northwest, Alaska, and in the United States in general. The loss of large trees in riparian areas in the Pacific Northwest is difficult to quantify, but Malanson (1993) estimated that about 70 percent of natural riparian communities have been lost as a result of human activities. In western Oregon and Washington, most riparian areas are in an early succession condition (<60 years old) (Carlson 1991). In southeast Alaska, commercial timber was harvested from about 13 percent of the riparian zones in old-growth forests on the Tongass National Forest between 1954 and 1995 (USDA Forest Service 1997).

There were several reasons for the delay in implementing forest practices for protection and maintenance of riparian and aquatic ecosystems. The first was "burden of proof" in establishing that forest practices damaged aquatic habitats and fish production. Without scientific proof, the timber industry and timber managers were reluctant to respond to concerns that timber harvest was damaging fish habitat in the Northwest. Second, little research had been completed on the effects of forest practices on aquatic ecosystems when industrial forestry accelerated following World War II. Because ecological research requires long timeframes for scientifically sound results, credible evidence that timber harvest near streams caused damage to aquatic habitats was not available until the early 1970s. The Alsea Watershed Study in western Oregon (Moring and Lantz 1975) was one of the first comprehensive studies of the effects of forest harvest on streams and fish habitats, and the results of that work contributed to enactment of the Oregon Forest Practices Act in 1972. In that act, and in subsequent acts in other states, an attempt was made to develop a set of BMPs that did not interfere with timber production, yet provided adequate protection for streams and fish habitats. Although that was a worthy goal, 30 years later managers are still seeking strategies that will meet their stated management goals and achieve the desired balance between timber harvest and riparian and aquatic habitat protection.

A third reason was that evaluation of the effectiveness of forest practice rules for aquatic ecosystem protection requires long-term monitoring. At least several years, and realistically perhaps several decades, of implementation and monitoring are needed to fully assess the effects that forest practice rules, or amendments to the rules, have on the environment. Given the issues of burden of proof, the time required for credible scientific research results, and the time required for monitoring and evaluating the effects of forest practices, it is little wonder that development of forest practice rules that could meet the goals of states and federal agencies required decades.

The phases in development of forest practice rules followed a consistent pattern across the Pacific Northwest and Alaska. Initial rule sets called "best management practices" were negotiated between state agencies, tribes, the timber industry, and other parties. When the rules were established or amended, the goal was to find the minimum level of protection needed to maintain the productivity of riparian and aquatic habitats. The resulting BMPs were the normative decisions of managers who had examined the available biological, social, economic, and political information and attempted to balance the needs of all parties. After a few years of implementation and feedback from anecdotal evidence, new research studies, and ongoing monitoring and evaluation, the BMPs were deemed insufficient to meet the management goals for riparian and aquatic habitat characteristics such as water quality, streambank stability, and aquatic habitat structure, and with much debate and contention, they were revised through another normative decisionmaking process. The revised set of BMPs generally reduced timber harvest and provided more protection for the ecological processes that form and maintain riparian and aquatic habitats. After another period of implementation and evaluation, forest managers and regulatory agencies concluded that the practices still did not meet stated riparian management goals, and the process was repeated until the current sets of rules evolved.

In retrospect, the term "best management practices" was a misnomer in terms of providing protection sufficient to maintain the structure and functions of riparian ecosystems, or meet the stated riparian management goals of the agencies that formulated them. The BMPs were developed through the normative process that weighed, evaluated, and incorporated many types of information. However, in arriving at decisions, compromises were often made in social, political, economic, and ecological goals for riparian management. The best available scientific information for protection of riparian and aquatic habitats was not always incorporated into forest practice rules. Consequently, between 1970 and 1990 while BMPs were in effect, the quality of riparian and aquatic habitats on forested lands of the Northwest declined (USDA and USDI 1995) (fig. 8). Results from studies in the peer-reviewed literature suggest that past timber harvest practices negatively affected fish (e.g., Hartman and Scrivener 1990, Reeves et al. 1993, Scrivener and Brownlee 1989) and fish habitat (e.g., Hicks et al. 1991, McHenry et al. 1998, Reeves et al. 1993, Spence et al. 1996) in the Pacific Northwest and southeast Alaska. Studies found that salmonid species may respond positively to environmental changes at one life-history stage, but any gains can be lost or not realized because of negative responses at a later time or subsequent life-history stage (e.g., Holtby 1988, Murphy et al. 1986). We are not aware of any examples in the peer-reviewed literature where salmonid population or salmonid habitat responses to intensive timber harvest activities were positive. Acknowledging the impacts of forest management on riparian and aquatic habitats and understanding the reasons for them provides the basis for identifying and developing new management options.

The term "best management practices" was a misnomer in terms of providing protection sufficient to maintain the structure and functions of riparian ecosystems, or meet the stated riparian management goals of the agencies that formulated them.

Declining aquatic habitats on forested lands could be considered a cost of the lengthy incremental development of forest practices, but the process also yielded economic benefits. During this period (1970 to about 2000) more than 235 million

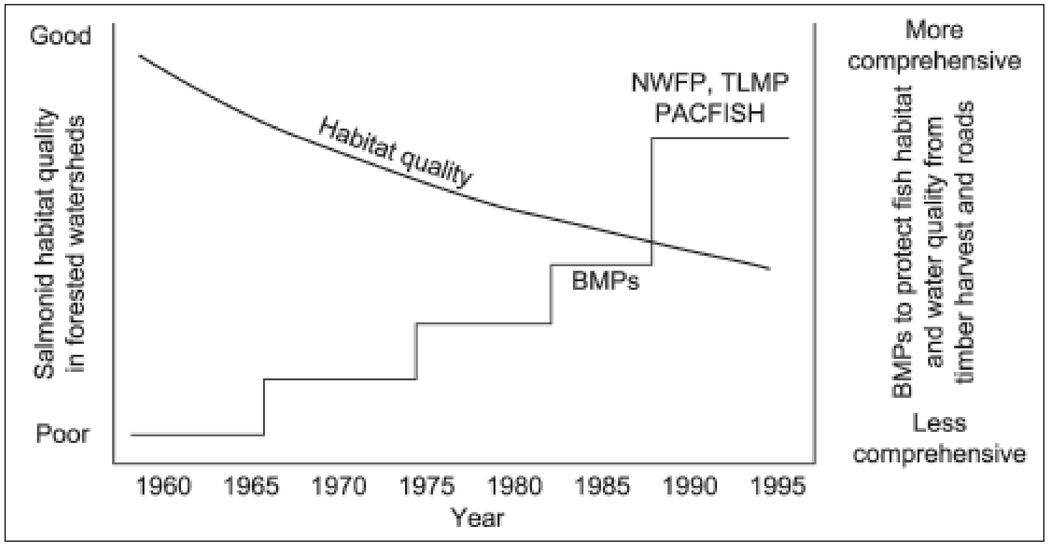


Figure 8—Theoretical chronological relationship between forest practice rules (BMPs) and riparian and fish habitat quality in forested watersheds of the Pacific Northwest and Alaska. BMP = best management practices, NWFP = Northwest Forest Plan, TLMP = Tongass Land Management Plan, PACFISH = Interim strategies for managing anadromous fish-producing watersheds in eastern Oregon and Washington, Idaho, and portions of California.

m of timber was harvested from the national forests of the Pacific Northwest, and the total harvest from both public and private lands in the region exceeded 590 million m . Much of the commercial timber in riparian zones within timber sales was harvested during this period. The exact amount is unknown because tallies of timber removed from riparian habitats were included with general harvest statistics.

The NWFP, PACFISH, and TLMP made the first substantive departures in the way forest practice rules were formulated (fig. 8). These plans were unlike previous site-specific schemes for management of riparian and aquatic resources in two ways. First, they addressed riparian management at the watershed scale with specific emphasis on maintaining ecosystem functions over the long term. Second, they rejected both the previous philosophy of trying to define and achieve the absolute minimum set of practices that would meet stated riparian management goals and the concept that goals could be met by implementing yet another set of BMPs. The new management philosophy under the NWFP represented a paradigm shift in how managers view resource coordination. In previous riparian rule sets, riparian and aquatic technical specialists shouldered the burden of proof for demonstrating resource damage from forestry activities and the need for more comprehensive forest practice rules to meet riparian management goals. Under the umbrella of the NWFP, the burden of proof shifted. Forest managers who wanted to alter the comprehensive default prescriptions for riparian management under the NWFP in order to pursue other management goals were required to demonstrate, through watershed analysis, that the changes would not compromise established riparian management goals. Additional concerns about rare and little-known organisms also made managers reluctant to alter default prescriptions. These factors have contributed to the controversy surrounding concurrent management of timber, riparian, and aquatic resources on federal lands in the Pacific Northwest.

With the comprehensive forest practices in the NWFP and TLMP and the provision within each strategy to use watershed analysis to tailor management plans to the characteristics of individual watersheds, there is a reasonable probability that ecosystem functions at large spatial scales will be maintained on Forest Service and BLM lands over the long term. The legacy of past management activities, however, will in some cases remain on the landscape for at least a century. One reason for such a lag is that renewed recruitment of large woody debris in stream channels can require a century or more following harvest of mature trees from riparian habitats (FEMAT 1993).

The legacy of past management activities will in some cases remain on the landscape for at least a century.

Without full implementation and evaluation of the aquatic habitat conservation strategies in the NWFP and TLMP, and considering that the legacy of past land management in the Pacific Northwest and southeast Alaska may persist for decades or longer, is it possible to look ahead at future scenarios for riparian and aquatic management, or is it too early to explore future options? Because the state of scientific knowledge continues to advance, we believe it is now possible to explore some additional science-based options for managers to consider.

Potential Options for Riparian Management Strategies

Thirty years of development have produced the current strategies for forest management on private and public lands of the Northwest and southeast Alaska. From the 1970s to the end of the 20^{th} century, these strategies were shaped by policymakers who variously considered economics, social values, scientific knowledge, and state and federal laws in their decision process. During the 1990s, new scientific findings, changing social values regarding forest management, and new and existing state and federal laws, figured prominently in development of the NWFP and TLMP, and in modification of state forest practice rules and management strategies. These features will likely continue to dominate any future changes in forest management on public forest lands of the Pacific Northwest and southeast Alaska and on private and public forest lands within this area.

The science underlying 1990s forest management strategies, like the NWFP and TLMP, emphasized:

- The importance of considering landscapes at large temporal and spatial scales, for example, watershed scales (Bolton and Monohan 2001, Hohler et al. 2001).
- Understanding the natural variability and natural disturbance regimes that shape and maintain the characteristics of particular landscapes (Cissel et al. 1998, 1999; Reeves et al. 1995).
- Understanding the interactions among upland, riparian, and aquatic ecosystems in forest lands (Benda et al. 1998, Reeves et al. 1995).

These scientific findings, largely from the 1990s, have provided a technical base for development of new forest management strategies.

Changing social values in the 1990s were perhaps even more important in shaping management strategies than new scientific information (Shindler and Cramer 1999). Increasing populations in the Pacific Northwest have led to increased public desire for recreation from forest land and the maintenance of visual aesthetics (Bliss 2000). These features, coupled with public desire to maintain the viability of prominent terrestrial and aquatic species on public and private forest lands (e.g., spotted owls and anadromous salmonids) (Lee et al. 1997, Thomas et al. 1993, USDA and USDI 1994b), also strongly influenced development of forest management strategies in the 1990s.

Finally, state and federal laws such as Oregon SB 1125 (revised stream protection rules), the Washington Salmon Recovery Act ESHB 22091, amendments to the federal Clean Water Act, the Safe Drinking Water Act, the Coastal Zone Management Act, and the ESA, also helped shape private and public forest management strategies in the 1990s. All of these features, science, social values, and law, will continue to shape future forest management strategies. We will examine some of these in more depth below, especially as they apply to public forest lands.

Temporal and Spatial Considerations

Before exploring alternatives to current schemes for management of riparian habitats in the Pacific Northwest and southeast Alaska, it is critical to review some spatial and temporal considerations for development of new management strategies. First, the current focus on federally owned forested landscape by land management agencies and regulatory agencies, although important and appropriate, is too narrow because it only addresses forested portions of river basins. Most major river basins in the Pacific Northwest are only partially forested and are subject to many land uses besides industrial forestry. Many of the riparian and aquatic habitats in flood plains of large low-gradient valleys, those that were formerly the most productive portions of major watersheds for salmonids and other aquatic species, have been highly altered by agriculture, urbanization, and hydropower installations.

Currently, aquatic habitats least affected by altered flows and disturbed riparian zones are located in forest lands managed by the federal government. These habitats have also been altered and simplified by forest management, but continue to produce salmonids at reduced levels. Although greater salmonid production, particularly coho and Chinook salmon, historically occurred in larger low-gradient downstream waters (Burnett et al. 2003) that are now poor salmonid producers because of dams, reservoirs, and agricultural activities (Clark et al. 1998), streams on forested lands currently provide refuge habitats for remnant populations of anadromous salmonids.

Management plans designed to maintain the integrity and functional characteristics of riparian and aquatic ecosystems and recover listed populations of salmonids, must consider all types of land uses at river basin scales, rather than depend solely on current strategies that focus recovery efforts primarily on forested watersheds, especially those in public ownership. Burnett et al. (2003) developed a process to identify portions of watersheds that have the highest potential to provide habitat for various species of anadromous salmonids. Their methods estimate gradient, valley width, and mean annual flow for reaches of the stream networks from digital elevation models (DEM) and provide species-specific formulas to assess the suitability of the measured features.

Management plans designed to maintain the integrity and functional characteristics of riparian and aquatic ecosystems and recover listed populations of salmonids, must consider all types of land uses at river basin scales, rather than depend solely on current strategies that focus recovery efforts primarily on forested watersheds.

Restoration of riparian and aquatic habitats on forested landscapes can contribute to stock recovery, but if done in isolation, it will not assure broad-scale recovery of listed salmonids. Recovery programs are at high risk of failure unless the spatial scales of the efforts are expanded to include all ownerships and land uses in river basins, and also address other factors that have affected listed fish (e.g., fish passage and commercial and sport fish harvest).

Focus on Forested Lands

Assuming that, in the future, state and federal regulatory agencies responsible for environmental quality and recovery of listed species equally address all land uses, ownerships, fish harvest, and other factors affecting fish populations, how can forest landowners participate in a coordinated effort to reduce the risks their operations pose to riparian and aquatic ecosystems and still meet their stated management

It could be beneficial for management entities to re-examine their (1) riparian management goals and practices, (2) scales at which the strategies apply, (3) overall strategies, and (4) monitoring and evaluation plans to see if efficiencies in forest resource use and protection can be achieved.

goals? Management strategies based on ecological principles could help managers achieve goals for timber production and riparian and aquatic resource protection. The state of scientific knowledge has recently advanced with regard to the effects of natural and human disturbances on forested landscapes at various scales, and how to apply that knowledge to resource management strategies. In recognition of this new information, it could be beneficial for management entities to re-examine their (1) riparian management goals and practices, (2) scales at which the strategies apply, (3) overall strategies, and (4) monitoring and evaluation plans to see if efficiencies in forest resource use and protection can be achieved.

First, the goals for management of riparian and aquatic ecosystems on federal, state, and private lands are generally similar, but the practices and guidelines for achieving those goals have historically differed by management entity. The variability in practices and guidelines, which still exists among state and federal rules for riparian management, can be related more to different management emphases as defined by policymakers, than to different biological and physical landscape features. Variable practices and guidelines, however, failed to meet the management goals of states and federal agencies as evidenced by their frequent revision over the past three decades.

State forest practices acts and rules for forestry operations on federal lands often require application of site-specific inflexible rules and practices within and among states and land ownerships. Even where flexibility is allowed through watershed analysis, managers often resort to uniform default prescriptions for a variety of reasons. Use of ecological principles in developing forest practice rules, and flexibility in their application, could enhance the probability of meeting riparian and aquatic habitat management goals while still producing timber, recreation opportunities, and other benefits from forests. For example, Berg (1995) demonstrated through modeling how active management of riparian zones could be economically as well as ecologically beneficial. Watershed analysis under the umbrella of the NWFP and TLMP has also shown that multiple benefits can be achieved through management of riparian zones. Adherence to inflexible default prescriptions, on the other hand, might preclude management options that would be available based on watershed analysis.

The management of riparian zones along small streams, which are generally defined as non-fish-bearing perennial and intermittent streams, is an emerging issue for policy- and decisionmakers. These streams may compose up to 90 percent of the stream network's length (Everest and Harr 1982, Everest et al. 1985). New aspects of their ecological role have recently been identified. For example, these channels can be important sources of food and energy for juvenile fish (Wipfli and Gregovich 2002). Small streams are also important sources of sediment and wood that create and maintain habitat in fish-bearing streams. Almost half of the volume of wood found in fish-bearing streams in a pristine coastal Oregon watershed originated from small, steep tributary streams (Reeves et al. 2003). Sediment is also stored in small streams, often as a result of wood accumulations. Stored sediment is metered out to the fish-bearing streams over time (May 2001, May and Gresswell 2003). The absence of wood results in these channels having bedrock exposed for extended periods because sediments move rapidly down the channel rather than being stored. The result is alteration of the sediment delivery regime and a reduction in the complexity of habitat in fish-bearing streams. Small streams are also the sites of habitat for several species of native amphibians (Bisson et al. 2002, Olson et al. 2000).

Consideration given to management of small streams varies widely by ownership and state. Riparian zones along small streams on federal lands receive more extensive protection than those on state and private lands. Murphy (1995) reviewed forest practice requirements for riparian zones in Pacific Northwest states and Alaska. He concluded that buffers on small non-fish-bearing streams were often inadequate for protection of water quality and that reliance on BMPs alone may be inadequate to protect headwater areas.

The variation in the degree of connection between small streams and fish-bearing streams provides options for managing riparian zones.

The variation in the degree of connection between small streams and fish-bearing streams provides options for managing riparian zones. In mountainous stream systems, debris torrents deliver substantial amounts of wood and sediment to fish-bearing streams from upslope areas (Reeves et al. 2003). However, the potential for debris torrents that originate in small streams to reach fish-bearing streams is highly variable. The primary features determining the degree of connection are the slope of the delivery stream and the angle at which it enters downstream waters (Benda and Cundy 1990). For example, see figure 9 for the location of small tributary streams in the Knowles Creek watershed with the highest potential to deliver sediment and wood to fish-bearing streams. A digital elevation model is available that can readily identify small streams that are potential contributors of large wood. All such streams have been identified in the Oregon Coast Range as part of the Coastal Landscape Analysis and Modeling Study. Specific riparian management goals for these streams could provide recruitment of large wood to downstream fish habitats. Commodity production could be emphasized in other parts of

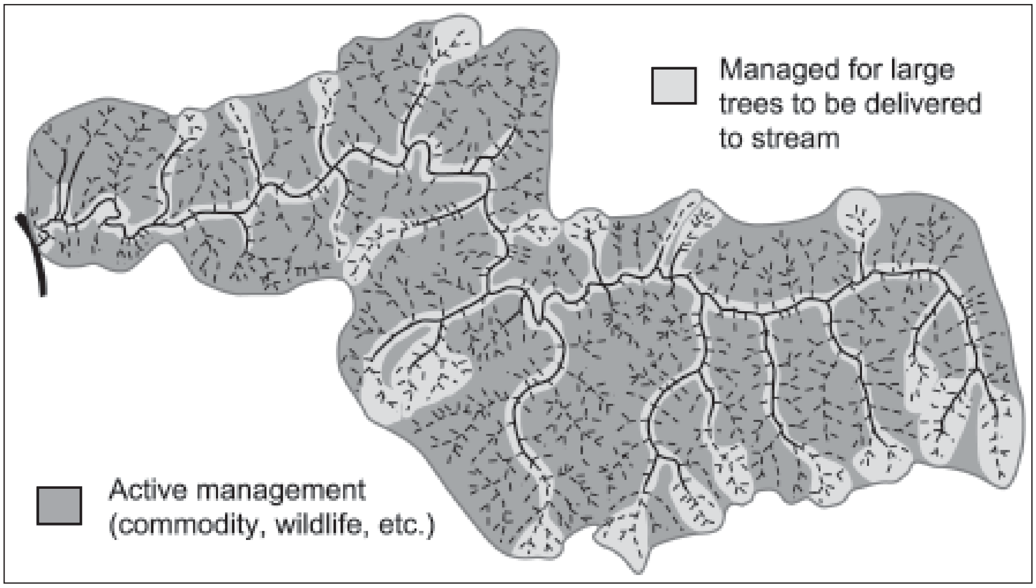


Figure 9—Location of small tributary streams in Knowles Creek watershed that are likely to deliver large wood to streams via debris torrents.

the network to the extent that the needs of wildlife, recreation, and other resources are met by protecting the streams with the highest potential to deliver large wood to fish-bearing streams.

The scale within which forest management practices are developed and implemented is the second critical issue that forest managers and regulators could address to improve the prospects of attaining riparian and aquatic habitat management goals. Most early forest practice rules sought to define the minimum width of buffer strips needed for aquatic habitat protection by examining the effects of individual riparian functions on aquatic habitats at the site scale. Attempting to quantify minimum buffer widths needed to maintain individual functions, however, overlooked other important functions and left no margin for error resulting from incomplete science or the unknown complexities of multiple functions operating in concert. For example, some site-scale studies have indicated that (also see table 2):

- Most large woody debris recruited to stream channels enters from riparian stands within 20 m of the channel (Martin et al. 1998, McDade et al. 1990, Murphy and Koski 1989).
- Tree canopies within 30 m of small streams provide the preponderance of shade to the water surface (Brazier and Brown 1973).

- Most sediment traveling from hillslopes to streams is effectively retained by buffers about 50 m wide (Ketcheson and Megahan 1996, Megahan and Ketcheson 1996, U.S. Army Corps of Engineers 1991), although steep hillslopes require greater widths for effective filtration (Lee et al. 1997).
- Brown bear feeding, loafing, and daybed areas in late-successional forests extend up to 150 m from salmon streams (USDA Forest Service 1997).

The degree to which studies of this type apply off site, or can be extrapolated to larger scales is sometimes unclear, but problems with such extrapolations have been documented. For example, McDade et al. (1990) found that about 90 percent of large woody debris came from within 20 m of the study stream. Their results, however, were based only on pieces for which they could document the source, thus excluding pieces transported into their study areas by high water or debris flows, and are therefore incomplete. Other more recent and comprehensive studies have shown very different results. For example, May and Gresswell (2003) have shown that 63 percent of debris flows originating in headwater basins of the Oregon Coast Range deliver wood directly to mainstem rivers. And, in a comprehensive study of wood recruitment in an Oregon coastal stream, Reeves et al. (2003) found that about 65 percent of the pieces of wood in the channel were delivered from upslope by landslides and debris flows and only 35 percent originated from streamside sources. Managers and policymakers need to carefully consider the validity of the available science when developing landscape management plans and policies.

Data from site-scale studies, however, have often been used to define buffer widths for private, state, or federal forest practices with uniform prescriptions for fish-bearing streams and streams with important effects on downstream water quality. Studies of this type, however, ignore watershed-scale ecological processes and fail to consider:

- Cumulative effects of forest practices at watershed scales.
- The extensive legacy of past forest practices on riparian and aquatic habitats.
- Holistic ecosystem-level functions of riparian areas that affect adjacent and remote terrestrial and aquatic ecosystems and vary by watershed or ecoregion.

In contrast, strategies currently in use on federal lands in the Northwest and southeast Alaska and on state and private lands in Washington have the option to use watershed- and provincial-scale scientific information in watershed analyses to pursue goals for riparian and aquatic habitat management. This leap in scale has challenged managers and policymakers in other jurisdictions to consider riparian and aquatic ecosystems at larger spatial scales, as opposed to the past focus on site, and in some cases watershed scales. Addressing larger spatial scales is often viewed simply as aggregating information from small scales for consideration at larger scales. However, O'Neill et al. (1986) pointed out that aggregation results in false and unattainable expectations for aquatic and riparian ecosystems, which in turn contributes to the contention surrounding riparian issues.

Hierarchy theory provides an appropriate framework for considering ecosystem issues at and between different spatial scales (Overton 1977). Each level within the hierarchies of ecosystems has unique properties and behaviors that are expressed over time. The properties of lower levels of organization are "averaged, filtered, and smoothed" as they are aggregated at higher levels of organization (O'Neill et al. 1986). Consequently, the range and variability in the properties and conditions of systems are relatively wide at lower levels of organization as compared to higher levels (Wimberly et al. 2000). For riparian ecosystems, the range of conditions seen at the site scale might range from a recently disturbed site, where there are no or only a few large trees, to a fully stocked site. The range at the watershed scale is likely to be smaller, i.e., the likelihood that all riparian zones would have no or few trees, or that all would be fully stocked with large trees, is small. The range of variation in the condition of riparian zones over time at the landscape scale is even smaller, implying that not all riparian zones within the landscape are likely to be in "good" condition at any point in time nor are they likely to be "poor."

One of the major tasks in focusing riparian policies and management at landscape scales will be to understand how the condition of riparian zones varies through time at all spatial scales and the ecological, social, and economic implications of this variation.

Understanding the relation between different spatial scales is imperative to developing successful future management policies and activities for riparian zones. The initial focus on riparian zones was to manage for a desired set of conditions at a specific site. The conditions were rather generic and applied to all riparian systems. Similar rules and regulations were adapted as the focus moved to the watershed. The failure to articulate or to recognize the consequences of doing so has contributed to the often intense and divisive debate about riparian management policies and practices. Shifting the focus to landscape levels will require recognition of the principles about hierarchy theory and the relation among levels of organization if future riparian policies are to be successful.

One of the major tasks in focusing riparian policies and management at landscape scales will be to understand how the condition of riparian zones varies through time at all spatial scales and the ecological, social, and economic implications of this variation. Currently, conditions of riparian ecosystems are expressed as a single condition (either density of certain size trees or basal area). This condition is expected (unrealistically) to be relatively constant through time and to be present on all riparian zones at the same time. Assuming that this expectation can simply be applied to higher spatial levels is at least partially responsible for the current disenchantment with riparian management. Focus at the landscape scale, however, will require an understanding of the dynamics of riparian systems over time at each spatial scale. It will also require that appropriate goals and objectives be established for the landscape. In the case of riparian zones, this will require identifying what is the appropriate fraction of the riparian zones that should be in "good" condition at any point in time. Also, it requires the articulation of policies that both recognize the dynamic nature of riparian zones and describe practices that allow the systems to express a range of desired conditions over time.

Third, there is emerging recognition that a comprehensive ecosystem approach to forest management could help managers achieve riparian management goals. As previously noted, we believe that forest practice rules applied from the 1970s to the early 1990s failed to achieve their goals for riparian management because they focused largely on defining minimum buffer widths for riparian protection at site scales. The strategies recently applied to national forest and BLM lands in western Oregon, Washington, and northwest California (NWFP), and to the Tongass National Forest in southeast Alaska (TLMP), can use watershed analysis to address ecosystem-level and watershed-scale processes that form and maintain riparian and aquatic habitats. This approach is likely to enhance protection of riparian ecosystems.

The basis for delineation of interim riparian zones in the NWFP, a less flexible and potentially less preferred strategy, was derived from two sets of curves showing the relation between various ecological functions provided by riparian zones and distance from the channel (figs. 3, 4). These curves were developed from the scientific literature that was available at the time and on professional judgment where sources of information were incomplete. The curves of ecological functions also provide a margin for error allowing for incomplete science, unknown cumulative effects, or strategic uncertainty in defining interim riparian zones prior to watershed analysis. We are unaware at this time of any evidence in the scientific literature that supports modifying or retracting the original curves. The science produced since then (i.e., 1993) has supported the original assumptions and judgments used in developing the FEMAT curves (e.g., Brosofske et al. 1997, Gomi et al. 2002, Reeves et al. 2003).

If provincial and watershed scales were universally employed in development of riparian management strategies on and off forested landscapes, a rational unified approach to management of riparian and aquatic ecosystems at the river basin scale could be achieved.

Forest practice rules currently in force in the Northwest and Alaska have not as yet been fully evaluated.

A fourth issue that could help managers attain riparian and aquatic habitat management goals is monitoring and evaluation of current forest practice rules. As previously noted, forest practice rules currently in force in the Northwest and Alaska have not as yet been fully evaluated. Although state and federal practices for riparian management are variable, all share commonalities aimed at protection, maintenance, and restoration of riparian and aquatic ecosystems. The effectiveness of current strategies and practices in achieving their stated goals while allowing utilization of timber or other resources, however, remains unknown. Large-scale, long-term, coordinated interagency monitoring efforts could help to resolve this issue. However, monitoring efforts of this scale are costly, have rarely been attempted, and even more rarely successfully completed. Some long-term monitoring is in progress in southeast Alaska (Martin et al. 1998), Oregon (State of Oregon 1997), and in the Northwest (Reeves et al. 2004), but results are as yet incomplete.

Considerations for Future Riparian Management on Forest Lands

Is it prudent to suggest alternative strategies for riparian management at this time given that current forest practice rules have not been fully evaluated? We believe the answer is yes and that moving forward now could:

- Result in new strategies that better address multiple resource management objectives at large spatial scales and timeframes.
- Facilitate concurrent monitoring and evaluation of several new and existing riparian management strategies.
- Develop new long-term management scenarios based on natural disturbance regimes that maintain the structure and function of riparian ecosystems within historical norms at the large watershed scale.
- Result in silvicultural advances for rapid restoration of riparian vegetation in the Pacific Northwest and parts of southeast Alaska that were historically damaged or destroyed by human activities.

The next steps in management of riparian and aquatic habitats in forested watersheds will build on recent advances in riparian management policies and require an extension of current thinking. Many current forest management strategies rely on inflexible site-specific management prescriptions because of their simplicity and ease of application at the field level. Most of these strategies allow some harvest of standing timber in riparian zones within a tree-length of streams, contributing to future loss of woody debris and channel structure. Even the NWFP and TLMP have inflexible default interim prescriptions that managers often apply in lieu of flexible custom watershed-scale designs that could be used.

Criteria for Next Steps

Short-term strategies could be developed within the context of watershed analysis as described in the Washington forest practice rules, NWFP, and TLMP. However, meeting riparian management goals at the large watershed scale is unlikely to succeed unless:

- Management plans account for and address all land uses including agriculture, urbanization, and dams.
- All involved stakeholders are included in policy decisionmaking.
- The effects are intensively monitored at large temporal and spatial scales.
- Plans address the sites in specific watersheds where key ecological processes contribute to maintenance of the quality of riparian and aquatic habitats.
- Plans account for the natural variations in watershed productivity at regional scales.

Strategies that account for the dynamic nature of natural watershed processes, the natural spatial and temporal fluctuations in the quality of riparian and aquatic habitats within watersheds, and natural variations in the structure and function of riparian ecosystems by ecoregion and geomorphic province could maintain and restore the structure and function of riparian ecosystems. One element of these strategies could emphasize silvicultural options for reducing the time required for riparian coniferous regeneration to achieve sizes that contribute large woody debris to stream channels. Focusing on these issues would strengthen future management strategies.

The probability of forest managers meeting riparian management goals, especially on state and private lands, could be enhanced by strategies that concurrently address two landscape conditions:

- Areas highly disturbed by human activities
- Areas largely undisturbed by human activities

Strategies that account for the dynamic nature of natural watershed processes, the natural spatial and temporal fluctuations in the quality of riparian and aquatic habitats within watersheds, and natural variations in the structure and function of riparian ecosystems by ecoregion and geomorphic province could maintain and restore the structure and function of riparian ecosystems.

Two timeframes:

- Current timeframe (short term)
- A timeframe some decades in the future (long term)

And, two spatial scales:

- The watershed scale
- A regional scale

These features, if considered in concert, could help managers attain their goals of sustained economical timber production from federal, state, and private forest lands consistent with sound management of soil, air, water, fish, wildlife, recreation, and scenic resources. Application of these features could maintain and restore the natural historical range of variability in riparian ecosystems but might result in timber production reduced from current levels. Human disturbances and their legacy are highly variable in watersheds across forested landscapes of the Pacific Northwest and southeast Alaska. Some watersheds are highly disturbed by human actions whereas others are not. Heavily disturbed watersheds may require different strategies than watersheds whose riparian and aquatic ecosystems are undisturbed or lightly disturbed by human activities and are well within historical norms of structure and function. Attempting to apply rigid management prescriptions at the watershed scale to these variable situations may not achieve desired riparian management goals.

Management strategies that consider both short and long timeframes enhance the probability of achieving riparian management goals. In the Pacific Northwest where the legacy of natural and human disturbances has altered habitats for numerous stocks of anadromous salmonids and other aquatic species listed as threatened or endangered under ESA, options for riparian management need to be broadened if recovery of stocks is to be achieved. In the near term (i.e., the next few decades), we believe the management strategies used in the NWFP, PACFISH, and TLMP that establish a landscape-scale network of habitat reserves, require watershed restoration, and either prescribe an extensive array of riparian buffers or require watershed analysis, could contribute to recovery of riparian and aquatic ecosystems. Full recovery of riparian structure and function from these actions, however, may require a century or more while riparian vegetation recovers sufficiently to again contribute large woody structure and bank stability to aquatic systems. While long-term recovery is taking place, ESA listings of more salmonid stocks and other aquatic species may occur, and additional extinctions are possible.

Management of riparian and aquatic ecosystems could also be addressed in a longer timeframe at the regional scale. The strategies used in the NWFP, PACFISH, and TLMP aim to restore all riparian and aquatic habitats to a high level of productivity and maintain them at that level in perpetuity. The strategies, however, fail to recognize the natural long-term dynamic processes of disturbance and renewal in riparian and aquatic systems and to recognize that, historically at the regional scale, productivity differed greatly among watersheds at any given point in time.

Management strategies recognizing the natural processes that degrade and renew riparian and aquatic ecosystems could help managers maintain long-term ecosystem productivity at the regional scale.

Management strategies recognizing the natural processes that degrade and renew riparian and aquatic ecosystems could help managers maintain long-term ecosystem productivity at the regional scale. Scientists are currently studying and modeling the long-term history of landscape succession in the Northwest (e.g., Benda et al. 1998, Boughton and Malvadkar 2002, Wimberly et al. 2000), and managers are beginning to incorporate this knowledge into management plans (Cissel et al. 1998). For example, as noted earlier, studies by Wimberly et al. (2000), indicate that during the past 3,000 years, at the province scale, the landscape of the Oregon Coast Range contained between 49 and 91 percent late-successional forest, and that the temporal and spatial distribution of late-successional forest stands varied with time across the region. Late-successional forests in the Coast Range now total about 11 percent of the landscape, well outside the historical range (fig. 6). One can assume that the productivity of riparian and aquatic ecosystems varied accordingly, and that the most productive watersheds for fishes also varied in time and space. To date, few management strategies have attempted to emulate natural landscape conditions where the productivity of watersheds and their riparian and aquatic habitats waxed and waned at large temporal and spatial scales. Long-term strategies that address riparian management at the large watershed or regional scale, that recognize natural variations in watershed productivity, and that plan to recover and maintain natural variability to assure long-term productivity at the regional scale are the next challenging step for forest managers.

Examples of Potential Riparian Management Strategies

Some good examples of ecologically based management strategies are emerging within single land ownerships at small watershed scales in the geographic area covered by the NWFP. Two examples from the Central Cascades Adaptive Management Area are worthy of note. Adaptive management areas were established for testing assumptions and practices in the NWFP and for developing and evaluating new management approaches. The two watersheds, Augusta Creek (7600 ha) and Blue River (23 900 ha), are subwatersheds of the McKenzie River watershed, tributary to the Willamette River in western Oregon. The plans for management of riparian and aquatic ecosystems in the Augusta Creek and Blue River watersheds (Cissel et al. 1998, 1999) are a significant departure from the inflexible default strategies in the NWFP and represent an ecologically-based, post-watershed-analysis implementation of the NWFP. Both plans are based on landscape strategies to sustain ecosystems with the goals of maintaining:

- Viable populations of native terrestrial and aquatic species.
- Ecosystem processes and structures.
- Long-term ecosystem productivity, including sustainable levels of timber harvest.

Both plans were based on historical fire regimes, the primary natural disturbance in the watersheds, rather than on the default interim strategy of the NWFP. Aquatic ecosystems and hillslope-to-stream disturbances were analyzed during the first phase in development of the plans. Particular attention was given to the history and potential of landslides and debris torrents and the susceptibility of certain areas of the watersheds to peak flows resulting from rain-on-snow events. Subsequently, reserves already designated under the Willamette National Forest Plan and the NWFP were delineated. Then the planning areas were subdivided into zones with similar ecological conditions and fire disturbance regimes, and management prescriptions were developed for each area. A network of aquatic reserves was then established in harmony with upslope management plans and natural disturbance processes. Aquatic reserves included riparian corridors along both sides of most major streams to meet riparian goals and provide linkage to other small watershed reserves located throughout the basins. In some cases, especially on small streams, no riparian reserves were designated. In those areas, extended timber rotations of 200+ years were prescribed. This, in essence, provided functional riparian reserves for about 140 years of each 200-year timber cycle for all small streams in those designated areas.

When the land allocations and management prescriptions were completed, the effects of the landscape plans were projected 200 years into the future with geographic information system models. After 100 years, the future landscape appeared significantly different from the existing landscape, and additional gradual changes continued until year 200. The landscape plans, in contrast to the pre-watershed-analysis default plan, resulted in:

- A less intense timber management regime with longer timber rotation age.
- Seventeen percent lower timber harvest but higher quality wood products, and more economically feasible harvest.
- A small-watershed reserve system designed to meet multiple resource objectives including maintenance of watershed processes and provision for late-successional forest habitats.
- A less extensive riparian reserve network (buffers eliminated on many streams in favor of long timber rotation ages) that allows for timber harvest more in accord with the historical spatial and temporal fire regime, yet meets aquatic and riparian objectives.
- Source management for large woody debris, sediment, and water quality to assure continued delivery of those features to aquatic ecosystems.
- A landscape that more closely approximates, yet does not exactly mimic, watersheds subjected only to natural disturbances.

The latter point is important. Management strategies cannot fully mimic natural disturbance regimes at small watershed scales because the resulting human disturbances are superimposed on existing natural disturbance regimes. The combination of natural and human disturbances may impose changes that push both structure and function of riparian ecosystems beyond historical norms, or possibly change structure but maintain function within historical norms. Long-term monitoring will be needed to assess the outcome. Nevertheless, the landscape strategies for Augusta Creek and Blue River watersheds come closer to emulating the natural processes that form and maintain riparian and aquatic ecosystems than any of their predecessors.

These two landscape plans were relatively easy to develop because they apply to small single-owner forested subwatersheds on an experimental forest where scientific energy has been focused for decades, and a large body of scientific information was readily available. Also, the NWFP provided an approved mechanism, watershed analysis, for developing landscape management strategies to meet NWFP goals. Broad application of landscape plans of this type, however, will be difficult because most subwatersheds lack the scientific information needed for their development. Although these plans are appropriate for their subwatersheds, their scale is too small to address riparian issues at the river basin or regional scale.

The combination of natural and human disturbances may impose changes that push both structure and function of riparian ecosystems beyond historical norms, or possibly change structure but maintain function within historical norms.

Options for other disturbance-based strategies for riparian management have been developed. Reeves et al. (1995) addressing the need for recovery of human-disturbed riparian and aquatic habitats in the Northwest, suggested that the short-term and long-term ecological processes that create and maintain freshwater habitats must be restored and protected. They assert that aquatic ecosystems throughout the regions are dynamic in time and space, and lack of consideration for their dynamic aspects has limited the effectiveness of habitat restoration programs. A new human-influenced disturbance regime that is analogous to historical natural disturbance regimes could facilitate recovery and persistence of aquatic and riparian habitats.

Reeves et al. (1995), using the Oregon Coast Range as an example, described several features of the proposed disturbance regime. First, they indicated that protecting riparian timber in source areas subject to mass erosion can accelerate recruitment of large woody debris to channels and help maintain aquatic habitat complexity in the long term. Second, they indicated that decreasing the frequency of disturbance from timber harvest by extending timber rotation age to 150 to 200 years is more in tune with the time required for favorable habitats to form following infusions of sediment and woody debris from wildfires and storms. Finally, they indicated that concentrating rather than dispersing management activities in large watersheds would more closely resemble the pattern generated by natural disturbances (fig. 10). Concentrating harvest activities in a single small sub-watershed may create less disturbance and fragmentation of habitats than dispersing the same amount of activity across the entire watershed. They also suggested that concentrating activities could be linked to planning for future reserves as compensation for existing reserves that will ultimately cycle through nonproductive phases.

Contrary to the concept that concentrating rather than dispersing activities is ecologically more similar to natural disturbances, most forest management activities in Northwest watersheds have been intentionally dispersed for decades.

Contrary to the concept that concentrating rather than dispersing activities is ecologically more similar to natural disturbances, most forest management activities in Northwest watersheds have been intentionally dispersed for decades. Dispersal was based on prior interpretations of scientific information that suggested ecological systems could accommodate and rapidly recover from human disturbances that were widely dispersed in time and space. Consequently, few opportunities currently exist in the Pacific Northwest to test the effects of concentrated versus dispersed human watershed disturbances. Testing this concept is technically feasible in southeast Alaska where some watersheds remain largely untouched by human activities. However, changes in forest practice rules might have to be made to allow concentration of forest harvest in individual subwatersheds before this theory could be evaluated.

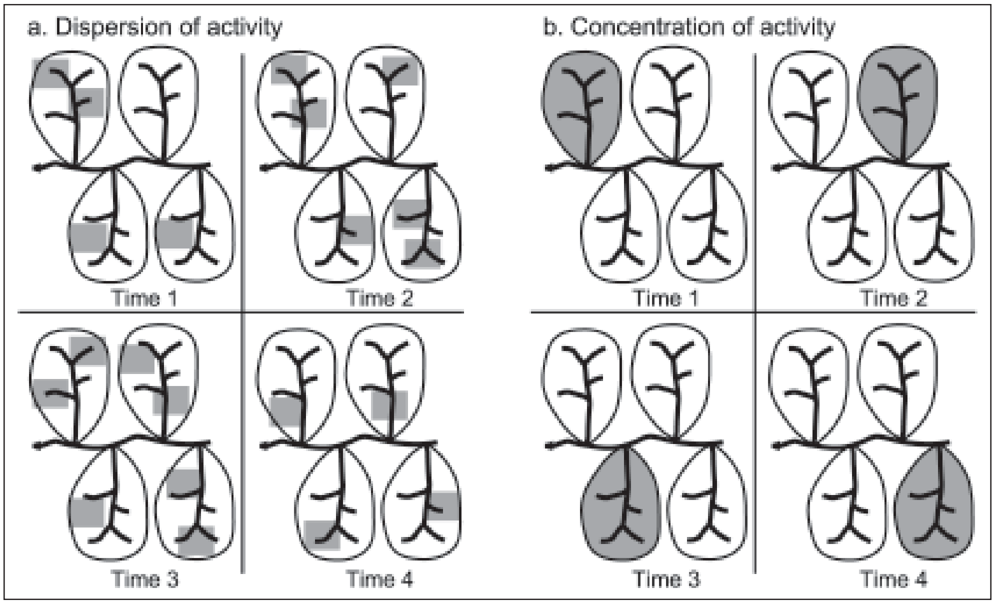


Figure 10—Examples of patterns resulting from (A) dispersing and (B) concentrating management activities in a watershed over time (from Reeves et al. 1995).

Development of landscape strategies at larger scales addressing multiple land ownerships and a variety of land uses, especially where participants might not share common goals, and where necessary scientific information may be lacking, can greatly complicate the process. At larger scales, conflicts between user groups over management of aquatic resources occur in nearly every river basin in the Pacific Northwest. State and federal agencies have often been ineffective in solving the broad array of riparian, aquatic, and water-related resource problems at this scale. In some cases, however, coalitions of user groups have demonstrated their willingness and ability to work together to solve problems related to land management and aquatic resources.

The Deschutes River Conservancy (DRC) provides a successful example of a coalition that has effectively addressed difficult issues related to resource management at the river-basin scale in Oregon. The DRC, a 14-member coalition representing all economic sectors in the basin, was formed in 1992 to address water-related conflicts, including riparian and aquatic habitat management. The conflicts revolve around rapidly increasing population; social values that no longer fully support current uses of terrestrial and aquatic resources and impacts from agriculture, ranching, and forest management; emerging interest in the region's recreation, tourism, residential, and industrial sectors; declining salmon runs;

mixed federal, state, tribal, and private land ownership; and the perception that environmental quality in the basin is deteriorating (Big River News 1997).

The DRC developed an assessment of basin resources, incentive-based approaches to addressing resource problems, and pilot projects to improve efficiency of agricultural water use in particular. Half of the water saved was dedicated to maintenance of instream flows for recreation and recovery of endangered salmonid species, and the remainder went to farming operations (Western Water Policy Review Advisory Commission 1998). The group also leased water to meet instream flow needs. The DRC is now a formally chartered, private corporation with a board composed of the basin's cattle, agricultural, environmental, recreational, tribal, hydropower, and land development interests and representatives from federal and state agencies. Congress has recognized the value of DRC and appropriated $1 million per year of federal matching funds for DRC projects.

Basin advisory groups provide a forum and a context for addressing riparian and aquatic habitat management at meaningful scales where advances in riparian management on the forested landscape can be coordinated with similar efforts on other land ownerships subjected to other land uses in river basins. Consequently, basin advisory groups can be an important vehicle for restoration of riparian and aquatic habitats and recovery of listed aquatic species in basins with mixed land ownerships and land uses. Land use planning at even larger scales, however, may be more effective than basin plans.

A province-scale research and planning effort, CLAMS, is under way in the coastal zone of Oregon. The CLAMS effort includes research to provide an integrated view of current conditions in the province, and potential landscape trajectories and consequences from pursuing various land management strategies. The project is precedent setting in several ways. First, it integrates ecological and socioeconomic interests across a variety of land ownerships and land uses, and addresses a key goal of recovering ESA-listed anadromous salmonid stocks through protection and restoration of riparian and aquatic habitats (Perez 2001). The program uses techniques and tools including satellite imagery of vegetation, roads, fire history, riparian forest condition, climate, geology, land ownership, and resource allocation patterns to accomplish province-scale planning (Perez 2001). The extensive, multilayered database is being used to develop landscape models that address cumulative effects of all land uses in long timeframes. A major strength of the project is the use of integrated ecosystem-level research to help policy-makers formulate management direction. Although the CLAMS project has not yet reached maturity, it has already demonstrated the usefulness of long-term integrated province-scale planning. Such efforts may be considered the harbinger of future ecosystem-level multiownership land use planning efforts.

We believe that continued movement toward science-based large-scale ecosystem-level management policies in which all concerned stakeholders are included in policy formulation is a promising direction for riparian management. The current state of scientific information on riparian ecosystems and disturbance ecology indicates that such large-scale efforts have a better chance of achieving riparian management goals than any previous management schemes. In reality, however, the future direction of riparian management will be determined, not by science, but by the normative decisions of policymakers who attempt to achieve a balance between ecosystem sustainability and the competing demands of resource users.

Continued movement toward science-based large-scale ecosystem-level management policies in which all concerned stakeholders are included in policy formulation is a promising direction for riparian management.

Conclusions

- The natural functions of riparian ecosystems are critically important to the maintenance of watershed hydrology, streamflows, water quality, stream nutrients, and habitat characteristics needed to maintain the viability of native aquatic species.
- An unusually rich assemblage of species uses riparian zones as compared to other ecosystems.
- Current natural disturbance regimes may be different than those of pre-European settlement (e.g., reduced frequency of stand-replacement fires).
- Human activities, including agriculture, urbanization, water developments, and forestry, have altered the structure and function of riparian ecosystems and their associated aquatic habitats over most of the landscape of the Pacific Northwest and a small portion of southeast Alaska.
- The structural characteristics of some riparian habitats in the Pacific Northwest are currently outside their natural historical range.
- Altered riparian ecosystems have contributed to changes in aquatic habitats, populations of aquatic species, and the listing of many aquatic species and fish stocks in the Pacific Northwest as threatened or endangered.
- Available evidence indicates that healthy riparian ecosystems and land management for resource production are not mutually exclusive; however, normative policy decisions can favor one outcome over the other.
- Improved riparian protection and restoration on forested lands is occurring, but recovery of altered habitats and listed species can only be accomplished by addressing all land uses at the river-basin scale.

- Current forest management strategies may not fully recognize or take advantage of known spatial and temporal variations in ecosystems.
- Despite more than half a century of timber harvest that has simplified riparian and aquatic habitats on forested landscapes in the Northwest, the highest water quality and best remaining fish habitats in the region are located on federal forest lands.
- Forest practice rules of the 1970s, 1980s, and early 1990s, collectively known as "best management practices" provided progressively more protection for riparian and aquatic habitats during the period, but nevertheless allowed harvest of more than 590 million m of timber with practices that we now see did not meet the stated goals of state and federal agencies.
- Current riparian management strategies in the NWFP and TLMP in southeast Alaska provide opportunities to achieve riparian ecosystem management at the watershed scale on federal forested lands.
- There is no scientific evidence that either the default prescriptions or the options for watershed analysis in the NWFP and TLMP provide more protection than necessary to meet stated riparian management goals.
- The current strategies for riparian management on private, state, and federal lands have not been fully evaluated for effectiveness.
- Additional alternative riparian management strategies could be implemented and evaluated in concert to shorten the time needed to realize effective strategies that fully meet riparian mangement goals.
- Emerging and future strategies for riparian management that are science-based, consider natural processes, and address large temporal and spatial scales in an interagency forum that includes all involved stakeholders appear to hold promise for the future.

English Equivalents

When you know:	Multiply by:	To find:
Hectares (ha)	2.47	Acres
Cubic meters (m^3)	35.3	Cubic feet
Meters (m)	3.28	Feet
Kilometers (km)	.6214	Miles
Square meters (m^2)	10.76	Square feet
Square kilometers (km^2)	.386	Square miles
Centimeters (cm)	.394	Inches
Cubic meters per second (m^3/s)	35.3	Cubic feet per second
Square meters per hectare (m^2/ha)	4.37	Square feet per acre
Kilometers per square kilometer (km/km^2)	1.61	Miles per square mile

Literature Cited

Aber, J.; Neilson, R.; McNulty, S. [et al.]. 2001. Forest processes and global environmental change: predicting the effects of individual and multiple stressors. BioScience. 51(9): 735-751.

Adams, P.W.; Stack, W.R. 1989. Streamwater quality after logging in southwest Oregon. Corvallis, OR: Oregon State University. 19 p. Project completion report (PNW 87-400) to USDA Forest Service, Pacific Northwest Research Station, Portland, Oregon.

Agee, J.K. 1991. Fire history along an elevational gradient in the Siskiyou Mountains, Oregon. Northwest Science. 65(4): 188-190.

Agee, J.K. 1993. Fire ecology of Pacific Northwest forests. Washington DC: Island Press. 493 p.

Alaska Department of Natural Resources [Alaska DNR]. 2000. Fact sheet: land ownership in Alaska. Anchorage, AK: Division of Mining, Land, and Water. http://www.dnr.state.ak.us/mlw/factsht/land_own.pdf. (12 May 2005).

Alaska Division of Forestry. 2001. Forest practices. http://www.dnr.state.ak.us/forestry/forestpractices.htm. (4 April 2005).

Alig, R.; Butler, B.J.; Swenson, J. 2000. Fragmentation and national trends in private forest lands: preliminary findings from the 2000 Renewable Resource Planning Act assessment. In: DeCoster, Lester A.; Sampson, N., eds. Proceedings, fragmentation 2000—a conference on sustaining private forests in the 21st century. Alexandria, VA: Sampson Group, Inc.: [Pages unknown].

Allan, J.D. 1995. Stream ecology: structure and function of running waters. London, UK: Chapman and Hall. 388 p.

Anderson, H.W. 1970. Relative contributions of sediment from source areas, and transport processes. In: Proceedings of a symposium on forest land uses and stream environment. Corvallis, OR: Oregon State University: 55-63.

Association of State Dam Safety Officials [ASDSO]. 2006. Storage projects. Lexington, KY. http://www.damsafety.org. (11 January 2006).

Baltz, D.M.; Vondracek, B.; Brown, L.R.; Moyle, P.B. 1987. Influence of temperature on microhabitat choice by fishes in a California stream. Transactions of the American Fisheries Society. 116: 12-20.

Beeson, C.E.; Doyle, P.E. 1995. Comparison of bank erosion at vegetated and non-vegetated channel bends. Water Resources Bulletin. 31(6): 983-990.

Benda, L.E. 1988. Debris flows in the Tyee sandstone formation of the Oregon Coast Range. Seattle, WA: University of Washington. 134 p. M.S. thesis.

Benda, L.E.; Cundy, T.W. 1990. Predicting deposition of debris flows in mountain channels. Canadian Geotechnical Journal. 27: 409-417.

Benda, L.E.; Miller, D.J.; Dunne, T. [et al.]. 1998. Dynamic landscape systems. In: Naiman, R.J.; Bilby, R.E., eds. River ecology and management: lessons from the Pacific coastal ecoregion. New York: Springer-Verlag: 261-288.

Benda, L.E.; Sias, J.C. 2002. A quantitative framework for evaluating the mass balance on in-stream organic debris. Forest Ecology and Management. 172: 1-16.

Bendix, J. 1994. Among-site variation in riparian vegetation of the southern California Transverse Ranges. American Midland Naturalist. 132(1): 136-151.

Berg, D.R. 1995. Riparian silvicultural system design and assessment in the Pacific Northwest Cascade Mountains, USA. Ecological Applications. 5(1): 87-96.

Beschta, R.L.; Bilby, R.E.; Brown, G.E. [et al.]. 1987. Stream temperature and aquatic habitat: fisheries and forestry interactions. In: Salo, E.O.; Cundy, T.W., eds. Streamside management: forestry and fishery interactions. Contrib. 57. Seattle, WA: University of Washington, Institute of Forest Resources: 192-232.

Big River News. 1997. The Deschutes basin at a crossroads. Portland, OR: Northwest Water Law and Policy Project, Northwestern School of Law, Lewis and Clark College. 3(2): [Pages unknown].

Bilby, R.E. 1979. The function and distribution of organic debris dams in forest stream ecosystems. Ithaca, NY: Cornell University. 143 p. Ph.D. dissertation.

Bilby, R.E. 1984. Removal of woody debris may affect stream channel stability. Journal of Forestry. 82: 609-613.

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

Bishop, D.M.; Stevens, M.E. 1964. Landslides on logged areas in southeast Alaska. Res. Pap. NOR-1. [Place of publication unknown]: U.S. Department of Agriculture, Forest Service, Northern Forest Experiment Station. 18 p.

Bisson, P.A.; Bilby, R.E.; Bryant, M.D. [et al.]. 1987. Large woody debris in forested streams in the Pacific Northwest: past, present, and future. In: Salo, E.O.; Cundy, T.W., eds. Streamside management: forestry and fishery interactions. Contrib. 57. Seattle, WA: University of Washington, Institute of Forest Resources: 143-190.

Bisson, P.A.; Raphael, M.G.; Foster, A.D.; Jones, L.L.C. 2002. Influences of site and landscape features on vertebrate assemblages in small streams. In: Johnson, A.C.; Haynes, R.W.; Monserud, R.A., eds. Congruent management of multiple resources: proceedings from the wood compatibility initiative workshop. Gen. Tech. Rep. PNW-GTR-563. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station: 61-72.

Bisson, P.A.; Rieman, B.E.; Luce, C. [et al.]. 2003. Fire and aquatic ecosystems of the Western USA: current knowledge and key questions. Forest Ecology and Management. 178: 213-229.

Bisson, P.A.; Sedell, J.R. 1984. Salmonid populations in streams in clearcut vs. old-growth forests of western Washington. In: Meehan, W.R.; Merrell, T.R.; Hanley, T.A., eds. Fish and wildlife relationships in old-growth forests: proceedings of a symposium. [Place of publication unknown]: American Institute of Fishery Research Biologists: 12-129.

Bliss, J.C. 2000. Public perceptions of clearcutting. Journal of Forestry. 48: 4-9.

Bolton, S.; Monohan, C. 2001. A review of the literature and assessment of research needs in agricultural streams in the Pacific Northwest as it pertains to freshwater habitat for salmonids. Seattle, WA: Center for Streamside Studies, University of Washington. 189 p.

Booth, D.B. 1991. Urbanization and the natural drainage system—impacts, solutions, and prognoses. Northwest Environmental Journal. 7: 93-118.

Bormann, B.T.; Spaltenstein, H.; McClellan, M.H. [et al]. 1995. Rapid soil development after windthrow disturbance in pristine forests. Journal of Ecology. 83: 747-757.

Botkin, D.; Cummins, K.; Dunne, T. [et al.]. 1995. Status and future of salmon of western Oregon and northern California: findings and options. Rep. 8. Santa Barbara, CA: Center for the Study of the Environment. 300 p.

Boughton, D.A.; Malvadkar, U.I. 2002. Extinction risk in successional landscapes subject to catastrophic disturbances. Conservation Ecology. 6(2): 2-18.

Brazier, J.R.; Brown, G.W. 1973. Buffer strips for stream temperature control. Res. Pap. 15. Corvallis, OR: Forest Research Laboratory, Oregon State University. 9 p.

Brosofske, K.D. 1996. Effects of harvesting on microclimate from small streams to uplands in western Washington. Houghton, MI: Michigan Technological University. 72 p. M.S. report.

Brosofske, K.D.; Chen, J.; Naiman, R.F.; Franklin, J.F. 1997. Harvesting effects on microclimate gradients from small streams to uplands in western Washington. Ecological Applications. 7(4): 1188-1200.

Brown, G.W.; Krygier, J.T. 1970a. Clearcut logging and sediment production in the Oregon Coast Range. Res. Pap. 768. Corvallis, OR: Oregon State University. 21 p.

Brown, G.W.; Krygier, J.T. 1970b. Effects of clearcutting on stream temperature. Water Resources Research. 6(4): 1133-1139.

Brown, G.W.; Krygier, J.T. 1971. Clear-cut logging and sediment production in the Oregon Coast Range. Water Resources Research. 7: 1189-1198.

Burnett, K.; Reeves, G.; Miller, D. [et al.]. 2003. A first step toward broad-scale identification of freshwater protected areas for Pacific salmon and trout in Oregon, USA. In: Beumer, J.P.; Grant, A.; Smith, D.C., eds. Aquatic protected areas: What works best and how do we know? Proceedings of the world congress on aquatic protected areas. North Beach, WA, Australia: Australian Society for Fish Biology: 144-154.

Burns, J.W. 1972. Some effects of logging and associated road construction on northern California streams. Transaction of the American Fisheries Society. 101: 1-17.

Buskirk, S.W.; Forrest, S.C.; Raphael, M.G.; Harlow, H.J. 1989. Winter resting site ecology of marten in the central Rocky Mountains. Journal of Wildlife Management. 53(1): 191-196.

Caldwell, J.E.; Doughty, K.; Sullivan, K. 1991. Evaluation of downstream temperature effects of type 4/5 waters. Timber, Fish, and Wildlife TFW Rep. WQ5-91-004. Olympia, WA: Department of Natural Resources. 71 p.

Calhoun, A.; Seeley, C. 1963. Logging damage to California streams—1962. Inland Fish. Admin. Rep. 63-2. [Place of publication unknown]: California Department of Fish and Game. 15 p.

Canham, C.D.; Papaik, M.J.; Latty, E.F. 2001. Interspecific variation in susceptibility to windthrow as a function of tree size and storm severity for northern temperate tree species. Canadian Journal of Forest Research. 31(1): 1-10.

Carlson, A. 1991. Characterization of riparian management zones and upland management areas with respect to wildlife habitat. Timber, Fish, and Wildlife Rep. TFW WLI-91-001. Olympia, WA: Washington Department of Natural Resources. 25 p. with appendices.

Chapman, D.W. 1962. Effects of logging upon fish resources of the west coast. Journal of Forestry. 60(8): 533-537.

Chapman, D.W.; Knudsen, E. 1980. Channelization and livestock impacts on salmonid habitat and biomass in western Washington. Transactions of the American Fisheries Society. 109: 357-363.

Chen, J. 1991. Edge effects: microclimatic patterns and biological responses in old-growth Douglas-fir forests. Seattle, WA: University of Washington. 174 p. Ph.D. dissertation.

Chen, J.; Naiman, R.J.; Franklin, J.F. 1995. Microclimatic patterns and forest structure across riparian ecosystems. Seattle, WA: Center for Forestry Research, University of Washington; final report; contract USDA, FS-PNW-378409.

Cherry, J.; Beschta, R.L. 1989. Coarse woody debris and channel morphology: a flume study. Water Resources Bulletin. 25(5): 1031-1036.

Cissel, J.H.; Swanson, F.J.; Grant, G.E. [et al.]. 1998. A landscape plan based on historical fire regimes for a managed forest ecosystem: the Augusta Creek study. Gen. Tech. Rep. PNW-GTR-422. Portland OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station. 82 p.

Cissel, J.H.; Swanson, F.J.; Weisberg, P.J. 1999. Landscape management plan using historical fire regimes: Blue River, Oregon. Ecological Applications. 9(4): 1217-1231.

Clark, G.M.; Maret, T.R.; Rupert, M.G. [et al.]. 1998. Water quality in the Upper Snake River Basin, Idaho and Wyoming, 1992-95. U.S. Geological Survey Circular 1160. Reston, VA: U.S. Department of the Interior, U.S. Geological Survey. http://water.usgs.gov/pubs/circ/circ1160. (4 January 2006).

Climate Impacts Group. 2004. Overview of climate change impacts in the U.S. Pacific Northwest. Seattle, WA: University of Washington. 13 p. http://www.cses.washington.edu/db/pdf/cigoverview353.pdf. (4 January 2006).

Clinton, S.M.; Edwards, R.T.; Naiman, R.J. 2002. Forest-river interactions: influence on hyporheic dissolved organic carbon concentrations in a floodplain terrace. Journal of the American Water Resources Association. 38(3): 619-631.

Coghlan, G.; Sowa, R. 1998. National forest road system and use. Washington, DC: U.S. Department of Agriculture, Forest Service, Engineering Staff. 28 p. http://www.fs.fed.us/eng/road_mgt/roadsummary. (11 April 2005).

Collier, K.J.; Bury, S.; Gibbs, M. 2002. A stable isotope study of linkages between stream and terrestrial food webs through spider predation. Freshwater Biology. 47: 1651-1659.

Cordone, A.J. 1956. Effects of logging on fish production. Inland Fish. Admin. Rep. 56-7. [Place of publication unknown]: California Department of Fish and Game. 98 p.

Correll, D. 2003. Vegetated stream riparian zones: their effects on stream nutrients, sediments, and toxic substances (an annotated and indexed bibliography of the world literature, including buffer strips and interactions with hyporheic zones and floodplains). http://www.unl.edu/nac/ripzone03.htm. (10 January 2006).

Dambacher, J.M. 1991. Distribution, abundance, and emigration of juvenile steelhead (*Oncorhynchus mykiss*), and analysis of stream habitat in the Steamboat Creek basin, Oregon. Corvallis, OR: Oregon State University. 129 p. M.S. thesis.

Deal, R.L.; Oliver, C.D.; Bormann, B.T. 1991. Reconstruction of mixed hemlock-spruce stands in coastal southeast Alaska. Canadian Journal of Forest Research. 21: 643-654.

Dent, L.F.; Walsh, J.B.S. 1997. Effectiveness of riparian management areas and hardwood conversions in maintaining stream temperature. Forest Practices Tech. Rep. 3. Salem, OR: Oregon Department of Forestry, Forest Practices Monitoring Program. 58 p.

Desbonnet, A.; Pogue, P.; Lee, V.; Wolf, N. 1994. Vegetated buffers in the coastal zone: a summary review and bibliography. Narragansett, RI: Rhode Island Sea Grant, University of Rhode Island. 71 p.

DeWitt, J.W. 1968. Streamside vegetation and small coastal salmon streams. In: Proceedings of a forum on the relation between logging and salmon. Juneau, AK: American Institute of Fishery Research Biologists: 38-47.

Drake, D.C.; Naiman, R.J.; Helfield, J.M. 2002. Reconstructing salmon abundance in rivers: an initial dendrochronological evaluation. Ecology. 83: 2971-2977.

Dyrness, T.C. 1965. The effects of logging and slash burning on understory vegetation in the H.J. Andrews Experimental Forest. Res. Note 31. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Forest and Range Experiment Station. 13 p.

Dyrness, T.C. 1967. Mass soil movements on the H.J. Andrews Experimental Forest. Res. Pap. PNW-42. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Forest and Range Experiment Station. 12 p.

Ebersole, J.L.; Liss, W.J.; Frissel, C.A. 1997. Restoration of stream habitat in the Western United States: restoration as reexpression of habitat capacity. Environmental Management. 21: 1-14.

Erman, D.C.; Newbold, J.D.; Roby, K.B. 1977. Evaluation of streamside buffer strips for protecting aquatic organisms. Davis, CA: California Water Resources Center, University of California. 50 p.

Everest, F.; Swanston, D.; Shaw, C., III [et al.]. 1997. Evaluation of the use of scientific information in developing the 1997 forest plan for the Tongass National Forest. Gen. Tech. Rep. PNW-GTR-415. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station. 69 p.

Everest, F.H.; Armantrout, N.B.; Keller, S.M. [et al.]. 1985. Salmonids. In: Brown, E.R., ed. Management of wildlife and fish habitats in forests of western Oregon and Washington. Part 1: Chapter narratives. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Region: 199-230.

Everest, F.H.; Beschta, R.L.; Scrivener, J.C. [et al.]. 1987. Fine sediment and salmonid production: a paradox. In: Salo, E.O.; Cundy, T.W., eds. Proceedings of a symposium. Streamside management: forestry and fishery interactions. Contrib. 57. Seattle, WA: University of Washington, Institute of Forest Resources: 98-142.

Everest, F.H.; Harr, R.D. 1982. Silvicultural treatments. In: Meehan, W.R., tech. ed. Influence of forest and rangeland management on anadromous fish habitat in western North America. Gen. Tech. Rep. PNW-96. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Forest and Range Experiment Station. 19 p.

Everest, F.H.; Kakoyannis, C.; Houston, L. [et al.]. 2004. A synthesis of scientific information on emerging issues related to use and management of water resources on forested landscapes of the Pacific Northwest. Gen. Tech. Rep. PNW-GTR-595. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station. 128 p.

Federal Register. 2000. Unified federal policy for a watershed approach to federal land and resource management. Federal Register. Volume 65, No. 202, October 18, 2000.

Feller, M.C. 1981. Effects of clearcutting and slash burning on stream temperature in southwestern British Columbia. Water Resources Bulletin. 17(5): 863-867.

Fennessy, M.S.; Cronk, J.K. 1997. The effectiveness and restoration potential of riparian ecotones for the management of nonpoint source pollution, particularly nitrate. Critical Reviews in Environmental Science and Technology. 27(4): 285-317.

Forest Ecosystem Management Assessment Team [FEMAT]. 1993. Forest ecosystem management: an ecological, economic, and social assessment. Portland, OR: U.S. Department of Agriculture; U.S. Department of the Interior [et al.]. [Irregular pagination].

Fredriksen, R.L. 1970. Erosion and sedimentation following road construction and timber harvest on unstable soils in three small western Oregon watersheds. Res. Pap. PNW-104. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Forest and Range Experiment Station. 19 p.

Frick, E.A.; Hippe, D.J.; Buell, G.R. [et al.]. 1998. Water quality in the Apalachicola-Chattahoochee-Flint Basin, Georgia, Alabama, and Florida, 1992-1995. U.S. Geological Survey Circular 1164. Reston, VA: U.S. Department of the Interior, U.S. Geological Survey. 38 p. http://water.usgs.gov/pubs/circ/circ1164. (11 April 2005).

Furniss, M.J.; Roelofs, T.D.; Yee, C.S. 1991. Road construction and maintenance. Special Publ. 19. Bethesda, MD: American Fisheries Society: 297-323.

Gara, R.I.; Littke, W.R.; Agee, J.K. [et al.]. 1985. Influence of fires, fungi, and mountain pine beetles on development of a lodgepole pine forest in south-central Oregon. In: Baumgartner, D.M., ed. Lodgepole pine: the species and its management. Pullman, WA: Cooperative Extension, Washington State University: 153-162.

Gibbons, D.R.; Salo, E.O. 1973. An annotated bibliography of the effects of logging on fish of the Western United States and Canada. Gen. Tech. Rep. PNW-10. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Forest and Range Experiment Station. 145 p.

Gilliam, J.W. 1994. Riparian wetlands and water quality. Journal of Environmental Quality. 23: 896-900.

Gomi, T.; Sidel, R.C.; Richardson, J.S. 2002. Understanding processes and downstream linkages of headwater streams. BioScience. 52: 905-916.

Gregory, S.; Ashkenas, L. 1990. Field guide for riparian management, Willamette National Forest. U.S. Department of Agriculture, Forest Service, Willamette National Forest. 65 p.

Gregory, S.V.; Bisson, P.A. 1997. Degradation and loss of anadromous salmonid habitat in the Pacific Northwest. In: Stouder, D.J.; Bisson, P.A.; Naiman, R.J., eds. Pacific salmon and their ecosystems. New York: Chapman and Hall: 277-314.

Gregory, S.V.; Swanson, F.J.; McKee, W.A.; Cummins, K.W. 1991. An ecosystem perspective of riparian zones. BioScience. 41: 540-551.

Hairston-Strang, A.B.; Adams, P.W. 1998. Potential large woody debris sources in riparian buffers after harvesting in Oregon, U.S.A. Forest Ecology and Management. 112: 67-77.

Hall, F.C.; McComb, C.; Ruediger, W. 1985. Silvicultural options. In: Brown, E.R., ed. Management of wildlife and fish habitats in forests of western Oregon and Washington. Part 1–Chapter narratives. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Region: 291-306. Chapter 14.

Hall, J.D.; Lantz, R.L. 1969. Effects of logging on the habitat of coho salmon and cutthroat trout in coastal streams. In: Northcote, T.G., ed. Symposium on trout and salmon in streams. Vancouver, BC: University of British Columbia: 355-375.

Hare, S. 1998. The Pacific decadal oscillation. Fisheries Forum. Seattle, WA: College of Ocean and Fishery Sciences, University of Washington. 6(1): 5, 10.

Hare, S.R.; Mantua, N.J.; Francis, R.C. 1999. Inverse production regimes: Alaska and the west coast Pacific salmon. Fisheries. 24 (1): 6-14.

Harris, A.S. 1989. Wind in the forests of southeast Alaska and guides for reducing damage. Gen. Tech. Rep. PNW-244. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station. 63 p.

Harris, A.S.; Farr, W.A. 1974. The forest ecosystem of southeast Alaska. 7: Forest ecology and timber management. Gen. Tech. Rep. PNW-25. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Forest and Range Experiment Station. 109 p.

Hartman, G.F.; Scrivener, J.C. 1990. Impacts of forestry practices on a coastal stream ecosystem, Carnation Creek, British Columbia. Canadian Bulletin of Fisheries and Aquatic Sciences. 223.

Haupt, H.F. 1959. Road and slope characteristics affecting sediment movement from logging roads. Journal of Forestry. 57: 329-332.

Helfield, J.M.; Naiman, R.J. 2001. Effects of salmon-derived nitrogen on riparian forest growth and implications for stream productivity. Ecology. 82: 2403-2409.

Helfield, J.M.; Naiman, R.J. 2002. Salmon and alder as nitrogen sources to riparian forests in a boreal Alaskan watershed. Oecologia. 133: 573- 582.

Heller, D.; Dose, J.; Doyle, J. [et al.]. 1991. Review of land and resource management plans. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Region. 8 p.

Hennon, P.E. 1995. Are heart rot fungi major factors of disturbance in gap-dynamics forests? Northwest Science. 69: 284-293.

Hicks, B.J.; Hall, J.D.; Bisson, P.A.; Sedell, J.R. 1991. Responses of salmonids to habitat changes. In: Meehan, W.R., ed. Influences of forest and rangeland management on salmonid fishes and their habitats. Special Publ. 19. Bethesda, MD: American Fisheries Society: 483-518.

Hillman, T.W. 1991. The effects of temperature on the spatial interactions of juvenile Chinook salmon and redside shiners and their morphological differences. Pocatello, ID: Idaho State University. 90 p. Ph.D. dissertation.

Hohler, D.; Sedell, J.; Olson, D. 2001. Aquatic conservation strategy. In: Haynes, R.W.; Perez, G.E., tech. eds. Northwest Forest Plan research synthesis. Gen. Tech. Rep. PNW-GTR-498. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station: 30-39.

Holtby, L.B. 1988. Effects of logging on stream temperatures in Carnation Creek, British Columbia and associated impacts on coho salmon (*Oncorhynchus kisutch*). Canadian Journal of Fisheries and Aquatic Sciences. 45: 502-515.

Holter, J. 2001. The history of Washington's forest practices rules. Olympia, WA: Washington State Department of Natural Resources. http://www.dnr.wa.gov/forestpractices/rules/. (8 October 2005).

Hornbeck, J.W.; Kochenderfer, J.N. 2000. Linkages between forests and streams: a perspective in time. In: Verry, E.S.; Hornbeck, J.W.; Dolloff, C.A., eds. Riparian management in forests of the continental Eastern United States. New York: Lewis Publishers: 89-98.

Ilhardt, B.L.; Verry, E.S.; Palik, B.J. 2000. Defining riparian areas. In: Verry, E.S.; Hornbeck, J.W.; Dolloff, C.A., eds. Riparian management in forests of the continental Eastern United States. New York: Lewis Publishers: 23-42.

Independent Multidisciplinary Science Team [IMST]. 1999. Recovery of wild salmonids in western Oregon forests: Oregon Forest Practices Act rules and the measures in the Oregon plan for salmon and watersheds. Tech. Rep. 1999-1 to the Oregon Plan for Salmon and Watersheds, Governor's Natural Resources Office, Salem, OR. Corvallis, OR: Oregon State University.

Iwamoto, R.N.; Salo, E.O.; Madje, M.A.; McComas, R.L. 1978. Sediment and water quality: a review of the literature including a suggested approach for water quality criteria. EPA 910/9-78-048. Seattle, WA: U.S. Environmental Protection Agency Region X. [Pages unknown].

Jones, J.A.; Swanson, F.J.; Wemple, B.C.; Snyder, K.U. 2000. Effects of roads on hydrology, geomorphology, and disturbance patches in stream networks. Conservation Biology. 14(1): 76-85.

Kaczynski, V.W.; Palmisano, J.F. 1993. Oregon's wild salmon and steelhead trout: a review of the impact of management and environmental factors. Salem, OR: Oregon Forest Industries Council. 328 p.

Karr, J.R.; Schlosser, I. 1977. Impact of nearstream vegetation and stream morphology on water quality and stream biota. EPA 600/3-77/097. Washington, DC: U.S. Environmental Protection Agency. [Pages unknown].

Kelsey, K.A.; West, S.D. 1998. 10: Riparian wildlife. In: Naiman, R.J.; Bilby, R.E., eds. River ecology and management: lessons from the Pacific coastal ecoregion. New York: Springer-Verlag: 235-252.

Ketcheson, G.L.; Megahan, W.F. 1996. Sediment production and downslope sediment transport from forest roads in granitic watersheds. Res. Pap. INT-RP-486. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Research Station. 11 p.

Kline, J.D.; Alig, R.J. 2001. A spatial model of land use change for western Oregon and western Washington. Res. Pap. PNW-RP-528. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station. 24 p.

Klock, G.O.; Helvey, J.D. 1976. Debris flows following wildfire in north central Washington. In: Proceedings of the third federal inter-agency sedimentation conference. Washington, DC: Water Resources Council: 91-98.

Koltun, G.F.; Landers, M.N.; Nolan, K.M.; Parker, R.S. 1997. Sediment transport and geomorphology issues in the water resources division. Proceedings of the U.S. Geological Survey sediment workshop: Expanding sediment research capabilities in today's USGS. [Place of publication unknown]: U.S. Geological Survey. http://water.usgs.gov/osw/techniques/workshop/koltun.html. (22 April 2005).

Kramer, M.G. 1997. Abiotic controls on windthrow and forest dynamics in a coastal temperate rainforest, Kuiu Island, southeast Alaska. Bozeman, MT: Montana State University. [Pages unknown]. M.S. thesis.

Krygier, J.T.; Hall, J.T. 1971. Forest land uses and the stream environment: Proceedings of a symposium. Corvallis, OR: College of Forestry, Department of Fisheries and Wildlife, Oregon State University. 252 p.

Larse, R.W. 1971. Prevention and control of erosion and stream sedimentation from forest roads. In: Krygier, J.T.; Hall, J.T., eds. Forest land uses and stream environment: Proceedings of a symposium. Corvallis, OR: Oregon State University: 76-83.

Larson, B.M.H.; Waldron, G.E. 2000. Catastrophic windthrow in Rondeau Provincial Park, Ontario. The Canadian Field-Naturalist. 114(1): 78-82.

Lawford, R.G.; Alaback, P.B.; Fuentes, E., eds. 1996. High-latitude rainforests and associated ecosystems of the west coast of the Americas: climate, hydrology, ecology and conservation. New York: Springer-Verlag. 409 p.

Lee, D.C.; Sedell, J.R.; Rieman, B.E. [et al.]. 1997. Broadscale assessment of aquatic species and habitats. In: Quigley, T.M.; Arbelbide, S.J., tech. eds. An assessment of ecosystem components in the Interior Columbia basin and portions of the Klamath and Great Basins. Gen. Tech. Rep. PNW-GTR-405. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station: 1057-1495. Volume 3, Chapter 4.

Leopold, L.B.; Wolman, M.G.; Miller, J.P. 1964. Fluvial processes in geomorphology. San Francisco, CA: W.H. Freeman and Company. 522 p.

Levno, A.; Rothacher, J. 1967. Increases in maximum stream temperatures after logging in old-growth Douglas-fir watersheds. Res. Note PNW-65. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Forest and Range Experiment Station. 12 p.

Lins, H.F. 1997. Regional streamflow regimes and hydroclimatology of the United States. Water Resources Research. 33: 1655-1667.

Lohmander, P.; Helles, F. 1987. Windthrow probability as a function of stand characteristics and shelter. Scandinavian Journal of Forest Research. 2(2): 227-238.

Long, C.J. 1995. Fire history of the central Coast Range, Oregon: a ca. 9000 year record from Little Lake. Eugene, OR: University of Oregon. 147 p. M.A. thesis.

Malanson, G.P. 1993. Riparian landscapes. Cambridge, UK: Cambridge University Press. 306 p.

Mantua, N.J.; Hare, S.R.; Zhang, Y. [et al.]. 1997. A Pacific climate oscillation with impacts on salmon production. Bulletin of the American Meteorological Society. 78: 1069-1079.

Martin, D.J. 2001. The influence of geomorphic factors and geographic region on large woody debris loading and fish habitat in Alaska coastal streams. North American Journal of Fisheries Management. 21: 429-440.

Martin, D.J.; Robinson, M.E.; Grotefendt, R.A. 1998. The effectiveness of riparian buffer zones for protection of salmonid habitat in Alaska coastal streams. Report prepared for Sealaska Corporation and the Alaska Forestry Association by Martin Environmental, 2103 N 62nd Street, Seattle, WA. 85 p.

Mason, R.R.; Scott, D.W.; Loewen, M.D.; Paul, H.G. 1998. Recurrent outbreak of the Douglas-fir tussock moth in the Malheur National Forest: a case history. Gen. Tech. Rep. PNW-GTR-402. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station. 14 p.

May, C.L. 2001. Spatial and temporal dynamics of sediment and wood in headwater streams in the central Oregon Coast Range. Corvallis, OR: Oregon State University. 159 p. Ph.D. dissertation.

May, C.L.; Gresswell, R.E. 2003. Spatial and temporal patterns of debris-flow deposition in the Oregon Coast Range, USA. Geomorphology. 1362(2003): 1-15.

McDade, M.H.; Swanson, F.J.; McKee, W.A. [et al.]. 1990. Source distances for coarse woody debris entering small streams in western Oregon and Washington. Canadian Journal of Forest Research. 20: 326-330.

McHenry, M.L.; Schott, E.; Conrad, R.H.; Grette, G.B. 1998. Changes in the quantity and characteristics of large woody debris in streams in the Olympic Peninsula, Washington, U.S.A. (1982-1993). Canadian Journal of Fisheries and Aquatic Sciences. 55: 1395-1407.

McKenzie, D.; Gedalof, Z.M.; Peterson, D.L.; Mote, P.W. 2004. Climatic change, wildfire, and conservation. Conservation Biology. 18(4): 890-902.

Meehan, W.R. 1968. Relationship of shade cover to stream temperature in southeast Alaska. In: Proceedings of a forum on the relation between logging and salmon. Juneau, AK: American Institute of Fishery Research Biologists: 115-131.

Meehan, W.R., ed. 1991. Influences of forest and rangeland management on salmonid fishes and their habitats. Special Publ. 19. Bethesda, MD: American Fisheries Society. 751 p.

Meehan, W.R.; Farr, W.A.; Bishop, D.M.; Patric, J.H. 1969. Effects of clearcutting on salmon habitat in two southeast Alaska streams. Res. Pap. PNW-82. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Forest and Range Experiment Station. 45 p.

Megahan, W.F.; Ketcheson, G.L. 1996. Predicting downslope travel of granitic sediments from forest roads in Idaho. Water Resources Bulletin. 32(2): 371-382.

Miller, C.; Staebler, R.; Coufal, J.E. 1999. The greatest good: 100 years of American forestry. Bethesda, MD: Society of American Foresters. 136 p.

Mills, T.; Everest, F.; Janik, P. [et al.]. 1998. Science-management collaboration: lessons from the revision of the Tongass National Forest Plan. Western Journal of Applied Forestry. 13(3): 90-96.

Minshall, G.W. 2003. Responses of stream benthic macroinvertebrates to fire. Forest Ecology and Management. 178: 155-161.

Minshall, G.W.; Cummins, K.W.; Peterson R.C. [et al.]. 1985. Development in stream ecosystem theory. Canadian Journal of Fisheries and Aquatic Sciences. 42: 1045-1055.

Minshall, G.W.; Robinson, C.T.; Lawrence, D.E. 1997. Immediate and mid-term responses of lotic ecosystems in Yellowstone National Park, USA to wildfire. Canadian Journal of Fisheries and Aquatic Sciences. 54: 2509-2525.

Minshall, G.W.; Royer, T.V.; Robinson, C.T. 2001. Response of the Cache Creek macroinvertebrates during the first 10 years following disturbance by the 1988 Yellowstone wildfires. Canadian Journal of Fisheries and Aquatic Sciences. 58: 1077-1088.

Montgomery, D.R. 1999. Process domains and the river continuum. Journal of the American Water Resources Association. 35(2): 397-410.

Moore, F. 1971. Commentary–North Umpqua situation. In: Krygier, J.T.; Hall, J.T., eds. Forest land uses and stream environment: proceedings of a symposium. Corvallis, OR: College of Forestry and Department of Fisheries and Wildlife, Oregon State University: 237-239.

Moring, J.R. 1975. The Alsea Watershed study: effects of logging on the aquatic resources of three headwater streams of the Alsea River, Oregon, Part II–Changes in environmental conditions. Fish. Res. Rep. 9, Federal Aid to Fish Restoration Project AFS-58. Corvallis, OR: Oregon Department of Fish and Wildlife. 39 p.

Moring, J.R.; Lantz, R.L. 1975. The Alsea Watershed study: effects of logging on the aquatic resources of three headwater streams of the Alsea River, Oregon, Part I–Biological studies. Fish. Res. Rep. 9, Federal Aid to Fish Restoration Project AFS-58. Corvallis, OR: Oregon Department of Fish and Wildlife. 66 p.

Morman, D. 1993. Riparian rules effectiveness study. Salem, OR: Oregon Department of Forestry, Forest Practices Program. 198 p.

Morrison, P.H. 1975. Ecological and geomorphological consequences of mass movements in the Alder Creek watershed and implications for forest management. Eugene, OR: University of Oregon. [Pages unknown]. Bachelor's thesis.

Morrison, P.H.; Swanson, F.J. 1990. Fire history and pattern in a Cascade Range landscape. Gen. Tech. Rep. PNW-GTR-254. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Forest and Range Experiment Station. 77 p.

Murphy, M.L. 1995. Forestry impacts on freshwater habitat of anadromous salmonids in the Pacific Northwest and Alaska—requirements for protection and restoration. Decision Analysis Series 7. Silver Spring, MD: U.S. Department of Commerce, National Oceanic and Atmospheric Administration, Coastal Ocean Office. 156 p.

Murphy, M.L.; Hall, J.D. 1981. Varied effects of clear-cut logging on predators and their habitat in small streams of the Cascade Mountains, Oregon. Canadian Journal of Fisheries and Aquatic Sciences. 38: 137-145.

Murphy, M.L.; Heifetz, J.; Johnson, S.W. [et al.]. 1986. Effects of clear-cut logging with and without buffer strips on juvenile salmonids in Alaskan streams. Canadian Journal of Fisheries and Aquatic Sciences. 43: 1521-1533.

Murphy, M.L.; Koski K. 1989. Input and depletion of woody debris in Alaska streams and implications for streamside management. North American Journal of Fisheries Management. 9(4): 427-436.

Naiman, R.J. 1983. The annual pattern and spatial distribution of aquatic oxygen metabolism in boreal forest watersheds. Ecological Monographs. 53: 73-94.

Naiman, R.J., ed. 1992. Watershed management: balancing sustainability and environmental change. New York: Springer-Verlag. 542 p.

Naiman, R.J.; Beechie, T.J.; Benda, L.E. [et al.]. 1992. Fundamental elements of ecologically healthy watersheds in the Pacific Northwest coastal region. In: Naiman, R.J., ed. Watershed management: balancing sustainability and environmental change. Seattle, WA: University of Washington, Center for Streamside Studies: 127-188.

Naiman, R.J.; Bilby, R.E.; Schindler, D.E.; Helfield, J.M. 2002. Pacific salmon, nutrients, and the dynamics of freshwater and riparian ecosystems. Ecosystems. 5: 399-417.

Naiman, R.J.; Decamps, H.; Pastor, J.; Johnson, C.A. 1988. The potential importance of boundaries to fluvial ecosystems. Journal of the North American Benthological Society. 7: 289-306.

Naiman, R.J.; Decamps, H.; Pollock, M. 1993. The role of riparian corridors in maintaining regional biodiversity. Ecological Applications. 3(2): 209-212.

Naiman, R.J.; Sedell, J.R. 1980. Relationships between metabolic parameters and stream order in Oregon. Canadian Journal of Fisheries and Aquatic Sciences. 37: 834-847.

Nakano, S.; Miyasaka, H.; Kuhara, N. 1999. Terrestrial-aquatic linkages: riparian arthropod inputs alter trophic cascades in a stream food web. Ecology. 80: 2435-2441.

National Oceanic and Atmospheric Administration [NOAA]. 2001. Top ten Idaho weather events in the 20th century. http://www.wrh.noaa.gov/pqr/paststorms/index.php. (03 January 2006).

National Park Service [NPS]. 2005. National Parks of Alaska. Anchorage, AK: U.S. Department of the Interior, GIS Data Clearinghouse. http://www.nps.gov/akso/gis/. (10 January 2006).

National Research Council [NRC]. 1992. Restoration of aquatic ecosystems. Washington, DC: National Academy Press. 552 p.

National Research Council [NRC]. 1996. Upstream: salmon and society in the Pacific Northwest. Washington, DC: National Academy Press. 452 p.

National Research Council [NRC]. 1999. New strategies for America's watersheds. Washington, DC: National Academy Press. 311 p.

National Weather Service. 1999a. Historical storms of Oregon. http:/www.wrh.noaa.gov/pqr/paststorms/index.php. (03 January 2006).

National Weather Service. 1999b. National Weather Service unveils Washington's 1999 year-end weather statistics and top weather/water/climate events of the 20th century. http://www.wrh.noaa.gov/pqr/paststorms/washington10.php. (03 January 2006).

National Weather Service. 2000. Historical review of windstorms in Oregon. http://www.wrh.noaa.gov/pqr/paststorms/wind.php. (03 January 2006).

Nehlson, W.; Williams, J.E.; Lichatowich, J.A. 1991. Pacific salmon at the crossroads: stocks at risk from California, Oregon, Idaho, and Washington. Fisheries. 16: 4-21.

Norris L.A.; Lorz, H.W.; Gregory, S.V. 1991. Forest chemicals. Special Publ.19. Bethesda, MD: American Fisheries Society: 207-296.

Northwest Indian Fisheries Commission [NWIFC]. 2001. Tribal participation in the TFW agreement. Olympia, WA. http://www.nwifc.org/newsinfo/documents/2004_tfwff.pdf. (10 January 2006).

Noss, R.F. 1983. A regional landscape approach to maintain diversity. BioScience. 33(11): 700-706.

Notenboom, J.; Plenet, S.; Turquin, M.J. 1994. Groundwater contamination and its impact on groundwater animals and ecosystems. In: Gibert, J.; Danielopol, D.L.; Stanford, J.A., eds. Groundwater ecology. San Diego, CA: Academic Press: 477-504.

Nowacki, G.J.; Kramer, M.G. 1998. The effects of wind disturbance on temperate rain forest structure and dynamics of southeast Alaska. Gen. Tech. Rep. PNW-GTR-421. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station. 25 p. (Shaw, C.G., III, tech. coord.; Julin, K.R., ed. Conservation and resource assessments for the Tongass land management plan revision).

Nriagu, J.O.; Lakshminarayana, J.S.S. 1989. Aquatic toxicology and water quality management. New York: Wiley and Sons. 292 p.

Oakley, A.L.; Collins, J.A.; Everson, L.B. [et al.]. 1985. Riparian zones and freshwater wetlands. In: Brown, E.R., ed. Management of wildlife and fish habitats in forests of western Oregon and Washington. Part 1–Chapter narratives. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Region: 57-80.

Obedzinski, R.A.; Shaw, C.G., III; Neary, D.G. 2001. Declining woody vegetation in riparian ecosystems of the Western United States. Western Journal of Applied Forestry. 16(4): 169-181.

Odum, E.P. 1979. Ecological importance of the riparian zone. In: Strategies for protection and management of floodplain wetlands and other riparian ecosystems. Gen. Tech. Rep. WO-12. Washington, DC: U.S. Department of Agriculture, Forest Service: 2-4.

Oliver, C.D.; Hinckley, T.M. 1987. Species, stand structures, and silvicultural manipulation patterns for the streamside zone. In: Salo, E.O.; Cundy, T.W., eds. Streamside management: forestry and fishery interactions. Contrib. 57. Seattle, WA: University of Washington, Institute of Forest Resources: 257-275.

Olson, D.H.; Chan, S.S.; Weaver, G. [et al.]. 2000. Characterizing stream, riparian, and upslope habitats and species in Oregon managed headwater forests. In: Wiggington, J.; Beschta, R., eds. Riparian ecology and management in multi-land use watersheds. AWRA Publication TPS-00-2. International conference of the American Water Resources Association. Middleburg, VA: American Water Resources Association: 83-88.

O'Neill, R.V.; DeAngelis, D.L.; Waide, J.B.; Allen, T.F.H. 1986. A hierarchical concept of ecosystems. MPB 23. Princeton, NJ: Princeton University Press. 254 p.

Oregon Department of Forestry [ODF]. 1995. The evolution of Oregon's forest practice rules. Salem, OR: Oregon Department of Forestry. http://egov.oregon.gov/ODF/PRIVATE_FORESTS/docs/FPAhistory2003.pdf. (11 January 2006).

Oregon Department of Forestry [ODF]. 1999. Protection of streams and waters: frequently asked questions and their answers. http://egov.oregon.gov/ODF/PRIVATE_FORESTS/docs/FPAhistory2003.pdf. (11 January 2006).

Oregon Department of Forestry [ODF]. 2002. What are the Oregon forest practice rules? http://www.forestlearn.org/forests/ofpa.htm. (03 January 2006).

Oregon Revised Statutes. 1999. Chapter 527 Insect and disease control; forest practices. Salem, OR: Oregon State Legislature. http://www.leg.state.or.us/ors/527.html. (26 April 2005).

Oregon State Archives. 2002. Recent legislation and the environment. Salem, OR. http://arcweb.sos.state.or.us/50th/environment/environmentlegis.html. (26 April 2005).

Ott, R.A. 1997. Natural disturbances at the site and landscape levels in temperate rainforests of southeast Alaska. Fairbanks, AK: University of Alaska. [Pages unknown]. Ph.D. dissertation.

Overton, W.S. 1977. A strategy for model construction. In: Hall, C.A.S.; Day, J.W., eds. Ecosystem modeling in theory and practice: an introduction with case histories. New York: John Wiley and Sons: 50-73.

Packer, P.E. 1957. Criteria for designing and locating logging roads to control sediment. Forest Science. 13(1): 2-18.

Packer, P.E.; Christensen, G.F. 1964. Guides for controlling sediment from secondary logging roads. Ogden, UT, and Missoula, MT: U.S. Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station and Northern Region. 42 p.

Palone, R.S.; Todd, A.H. 1997. Chesapeake Bay riparian handbook: a guide for establishing and maintaining riparian forest buffers. NA-PT-02-97. Radnor, PA: U.S. Department of Agriculture, Forest Service, Northeastern Area State and Private Forestry. [Paged in sections].

Patton, D.R. 1975. A diversity index for quantifying habitat "edge." Wildlife Society Bulletin. 3(4): 171-173.

Paustian, S.J. 1992. A channel type users guide for the Tongass National Forest, southeast Alaska. R10-TP-26. Juneau, AK: U.S. Department of Agriculture, Forest Service, Alaska Region. 179 p.

Pease, J. 1993. Land use and ownership. In: Jackson, P.; Kimerling, A., eds. Atlas of the Pacific Northwest. 8th ed. Corvallis, OR: Oregon State University Press: 31-39.

Perez, G. 2001. Brief description of the Coastal Landscape Analysis and Modeling Study, H.J. Andrews, the Augusta Creek Study, and "survey and manage" species. In: Haynes, R.W.; Perez, G.E., tech. eds. Northwest Forest Plan research synthesis. Gen. Tech. Rep. PNW-GTR-498. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station: 122-123.

Peterson, N.; Hendry, A.; Quinn, T.P. 1992. Assessment of cumulative effects on salmonid habitat: some suggested parameters and target conditions. Timber, Fish, Wildlife TFW-F3-92-001. Olympia, WA: Department of Natural Resources. 75 p.

Platts, W.S.; Megahan, W.F. 1975. Time trends in riverbed sediments composition in salmon and steelhead spawning areas: South Fork Salmon River, Idaho. Transactions of the North American Wildlife and Natural Resources Conference. 40: 229-239.

Public Land Statistics. 2000. Public land statistics. BLM/BC/ST-00/001+1165. Volume 184. [Place of publication unknown]: U.S. Department of the Interior, Bureau of Land Management. http://www.blm.gov/natacq/pls99/Pls99home.html. (27 April 2005).

Raedeke, K.J., ed. 1988. Streamside management: riparian wildlife and forestry interactions. Contrib. 59. Seattle, WA: University of Washington, Institute of Forest Resources. 277 p.

Raphael, M.G.; Bisson, P.A.; Jones, L.L.C.; Foster, A.D. 2002. Effects of streamside forest management on the composition and abundance of stream and riparian fauna of the Olympic Peninsula. In: Johnson, A.C.; Haynes, R.W.; Monserud, R.A., eds. Congruent management of multiple resources: proceedings from the Wood Compatibility Initiative workshop. Gen. Tech. Rep. PNW-GTR-563. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station: 27-40.

Raphael, M.G.; Jones, L.L.C. 1997. Characteristics of resting and denning sites of American martens in central Oregon and western Washington. In: Proulx, G.H.; Bryant, H.N.; Woodard, P.M., eds. *Martes*: taxonomy, ecology, techniques, and management: proceedings of the second international *Martes* symposium. Edmonton, AB: The Provincial Museum of Alberta: 146-165.

Rashin, E.; Graber, C. 1992. Effectiveness of Washington's forest practice riparian management zone regulations for protection of stream temperature. Ecology Publication 92-64. TFW-WQ6-92-001. Olympia, WA: Washington State Department of Ecology Environmental Investigations and Laboratory Services Program, Watersheds Assessments Program. 59 p.

Reeves, G.H.; Benda, L.E.; Burnett, K.M. [et al.]. 1995. A disturbance-based ecosystem approach to maintaining and restoring freshwater habitats of evolutionarily significant units of anadromous salmonids in the Pacific Northwest. In: Nielson, J.L.; Powers, D.A., eds. Evolution and the aquatic ecosystem: defining unique units in population conservation. Bethesda, MD: American Fisheries Society Symposium 17.

Reeves, G.H.; Burnett, K.M.; McGarry, E.V. 2003. Sources of large wood in the main stem of a fourth-order watershed in coastal Oregon. Canadian Journal of Forest Research. 33: 1363-1370.

Reeves, G.H.; Everest, F.H.; Hall, J.D. 1987. Interactions between the redside shiner (*Richardsonius balteatus*) and the steelhead trout (*Salmo gairdneri*) in western Oregon: the influence of water temperature. Canadian Journal of Fisheries and Aquatic Sciences. 44: 1603-1613.

Reeves, G.H.; Everest, F.H.; Sedell, J.R. 1993. Diversity of juvenile salmonid assemblages in coastal Oregon basins with different levels of timber harvest. Transactions of the American Fisheries Society. 122: 309-317.

Reeves, G.H.; Hall, J.D.; Roelofs, T.D. [et al.]. 1991. Rehabilitating and modifying stream habitats. In: Meehan, W.R., ed. Influences of forest and rangeland management on salmonid fishes and their habitats. Special Publ. 19. Bethesda, MD: American Fisheries Society: 519-558.

Reeves, G.H.; Hohler, D.B.; Larsen D.P. [et al.]. 2004. Effectiveness monitoring for the aquatic and riparian component of the Northwest Forest Plan: conceptual framework and options. Gen. Tech. Rep. PNW-GTR-577. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station. 71 p.

Reid, L.M.; Dunne, T. 1984. Sediment production from forest road surfaces. Water Resources Research. 20: 1753-1761.

Reinhold, J.W.; Witt, J.M. 1992. Oregon pesticide use estimates for 1987. Extension Miscellaneous 8507. Corvallis, OR: Oregon State University Extension Service. 75 p.

Rinella, F.A.; Janet, M.L. 1998. Seasonal and spatial variability of nutrients and pesticides in streams of the Willamette Basin, Oregon, 1993-95. Water-Resources Investigations Rep. 97-4082-C. Portland, OR: U.S. Department of the Interior, U.S. Geological Survey. 59 p.

Ringler, N. 1970. Effects of logging on the spawning bed environment in two Oregon coastal streams. Corvallis, OR: Oregon State University. 96 p. M.S. thesis.

Rinne, J.N. 1996. Short-term effects of wildfire on fishes and aquatic macroinvertebrates in the Southwestern United States. North American Journal of Fisheries Management. 16: 653-658.

Robison, E.G.; Runyon, J.; Andrus, C. 1999. Cooperative stream temperature monitoring: project completion report for 1994-1995. Salem, OR: Oregon Department of Forestry. 42 p.

Robison, E.G.; Beschta, R.L. 1990. Identifying trees in riparian areas that can provide coarse woody debris to streams. Forest Science. 36(3): 790-801.

Rogers, P. 1996. Disturbance ecology and forest management: a review of the literature. Gen. Tech. Rep. INT-GTR-336. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Research Station. 16 p.

Ruel, J.-C. 2000. Factors influencing windthrow in balsam fir forests: from landscape studies to individual tree studies. Forest Ecology and Management. 135: 169-178.

Ruel, J.-C.; Pin, D. 1993. Windthrow along electrical distribution lines in a rural setting. Journal of Arboriculture. 19: 271-277.

Ruel, J.-C.; Pin, D.; Cooper, K. 2001. Windthrow in riparian buffer strips: effect of wind exposure, thinning, and strip width. Forest Ecology and Management. 143: 105-113.

Runyon, J.; Andrus, C. 1994. Forest stream cooperative monitoring–water temperature monitoring protocol. Salem, OR: Oregon Department of Forestry, Forest Practices Section. 14 p.

Rupp, T.S.; Chapin, F.S., III; Starfield, A.M. 2000. Response of arctic vegetation to transient climatic change on the Seward Peninsula in northwest Alaska. Global Change Biology. 6(5): 541.

Sadler, R.R. 1970. Buffer strips—a possible application of decision theory. Tech. Note 152. Eugene, OR: U.S. Department of the Interior, Bureau of Land Management. 11 p.

Salo, E.O.; Cundy, T.W., eds. 1987. Streamside management: forestry and fishery interactions. Contrib. 57. Seattle, WA: University of Washington, Institute of Forest Resources. 471 p.

Sanzone, D.M.; Meyer, J.L.; Marti, E. [et al.]. 2003. Carbon and nitrogen transfer from a desert stream to riparian predators. Oecologia. 134: 238-250.

Schlosser, I.J.; Karr, J.R. 1981. Water quality in agricultural watersheds: impact of riparian vegetation during base flow. Water Resources Bulletin. 17(2): 233-240.

Schoen, J.W. 1977. The ecological distribution and biology of wapiti (*Cervus elaphus*) in the Cedar River watershed. Seattle, WA: University of Washington. 405 p. Ph.D. dissertation.

Schoonmaker, P.K.; von Hagen, B.; Wolf, E.C., eds. 1997. The rain forests of home: profile of a North American bioregion. Washington, DC: Island Press. 431 p.

Schwer, C.B.; Clausen, J.C. 1989. Vegetative filter treatment of dairy milkhouse wastewater. Journal of Environmental Quality. 18: 446-451.

Scrivener, J.C.; Brownlee, M.J. 1989. Effects of forest harvesting on gravel quality and incubation survival of chum salmon (*Oncorhynchus keta*) and coho salmon (*O. kisutch*) in Carnation Creek, British Columbia. Canadian Journal of Fisheries and Aquatic Sciences. 46: 681-696.

Sedell, J.R.; Bisson, P.A.; Swanson, F.J.; Gregory, S.V. 1988. What we know about large trees that fall into streams and rivers. In: Maser, C.; Tarrant, R.F.; Trappe, J.M.; Franklin, J.F., tech. eds. From the forest to the sea: a story of fallen trees. Gen. Tech. Rep. PNW-GTR-229. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station: 47-81.

Sedell, J.R.; Froggatt, J.L. 1984. Importance of streamside forests to large rivers: the isolation of the Willamette River, Oregon, USA, from its floodplain by snagging and forest removal. Verhandlungen Internationale Vereinigen Limnologie. 22: 1828-1834.

Sedell, J.R.; Leone, F.N.; Duval, W.S. 1991. Water transportation and storage of logs. In: Meehan, W., ed. Influences of forest and rangeland management on salmonid fishes and their habitats. Special Publ. 19. Bethesda, MD: American Fisheries Society: 325-368.

Shaw, A.E.; Richardson, J.S. 2001. Direct and indirect effects of sediment pulse duration of stream invertebrate assemblages and rainbow trout (*Oncohynchus mykiss*) growth and survival. Canadian Journal of Fisheries and Aquatic Sciences. 58: 2213-2221.

Sheridan, W.L.; McNeil, W.J. 1968. Some effects of logging on two salmon streams in Alaska. Journal of Forestry. 66(2): 128-133.

Shindler, B.; Cramer, L.A. 1999. Shifting public values for forest management: making sense of wicked problems. Western Journal of Applied Forestry. 14(1): 28-34.

Sidle, R.C.; Pearce, A.J.; O'Loughlin, C.L. 1985. Hillslope stability and land use. Water Resources Monograph Series 11. Washington, DC: American Geophysical Union. 140 p.

Sinton, D.S.; Jones, J.A.; Ohmann, J.L.; Swanson, F.J. 2000. Windthrow disturbance, forest composition, and structure in the Bull Run basin, Oregon. Ecology. 81(9): 2539-2556.

Spence, B.C.; Hughes, R.M.; Lomnicky, G.A.; Novitzki, R.P. 1996. An ecosystem approach to salmonid conservation. Volume 1: Technical foundation. Report prepared for the National Marine Fisheries Service; Environmental Protection Agency, Region 10; and the U.S. Fish and Wildlife Service by ManTech Environmental Technology, Inc. [Pages unknown]. On file with: ManTech Environmental Technology, Inc., 1600 Western Blvd., Corvallis, OR.

Stanford, J.A.; Ward, J.V. 1993. An ecosystem perspective on alluvial rivers: connectivity and the hyporheic corridor. Journal of the North American Benthological Society. 12: 48-68.

State of Oregon. 1997. Coastal salmon restoration initiative. Salem, OR: Governor's Office. [Pages unknown].

Steinblums, I.J.; Froelich, H.A.; Lyons, J.K. 1984. Designing stable buffer strips for stream protection. Journal of Forestry. 82: 49-52.

Stipe, L.E. 1987. Outbreak chronology. In: Brookes, M.H.; Campbell, R.W.; Colbert, J.J.; Mitchell, R.G.; Stark, R.W., tech. cords. Western spruce budworm. Tech. Bull. 1694. Washington, DC: U.S. Department of Agriculture, Forest Service: 2-4.

Stoszek, K.J.; Mica, P.G. 1978. Outbreaks, sites, and stands. In: Brookes, M.H.; Stark, R.W.; Campbell, R.W., eds. The Douglas-fir tussock moth: a synthesis. Tech. Bull. 1585. Washington, DC: U.S. Department of Agriculture, Forest Service: 56-59.

Sullivan, K.; Lisle, T.E.; Dolloff, C.A. [et al.]. 1987. Stream channels: the link between the forests and fishes. In: Salo, E.O.; Cundy, T.W., eds. Streamside management: forestry and fishery interactions. Contrib. 57. Seattle, WA: University of Washington, Institute of Forest Resources: 39-97.

Swanson, F.J.; Benda, L.E.; Duncan, S.H. [et al.]. 1987. Mass failures and other processes of sediment production in Pacific Northwest forest landscapes. In: Salo, E.O.; Cundy, T.W., eds. Streamside management: forestry and fishery interactions. Contrib. 57. Seattle, WA: University of Washington, Institute of Forest Resources: 9-38.

Swanson, F.J.; Lienkaemper, G.W. 1978. Physical consequences of large organic debris in Pacific Northwest streams. Gen. Tech. Rep. PNW-GTR-69. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Forest and Range Experiment Station. 12 p.

Swanston, D.N. 1969. Mass wasting in coastal Alaska. Res. Pap. PNW-83. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Forest and Range Experiment Station. [Pages unknown].

Swanston, D.N. 1971. Principal mass movement processes influenced by road-building, logging and fire. In: Krygier, J.T.; Hall, J.D., eds. Forest land uses and the stream environment. Corvallis, OR: Oregon State University: 29-40.

Swanston, D.N. 1974. Slope stability problems associated with timber harvesting in mountainous regions of the Western United States. Gen. Tech. Rep. PNW-GTR-21. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station. 14 p.

Swanston, D.N. 1991. Natural processes. In: Meehan, W.R., ed. Influences of forest and rangeland management on salmonid fishes and their habitats. Special Publ. 19. Bethesda, MD: American Fisheries Society: 139-179.

Swanston, D.N.; Shaw, C.G., III; Smith, W.P. [et al.]. 1996. Scientific information and the Tongass land management plan: key findings derived from the scientific literature, species assessments, resource analyses, workshops, and risk assessment panels. Gen. Tech. Rep. PNW-GTR-386. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station. 30 p. (Shaw, C.G., III, tech. coord.; Conservation and resource assessments for the Tongass land management plan revision).

Swanston, D.N.; Swanson, F.J. 1976. Timber harvesting, mass erosion, and steepland forest geomorphology in the Pacific Northwest. In: Coates, D.R., ed. Geomorphology and engineering. Stroudsburg, PA: Dowden, Hutchinson, and Ross, Inc.: 199-221.

Teensma, P.D.A. 1987. Fire history and fire regimes of the central western Cascades of Oregon. Eugene, OR: University of Oregon. 188 p. Ph.D. dissertation.

Teensma, P.D.A.; Rienstra, J.T.; Yeiter, M.A. 1991. Preliminary reconstruction and analysis of change in forest stand age classes of the Oregon Coast Range from 1850 to 1940. Tech. Note T/N OR-9. Portland, OR: U.S. Department of the Interior, Bureau of Land Management. 9 p. [plus maps].

Thomas, J.W.; Maser, C.; Rodiek, J.E. 1979. Riparian zones. In: Thomas, J.W., tech. ed. Wildlife habitats in managed forests–the Blue Mountains of Oregon and Washington. Agric. Handb. 553. Washington, DC: U.S. Department of Agriculture, Forest Service: 40-47.

Thomas, J.W.; Raphael, M.G.; Anthony, R.G. [et al.]. 1993. Viability assessments and management considerations for species associated with late-successional and old-growth forests of the Pacific Northwest. The report of the scientific analysis team. Portland, OR: U.S. Department of Agriculture, Forest Service, National Forest System, Forest Service Research. 530 p.

Tongass National Forest Interdisciplinary Team. 1990. Analysis of the management situation for the revision of the Tongass land management plan. Juneau, AK: U.S. Department of Agriculture, Forest Service, Alaska Region. [Pages unknown].

Trombulak, S.C.; Frissell, C.A. 2000. Review of ecological effects of roads on terrestrial and aquatic communities. Conservation Biology. 14(1): 18-30.

Ulanova, N.G. 2000. The effects of windthrow on forests at different spatial scales: a review. Forest Ecology and Management. 135: 155-167.

University of Washington. 2004. Stream riparian bibliography. Joint effort of the University of Washington Center for Water and Watershed Studies, U.S. Forest Service, Stream Systems Technology Center and Rocky Mountain Research Station. http://riparian.cfr.washington.edu/. (11 January 2006).

U.S. Army Corps of Engineers. 1991. Buffer strips for riparian zone management. Waltham, MA: New England Division. 56 p.

U.S. Bureau of the Census. 1997. Projections of the total population of states: 1995 to 2025. Washington, DC. http://www.census.gov/population/projections/state/stpjpop.txt. (28 April 2005).

U.S. Department of Agriculture [USDA], Economic Research Service. 1995. Major uses of land in the United States, 1992. Agric. Economic Rep. 723. Washington, DC. 39 p.

U.S. Department of Agriculture, Forest Service [USDA Forest Service]. 1977. The Nation's renewable resources—an assessment, 1975. Forest Resour. Rep. 21. Washington, DC. [Pages unknown].

U.S. Department of Agriculture, Forest Service [USDA Forest Service]. 1986. Aquatic habitat management handbook. Forest Service Handb. 2609.24. Juneau, AK: Alaska Region. [Pages unknown].

U.S. Department of Agriculture, Forest Service [USDA Forest Service]. 1989. Draft riparian concept paper. Juneau, AK: Alaska Region. On file with: Fred H. Everest, University of Alaska Southeast, Sitka Campus, 1332 Seward Avenue, Sitka, AK 99835.

U.S. Department of Agriculture, Forest Service [USDA Forest Service]. 1991. Riparian review. Juneau, AK: Alaska Region. 14 p.

U.S. Department of Agriculture, Forest Service [USDA Forest Service]. 1995. Report to Congress: anadromous fish habitat assessment. R10-MB-279. Juneau, AK: Pacific Northwest Research Station and Alaska Region. [Variable pagination].

U.S. Department of Agriculture, Forest Service [USDA Forest Service]. 1997. Tongass land management plan revision. Final environmental impact statement Part 1: summary, chapters 1 and 2, and chapter 3 (physical and biological environment). R10-MB-338b. Washington, DC. [Irregular pagination].

U.S. Department of Agriculture, Forest Service [USDA Forest Service]. 2000. Alaska's forestry program summary fact sheets. Anchorage, AK: Region 10, State and Private Forestry. http://www.fs.fed.us/r10/spf/facts/spffactrght.htm. (28 April 2005).

U.S. Department of Agriculture, Forest Service; U.S. Department of the Interior, Bureau of Land Management [USDA and USDI]. 1994a. Environmental assessment for the implementation of interim strategies (PACFISH) for managing anadromous fish-producing watersheds in eastern Oregon and Washington, Idaho, and portions of California. Washington, DC. [Pages unknown].

U.S. Department of Agriculture, Forest Service; U.S. Department of the Interior, Bureau of Land Management [USDA and USDI]. 1994b. Record of decision for amendments to Forest Service and Bureau of Land Management planning documents within the range of the northern spotted owl. [Place of publication unknown]. 74 p. [plus attachment A: standards and guidelines].

U.S. Department of Agriculture, Forest Service; U.S. Department of the Interior, Bureau of Land Management [USDA and USDI]. 1995. Decision notice and environmental assessment for the interim strategies for managing anadromous fish producing watersheds in eastern Oregon and Washington, Idaho, and portions of California. Washington, DC. [Pages unknown].

USDI Bureau of Land Management. 1991. Riparian-wetland initiative for the 1990s. BLM/WO/GI-91/001+4340. Washington, DC. 50 p.

U.S. Environmental Protection Agency [US EPA]. 1998. Climate change and Alaska. EPA 236-F-98-007b. Washington, DC: U.S. Environmental Protection Agency, Climate and Policy Assessment Division. 4 p.

U.S. Fish and Wildlife Service [US FWS]. 2000. Threatened and endangered species system (TESS). http://ecos.fws.gov/tess_public/TESSWebpageLead?lead_region=1&listings=0&type=L. (28 April 2005).

U.S. General Services Administration [US GSA]. 2000. Summary report of real property owned by the United States throughout the world. Washington, DC. [Pages unknown].

Van Deventer, J.S. 1992. A bibliography of riparian research and management: fish, wildlife vegetation, and hydrologic responses to livestock grazing and other land use activities. Moscow, ID: Idaho Riparian Cooperative, University of Idaho. [Pages unknown].

Vannote, R.L.; Minshall, G.W.; Cimmins, K.W. [et al.]. 1980. The river continuum concept. Canadian Journal of Fisheries and Aquatic Sciences. 37: 130-137.

Verry, E.S.; Hornbeck, J.W.; Dolloff, C.A., eds. 2000. Riparian management in forests of the continental Eastern United States. New York: Lewis Publishers. 402 p.

Volkman, J. 1997. A river in common: the Columbia River, the salmon ecosystem, and water policy. Springfield, VA: U.S. Department of Commerce, National Technical Information Service. 206 p.

Washington State Department of Ecology. 2003. Status of high and significant hazard dams in Washington with safety deficiencies. Publ. 03-11-004. Olympia, WA. http://www.ecy.wa.gov/pubs/0311004.pdf. (03 January 2006).

Washington State Legislature. 05/31/2005 [Last updated]. Title 222 WAC: Forest practices board. Olympia, WA. http://apps.leg.wa.gov/wac/default.aspx?cite=222. (03 January 2006).

Weaver, W.; Hagans, D.; Madej, M.A. 1987. Managing forest roads to control cumulative erosion and sedimentation effects. In: Proceedings, California watershed management conference. Tech. Rep. 11. Berkeley, CA: University of California, Wildland Resources Center: 119-124.

Welsch, D.J. 1991. Riparian forest buffers. NA-PR-01-91. Radnor, PA: U.S. Department of Agriculture, Forest Service, Northeastern Area State and Private Forestry. 20 p.

Wenger, S. 1999. A review of the scientific literature on riparian buffer width, extent and vegetation. Athens, GA: Office of Public Service and Outreach, Institute of Ecology, University of Georgia. 59 p.

Wenger, S.J.; Fowler, L.F. 2000. Protecting stream and river corridors. [Public Policy Research Series]. Athens, GA: Carl Vinson Institute of Government, University of Georgia. 68 p.

Wentz, D.A.; Bonn, B.A.; Carpenter, K.D. [et al.]. 1998. Water quality in the Willamette Basin, Oregon, 1991-95. Circular 1161. [Place of publication unknown]: U.S. Department of the Interior, U.S. Geological Survey. 34 p. http://pubs.usgs.gov/circ/1998/circ1161/. (28 April 2005).

Western Water Policy Review Advisory Commission. 1998. Water in the West: challenge for the next century. Report of the Western Water Policy Review Advisory Commission. Albuquerque, NM. [Irregular pagination].

Wetzel, S.A.; Fonda, R.W. 2000. Fire history of Douglas-fir forests in the Morse Creek drainage of Olympic National Park, Washington. Northwest Science. 74(4): 263-279.

Whitelaw, E. 1992. Oregon’s real economy. Old Oregon. 1: 31-33.

Williams, J.E.; Wood, C.A.; Dombeck, M.P., eds. 1997. Watershed restoration: principles and practices. Bethesda, MD: American Fisheries Society. 561 p.

Wimberly, M.C.; Spies, T.A.; Long, C.J.; Whitlock, C. 2000. Simulating historical variability in the amount of old forests in the Oregon Coast Range. Conservation Biology. 14(1): 167-180.

Wipfli, M.S.; Gregovich, D.P. 2002. Export of invertebrates and detritus from fishless headwater streams in southeastern Alaska: implications for downstream salmonid production. Freshwater Biology. 47: 957-969.

Wipple, W., Jr.; DiLouie, J.M.; Pytalr, T., Jr. 1981. Erosional potential of streams in urbanizing areas. Water Resources Bulletin. 17: 36-45.

Wissmar, R.C.; Smith, J.E.; McIntosh, B.A. [et al.]. 1994. A history of resource use and disturbance in riverine basins of eastern Oregon and Washington (early 1800s-1990s). Northwest Science. 68(Special Issue): 1-35.

Wright, H.A.; Bailey, A.W. 1982. Fire ecology: United States and southern Canada. New York: John Wiley and Sons. 501 p.

Yount, J.D.; Niemi, G.J. 1990. Recovery of lotic communities and ecosystems from disturbance—a narrative review of case studies. Environmental Management. 14: 547-570.

Ziemer, R.R.; Lisle, T.E. 1998. Hydrology. In: Naiman, R.J.; Bilby, R.E., eds. River ecology and management: lessons from the Pacific Coastal ecoregion. New York: Springer-Verlag: 43-68. Chapter 3.

This Page Left Blank Intentionally

This Page Left Blank Intentionally

Pacific Northwest Research Station

Web site	http://www.fs.fed.us/pnw
Telephone	(503) 808-2592
Publication requests	(503) 808-2138
FAX	(503) 808-2130
E-mail	pnw_pnwpubs@fs.fed.us
Mailing address	Publications Distribution Pacific Northwest Research Station P.O. Box 3890 Portland, OR 97208-3890

U.S. Department of Agriculture
Pacific Northwest Research Station
333 S.W. First Avenue
P.O. Box 3890
Portland, OR 97208-3890