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A Review of Scientific Information on Issues Related to the Use and Management of Water Resources in the Pacific Northwest

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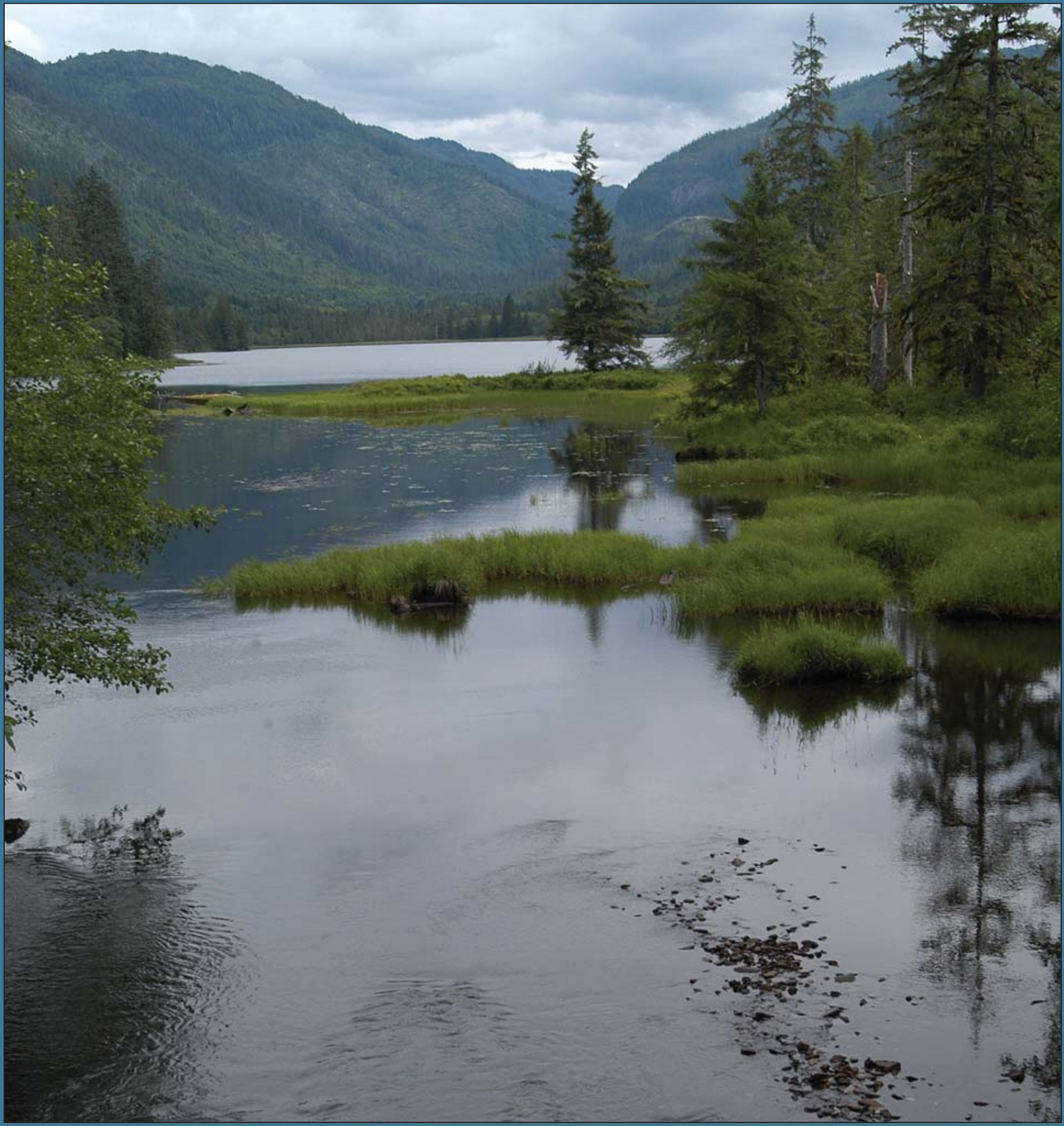

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Abstract

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Fresh water is a valuable and essential commodity in the Pacific Northwest States, specifically Oregon, Washington, and Idaho, and one provided abundantly by forested watersheds in the region. The maintenance and growth of industrial, municipal, agricultural, and recreational activities in the region are dependent on adequate and sustainable supplies of fresh water from surface and ground-water sources. Future development, especially in the semiarid intermountain area, depends on the conservation and expansion of the region's water resource. This synthesis reviews the state of our knowledge and condition of water resources in the Pacific Northwest.

Keywords: Water distribution, flow regimes, water demand, conflicts, tools, water use.

Preface

The water resources of the Pacific Northwest provide vital and diverse benefits to North Americans within and outside the region. Demands of the growing population of the Pacific Northwest have exploited and altered the region's water resources to the extent that the needs and desires of all user groups cannot be met within the existing paradigm of water use and management. Consequently, many ecological, social, and economic issues related to sustainable water resources use require urgent resolution as we enter the 21st century.

A comprehensive list of issues pertaining to sustainable water use in the West has recently been identified and discussed by the Western Water Policy Review Advisory Commission (1998) and the National Research Council (1999). The issues identified in these reviews are all relevant in the Pacific Northwest where many agencies and organizations are responsible for management of water resources (see app. 1). Because the state of knowledge for water resources management is incomplete, many organizations also are engaged in a variety of water resources research topics in the region, each focused on providing information to solve one or more of the issues. The Pacific Northwest (PNW) Research Station of the USDA Forest Service, is actively engaged in research to solve water-related issues on forested landscapes of the region. Because the Station is unable to simultaneously address all the pressing issues, a workshop hosted by the Station, and attended by more than 20 cooperators and interested parties from federal, state, local government, and private sector interests, was held at Pack Forest, Washington, in 1999, to help the Station focus its research program. The objectives of the workshop were to:

- Use the combined views and perspectives among the workshop participants to help the PNW Research Station better identify and understand key emerging issues and trends in relation to water resource management in forested watersheds of the Pacific Northwest.
- Identify key information gaps in understanding how these issues and trends differ across the region.
- Identify current and proposed components of both short- and long-term research efforts within the PNW Research Station that best address emerging water issues.

These discussions played a key role in helping the Station frame the principal priorities for a PNW **Sustainable Water Research Initiative**. During the workshop, two overriding questions surfaced about the identification and resolution of water resource issues in the region. First, what is the state of existing scientific knowledge on current and emerging water-related issues in the region, especially in forested watersheds, and how can that knowledge base be used most effectively? Second, what new knowledge might be needed to address emerging issues? With these questions in mind, participants in the Pack Forest workshop and the PNW Sustainable Water Initiative Technical Oversight Group identified more than a dozen emerging water resources issues in the Pacific Northwest. Although the issues apply broadly to the region and affect all landscapes and user groups, they were framed to focus on the role that management of federal forested landscapes of the region could play in their resolution.

In the following sections, we review relevant scientific knowledge on the themes and issues in relation to the following overriding questions:

- How important are federal lands to resolution of water issues in the Northwest?
- Can management of federal watersheds improve water yield and water quality within the context of current knowledge?
- What new knowledge is needed to improve management of water resources in the region?
- We hope the review will be useful to managers, scientists, and other parties interested in management of the region's water resources, and the resolution of problems and conflicts related to water use.

Executive Summary

Archaeological evidence of water developments in early civilizations is widespread, and the technical capabilities of the ancients to impound and convey water were in some cases remarkably sophisticated. However, mastery of irrigated agriculture and the ability to cope with variations in climate cycles and human population expansion were never achieved. Early water developments often proved unreliable, at times contributing to the development of civilizations and at other times to their demise.

Many of the water management problems encountered by early civilizations persist today, but on a larger scale and with greater frequency. Human populations, which increased sharply in the 20th century, still face problems with salinization of irrigated land, uncertainty in water supplies associated with climate cycles, and sufficient water supply to meet demands. An even more critical problem in the 21st century is human contamination of water resources at the global scale.

Freshwater is a valuable and essential commodity in the Pacific Northwest, specifically in the states of Oregon, Washington, and Idaho, and one provided abundantly by forested watersheds in the region. The maintenance and growth of industrial, municipal, agricultural, and recreational activities in the region rely on adequate and sustainable supplies of freshwater from surface- and ground-water sources. Future development, especially in the semiarid intermountain area, depends on the conservation and expansion of the region's water resources.

The need to protect and conserve the water resources of the Pacific Northwest was apparent by the beginning of the 20th century. The U.S. Congress established the Forest Service in 1905 to provide the Nation with a sustainable supply of high-quality water and timber. National forests are the Nation's largest single source of freshwater. In the Western United States, national forests produce about one-third of the region's total annual runoff, and the fraction is even higher in the Pacific Northwest. The 29 national forests in Oregon, Washington, and Idaho include most of the high-elevation watersheds in the region, receive abundant rainfall, and generate abundant runoff.

Water development in the Pacific Northwest historically followed a three-phase pattern reflecting social change in the United States in the 19th and 20th centuries. The first phase of water development (exploitation phase) consisted of relatively small, scattered efforts to provide water for irrigation, domestic and municipal use, and local electric power generation.

As human populations increased, more sophisticated engineering and larger scale projects were typical of the second phase (reclamation phase) of water development. Society generally accepted the premise that water resources could be controlled through engineering to maximize human benefits.

The third phase (mitigation phase) of water development began in the late 1960s, and sought to mitigate or, in some cases, reverse environmental effects caused by the reclamation phase. A gradual shift occurred from engineering developments to protection and conservation of water resources, and recognition that instream uses of water for recreation and species viability were beneficial.

There are three objectives in this paper: The first is to review and synthesize scientific information on water-related issues that apply primarily to the Pacific Northwest states of Oregon, Washington, and Idaho, with emphasis on the following topics:

- How the distribution of water affects the management of aquatic resources.
- How altered flow regimes and water quality affect water supply and use.
- How demands for water create conflicts over water use.
- How new and existing tools can help people find solutions for sustainable water.

Second is to assess what areas of the landscape and what water uses have the greatest effects on water supply and quality in the Pacific Northwest. Third is to assess the most important scientific contributions the Pacific Northwest (PNW) Research Station of the U.S. Department of Agriculture (USDA) Forest Service could make toward solving future problems with water resources.

Although we recognize the importance of scientific knowledge in resolving problems related to management of natural resources, we also recognize that science is not the only consideration in decisions about the use and management of water resources. Managers also use social and economic considerations, politics, and other factors in making decisions about the use of natural resources, including water. We reviewed the scientific knowledge relevant to each theme and issue and identified the role the PNW Research Station could play in its resolution.

Theme 1: The Distribution of Water Affects Management of Aquatic Resources

The Pacific Northwest has abundant water resources, but the spatial and temporal distribution of precipitation and runoff in the region is more variable than in any other comparably sized area of the United States. The uneven distribution of water at the regional scale is related to the region's climate and topography. Seasonal and spatial variability in precipitation and runoff complicate management of the water resources of the region and create persistent problems and conflicts in some geographic areas between offstream and instream uses of water and between certain user groups.

Extremes in precipitation occur within the normal weather regimen of the Pacific Northwest. Precipitation in the region is also highly variable seasonally. Most precipitation falls in winter; summers are generally warm and dry. Natural flow regimes are also highly variable across the region. Variability of water resources is further increased by climatic cycles of variable duration and predictability. The most obvious temporal cycle is the annual cycle of seasons driving the hydrographs specific to certain geographic and climatic zones. But, other longer term events (e.g., El Niño-Southern Oscillation, Pacific Decadal Oscillation, and global climate change) contribute to the range of variability in water resources in the region.

Variability of runoff parallels that of precipitation. Variations in the amount of runoff are related directly to amounts of precipitation, but timing of runoff is controlled largely by climatic and orographic factors. Detailed analysis of water production at the watershed scale is generally lacking across the region. Although little opportunity exists to increase water yield from national forests, land management activities there can greatly affect water quality but only minimally affects timing of water delivery downstream. Forest management can affect sediment yield, water temperature, habitat structure, nutrient loading, and can introduce toxic contaminants.

Theme 2: Altered Flow Regimes and Water Quality Affect Water Supply and Use

Humans have altered natural flow regimes over large areas of the Pacific Northwest affecting both natural ecosystems and human populations. Our actions have changed the natural distribution of surface and subsurface waters. In addition, activities that change the quality of natural waters by altering sediment loading, and thermal, chemical, or nutrient characteristics may have widespread and discernable impacts on aquatic ecosystems and water use. Changes in instream storage, offstream consumptive uses of water, and large-scale land use activities are leading causes of altered flows, whereas sedimentation, human sewage, industrial and agricultural wastes, and thermal loading from land use activities are major modifiers of water quality.

Dams and storage reservoirs located on main-stem rivers and their tributaries in the Pacific Northwest have caused massive alterations of natural streamflows. Peak flows have been greatly reduced while summer flows often increased. Diversion of streamflows and pumping of surface water for offstream uses are also major causes of altered flow regimes. Diversion of stream waters and overdrafting (defined as removing ground water faster than it can be naturally recharged) of aquifers to meet human needs is most prevalent during periods of low summer flow and occurs extensively in the intermountain region. Irrigated agriculture, the largest offstream use of water in the Pacific Northwest, also has a profound effect on natural flow regimes.

Land use activities (e.g., logging, roads, and grazing) and wildfires that change vegetative cover, cause extensive soil compaction, or generally accelerate surface runoff also can alter the natural characteristics of annual, peak, and minimum flow regimes. Forests influence floods and peak streamflows because land use activities can substantially increase peak discharges resulting from small storm events in small watersheds. Although increases in peak flows related to logging have been observed in small watersheds, such changes are more difficult to detect in larger basins. Also, because increases in low summer flows from small watersheds are generally widely scattered in time and space within larger basins, they are difficult to detect and thus insignificant in larger downstream waters.

Changes in water quality also can alter the characteristics of natural flow regimes. Human activities that cause chronic or acute changes in water clarity and suspended and bedload sediments, temperature, inorganic chemicals, nutrients, or pathogens alter natural conditions of flowing waters and can affect both instream and offstream uses of water. Changes in water quality can be independent of changes in the quantity of streamflow, but the two processes are often linked and may interact in synergistically complex ways. Turbidity and sediment are the most ubiquitous water pollutants in the Pacific Northwest. Although the relative contribution of these pollutants from various human actions can be difficult to quantify, some information can be derived from state and federal lists of impaired water bodies. For example, about 6 percent of total stream length in Oregon and Idaho is impaired by sediment, siltation, and turbidity. About 40 percent of the impaired stream length is on lands managed by the Forest Service and U.S. Department of the Interior, Bureau of Land Management. The remaining 60 percent is in other ownerships that are affected by mining, agriculture, industry, and urbanization. Most of the affected streams on federal land are small in relation to affected waters in other ownerships downstream. Affected stream kilometers alone do not indicate the magnitude of the problem in the different land ownerships. Agriculture, mining, and highways have introduced millions of metric tons of sediments contaminated with various toxins into the region’s rivers.

The sediments and toxins interact synergistically in the region's aquatic ecosystems. Thermal changes in the natural flow patterns of Northwest streams cross all geographic scales from headwater catchments to entire river basins. Land use activities, such as mining and timber harvest, are most pervasive in the headwaters, whereas agriculture and reservoir operations affect waters downstream. At large scales (i.e., basins and watersheds), the greatest alterations of natural temperature regimes are caused by releases from storage reservoirs and withdrawal and return of irrigation water. Although knowledge of the extent is incomplete, data suggest that about 6 percent of the region's streams are impaired by thermal pollution. About one-third of the impaired stream kilometers are on lands managed by the Forest Service and Bureau of Land Management; the remainder is in other ownerships downstream.

Chemical contamination can potentially affect water at all scales, including small headwater streams, main-stem rivers, and lakes and reservoirs of all sizes. The most prominent effects in the Pacific Northwest, however, occur at the river-basin scale in waters draining agricultural lands, or downstream of large mining operations, and urban areas. Because many agricultural chemicals and toxic heavy metal pollutants persist in the water, they can affect water quality for long distances downstream from the site of introduction.

Nutrients entering the water as fertilizers and domestic sewage affect the quality of Northwest waters. Use of fertilizer is rare on federal forest lands, whereas use on private forest lands is more common, but still limited. Agriculture is the greatest source of nutrient enrichment, in large quantities of nitrogen and phosphorous, instreams in the Pacific Northwest.

The effects of individual activities may appear minor when viewed in a basin-scale context, although cumulative effects of land management may affect water quality at varying distances downstream from the source. Even cumulative effects resulting from forest management may not represent dominant changes in water quality when viewed at the basin scale. Intentional or not, every human activity that alters natural waterflow patterns has biological, social, and economic tradeoffs. Whether the tradeoffs have been beneficial or detrimental, or even identified or realized, is a societal value judgment that differs among Pacific Northwest residents.

Although changes in flow regimes have facilitated high-value hydropower, industrial, and agricultural developments in the Northwest, they also have reduced the value of some of the region's prominent natural resources. Anadromous fishes, for example, were historically of enormous cultural, commercial, and recreational value in the Northwest. Changes in aquatic habitats owing to land management, dams, reservoirs, and irrigation diversions have reduced once-abundant fish populations to a vestige of historical levels, with some anadromous stocks now extinct, and many others listed as threatened or endangered. Incompatible or noncomplementary uses of water, such as fisheries and hydropower production, agriculture and recreation, or agriculture and drinking water supplies, require clear and accurate analysis of tradeoffs before informed policy decisions can be made.

Theme 3: Demands for Water Create Conflicts Over Water Use

Many policies, doctrines, laws, and traditions regulate and govern water use and allocation. These commonly are portrayed as one source of present-day conflict over water management. Conflict often is an inevitable consequence of competing interests and demands for the allocation of scarce resources. Conflicts over water typically occur between and among instream and offstream uses.

The doctrine of prior appropriation ("first in time, first in right") is the current basis of much of Western water law. Most Western waters are fully appropriated, and beneficial water use historically has focused on consumptive off-channel uses such as agriculture, industry, mining, and municipal needs, and production of hydropower. Recognition that free-flowing water could be left in channels for beneficial uses is inconsistent with most Western water law, and is slow to evolve.

Historical Western water law also conflicts with some more recent state and federal laws focused on the management and use of water resources. As demands for water resources have increased, especially in semiarid areas, so have the conflicts among water-related laws. The dilemma is that the same water needed for species viability may have previously been allocated and adjudicated to a water right holder for offstream use. Conflicts of this type are common across the region and may affect maintenance of aquatic biodiversity, recovery of threatened and endangered aquatic species, and water-oriented recreation. Conflicts between offstream and instream uses of water urgently need resolution for equitable and sustainable development of the region's water resources.

Theme 4: New and Existing Tools and Solutions for Sustainable Water Use

An extensive array of existing, new, and emerging tools for management of water resources exist in the Pacific Northwest; however, full implementation of these tools and development of additional tools and schemes are lacking. Specifically, there is a large array of political, administrative, and legal tools; economic and social tools; and technological tools. For example, Forest Service land use planning (e.g., best management practices, monitoring, Northwest Forest Plan's standards and guides), Clean Water Act total maximum daily loads, and other water quality standards can be used. Within the economic and social realms, it is possible to use taxes and subsidies, analyze water markets, work with watershed councils, and education and learning programs. There are also many technological tools including restoration technology, knowledge-based systems, geographic information systems, and forward-looking infrared radar. With all these tools available, and in creation, we have yet to fully implement or coordinate their use.

We analyzed each of the themes and issues in relation to the following overriding questions:

- How important are federal lands to resolution of water issues in the Northwest?
- Can management of federal watersheds improve water yield and quality within the context of current knowledge?
- What new knowledge is needed to improve management of water resources in the region?
- What is the appropriate role of the PNW Research Station in adding to needed new knowledge?

Pacific Northwest Research Station Water Resources Research

The PNW Research Station has been involved with water-related research for decades. Primary focus areas include forest and range hydrology in undisturbed landscapes, the effects of human and natural disturbances on the hydrology and slope stability of forest and rangelands, and the interactions among forest and rangeland management, water, and fish habitats. Since the 1970s, the Station has published nearly 1,000 papers on these subject areas. The research results have been extensively used to guide forest and range management in the Pacific

Northwest, as well as nationally and globally where the results were applicable. Management of forested landscapes has been greatly improved because of these studies. However, application of findings can be improved. The literature is hard to find, often written to peers (not those who need to apply it), published only in professional journals, not synthesized, and lacking obvious applicability.

What do we know and where do we go?

- Distribution of water does not match distribution of demand, and the problem is getting progressively worse.
- Land uses and dams greatly affect water quality and quantity of waterflow.
- Agriculture and associated agricultural practices have greater impacts on water resources than do forestry and forest practices in the Pacific Northwest.
- Historical laws for allocation of water resources are outdated and treat instream values poorly, if at all.
- The scale of impacts and the scales of authority to address these impacts are mismatched.
- There are many tools available for water management, but they are used ineffectively.

Variations in scale and land use present different stories

	Effects of forest management		Dams
Scale	Water quantity	Water quality	Water quantity
Site	Medium to high	Medium to high	Very high
Watershed	Medium	Medium to high	High
Subbasin	Low	Medium	Medium to high
Basin	Negligible	Low	Medium
Region	Negligible	Negligible	Medium

Contents

Introduction

Fresh water is a valuable and essential commodity in the Pacific Northwest states of Oregon, Washington, and Idaho, and one provided abundantly by most forested watersheds in the region. The maintenance and growth of industrial, municipal, agricultural, and recreational activities in the region rely on adequate and sustainable supplies of freshwater from surface- and ground-water sources. Future development, especially in the semiarid intermountain area, depends on the conservation and expansion of the region's water resources. Within the region, ecological and nonconsumptive human uses of water, such as maintenance of instream flows for threatened and endangered aquatic species and water-based recreation, are increasing social concerns.

Forested watersheds cover about one-third of the United States but catch more than half of the total precipitation and yield more than three-fourths of the total runoff (Norris et al. 1991). The Nation's forested watersheds receive on average >114 cm of precipitation and yield >50 cm of runoff annually, more than seven times the amounts from other lands (Storey 1965).

National forests are the Nation's largest single source of freshwater, which provides many ecological and human benefits. For example, communities that draw source water from the national forests and grasslands provide a public water supply to 60 million people, or one-fourth of the people served by public water supplies nationwide (Ryan and Glasser 2000). In the Western United States, national forests produce about one-third of the region's total annual runoff and an even higher portion in the Pacific Northwest states of Oregon, Washington, and Idaho. Estimates are that more than 38 percent (>80 billion m^3) of the Northwest's total annual runoff of >200 billion m^3 emanates from national forests (Sedell et al. 2000).

The quantity and high quality of water produced by national forests in the Pacific Northwest provide several benefits. Onsite, the water maintains terrestrial, riparian, and aquatic ecosystems, and provides recreation opportunities and domestic water for various users. Offsite, water from the national forests contributes to production of hydropower and helps meet regional demands for domestic, industrial, agricultural, and recreational uses. The annual value of water produced on the national forests of Oregon, Washington, and Idaho is conservatively estimated at about $950 million (Sedell et al. 2000).

Although water is perceived to be abundant in the Pacific Northwest, concerns about the future of the region's water resources are increasing. Demand for water is increasing with the area's rapidly growing population and level of economic activity. Increasing demands for both consumptive and nonconsumptive uses of water, which are often mutually exclusive, set the stage for new challenges in the coming decades. These challenges will be complicated by the often-uncoordinated efforts of the many agencies responsible for water management in the region (see app. 1). Consider the following factors driving water issues in the Northwest.

- In the past 20 years, the human population of the Northwest has increased 40 percent to about 10.6 million people; by 2025, it is projected to grow about another 30 percent, to approximately 13.9 million (Campbell 1997).
- Water in most Western streams is already overappropriated (Moody 1990, National Research Council 1992).

Figure 1—Interrelated processes and attributes (physical, ecological, social, and economic) occurring within watersheds of the Pacific Northwest.

- Water in some Pacific Northwest aquifers is being removed at unsustainable rates, risking future agricultural production in key areas (Stuebner 2000).
- Water in the Pacific Northwest is unevenly distributed, i.e., abundant west of the Cascade Range and scarce in the intermountain region (Muckleston 1979, 1993) where it is most needed for agriculture.
- In the past 20 years, participation in various water-based recreation activities has increased between 20 and 40 percent (Bowker et al. 1999, Brown 1999).
- More than 100 hydropower dams in the Pacific Northwest, including 38 on national forests in Oregon, Washington, and Idaho are due for relicensing (Sedell et al. 2000).

- Over 200 stocks of Pacific Northwest anadromous salmonids are considered at risk (Nehlsen et al. 1991). The listing of various salmon under the Endangered Species Act of 1973 (ESA) has broad socioeconomic implications for water use across the entire region (Larmer 2000).

Decades of water-related research in the Pacific Northwest have yielded an extensive base of scientific information on the physical, biological, social, and economic attributes of the region’s water resources and on the processes that control the quantity and quality of the region’s water resources. These interrelated attributes and processes operate in concert in Pacific Northwest watersheds (fig. 1), complicating the already complex task of integrating, interpreting, and synthesizing available scientific information. More than 50 federal, state, and nongovernmental organizations currently conduct some form of water-related research in the region (see app. 1), and an even greater diversity of organizations is responsible for management of water resources. The research organizations have generally addressed specific geographic areas and subject matter, based on their individual missions. For example, the Agricultural Research Service of the USDA focuses on the effects of agriculture on water resources, whereas the Forest Service, also of the USDA, focuses on forest and range hydrology and the effects of land management on water resources and riparian and aquatic habitats. Research organizations have published thousands of papers on the water resources of the Northwest. However, in spite of this extensive base of scientific knowledge, much remains unknown about the water resources of the region, and many challenges still face water managers and users. Much of the scientific information generated by these organizations has accumulated in the past two decades. This information is critically important for addressing conflicts over the region’s water resources.

Objectives

There are three objectives in this review: The first is to review and synthesize scientific information on water-related issues that apply primarily to the Pacific Northwest states of Oregon, Washington, and Idaho, with emphasis on the following topics:

- How the distribution of water affects the management of aquatic resources
- How altered flow regimes and water quality affect water supply and use.
- How demands for water create conflicts over water use.
- How new and existing tools help people find solutions for sustainable water.

Second is to assess what areas of the landscape (e.g., forested, agricultural, and urban), and what water uses (e.g., instream flow, hydropower production, agriculture, and domestic) have the greatest effects on water supply and quality in the Pacific Northwest. Third is to assess the most important scientific contributions the Pacific Northwest (PNW) Research Station of the U.S. Forest Service could make toward solving future problems with water resources.

Forested landscapes of Alaska were not included in this literature review and synthesis for three reasons: (1) the state of Alaska is sparsely populated, and where humans reside, water is abundant; (2) human disturbances of forested landscapes are relatively minor despite some commercial timber harvest and mining in the temperate rain forests of southeast Alaska; and (3) far less water-related scientific research has been conducted in Alaska.

Although we recognize the importance of scientific knowledge in resolving problems related to management of natural resources (Everest et al. 1997, Swanston et al. 1996), we also recognize that science is not the only consideration in decisions about water use and management. Managers also use social and economic considerations, politics, and other factors in making decisions about the use of natural resources (Mills et al. 1998), including water. We do, however, encourage the use of relevant scientific information and tools, including historical insights gained through archaeology, and appropriate global data, in management decisions on water use in the Northwest.

We begin with a brief historical look at water development in early civilizations and at emerging 21st-century global concerns for water resources, to provide context for emerging water resource issues in the Pacific Northwest.

Water and Early Civilization

The early alchemist Empedocles defined water as one of the four basic components (water, earth, air, and fire) of the cosmos (Kingsley 1997), and early civilizations often waxed or waned in response to changes in water supply (Postgate and Postgate 1994). Archaeological studies revealed that some early civilizations attempted to develop reliable water supplies for domestic and agricultural needs by constructing simple or complex systems of dams, canals, and aqueducts while maintaining equitable use of water through legislation (Aicher 1995, Brown 1994, Harper 2000). Some of the earliest laws regulating use and allocation of water resources were found in the Code of Hammurabi from the early Babylonian Empire (circa 2250 B.C.) (Harper 2000). Early water developments, however, often proved unreliable, at times contributing to development of civilizations and at other times to their demise. Shifting climatic factors often exerted more control on the water supplies of ancient civilizations than human attempts to design and develop water resources for expanding populations.

Evidence of water systems in ancient civilizations was widespread. For example, Mesopotamian civilization was thriving in the Tigris River Valley in the 23rd century B.C. (Crawford 1991). Mashkan-shapir, a major city on the Mesopotamian plain, was located about 32 km from the Tigris River and connected to the river by a network of irrigation canals. The irrigation system allowed the city to flourish for over a century but contributed to its decline. Flood irrigation, which was practiced in the area for decades, allowed water to stand in fields and evaporate, often resulting in deposition of mineral salts of sufficient concentration to eventually render soils unfit for agricultural use (Postel 1993). By 2300 B.C., salinization of soils in irrigated fields surrounding Mashkan-shapir was believed to have reduced agricultural production in the area to a fraction of its former level, resulting in abandoned fields and a declining Mesopotamian civilization.

The city of Rome provides a more successful example of ancient water developments. Extensive construction of aqueducts to supply the city with water began in 312 B.C. when the local water supply became inadequate for the growing population (Evans 1994). Eventually, 11 aqueducts were built, some bringing water from sources >64 km away. This water system provided about 1.3 million m^3 of water to the city daily for domestic and agricultural use (Hodge 1992) and allowed the city to flourish for centuries.

The Anasazi of the American Southwest provide another example of an ancient civilization that collapsed (Stuart 2000). In the sixth century A.D., the growing Anasazi population of Chaco Canyon depended primarily on agricultural production for food. Archaeological evidence indicates that dams, canals, and other water control features were constructed to capture and direct scarce water resources in an arid region (Frazier 1999). Despite the Anasazi's efforts to maintain water supplies for the pueblos and agricultural lands, a 50-year drought in the 12th century, at the peak of cultural development in Chaco Canyon, reduced crop production and is believed to have contributed to the demise of Anasazi civilization (Noble 1984).

Ancient technical capabilities to impound and convey water were remarkably sophisticated, but complete mastery of irrigated agriculture, and the ability to cope with variations in climate cycles and human population expansion has never been achieved. Human populations, which increased sharply in the 20th century, still face problems with salinization of irrigated land and variable water supplies associated with climate cycles. Global demands for water may soon outstrip supplies on most continents. Human contamination of water resources at the global scale is another issue that will need to be addressed in the 21st century.

Global Water Concerns in the 21st Century

Although problems with water supply, use, and development date back to the earliest civilizations, water shortages and water pollution have become much more acute, chronic, and widespread in modern times (Postel and Starke 1997, Simon 1998). Postel et al. (1996) estimate that humans currently appropriate half of the accessible annual global freshwater runoff as withdrawals for agriculture, cities, and industries, or indirectly for pollution control and other instream uses. Even with optimistic assumptions about new water projects to increase supplies and modest assumptions about growth in human demands, Postel (2000a) estimates that appropriation of accessible freshwater runoff could reach 70 percent of the available supply by 2025. If this level of use were realized, it would likely degrade aquatic ecosystems, decimate fish populations, and drive additional aquatic species to extinction. Current research indicates that these trends are already underway (Covich 1993, Naiman et al. 1995, Pringle 2000).

A recent survey of selected world experts on emerging environmental issues corroborated predictions of a pending global water crisis by identifying water scarcity and water pollution as two of the top four most critical global concerns of the 21st century (United Nations Environment Programme 1999). Rapidly increasing human populations and their needs for domestic, industrial, and agricultural water uses will be at the root of the problem (Hinrichsen et al. 1997). Changing climates also could worsen projected water shortages (Gleick 1993). Water shortages currently occur on every continent, including North America. Even in the Pacific Northwest region of the United States where water is perceived to be plentiful, droughts occur.

Population pressure, coupled with uneven water supplies, water pollution, and climate change, affect water quality and water supply at both global and local scales. Global human populations are projected to reach 9.3 billion by 2050 (USDC Bureau of the Census 1999), causing increased demand for all water uses. Increases in the population of the Pacific Northwest also are expected to continue through 2050. The increased population and its demand on water will continue to degrade water quality and lead to unsustainable consumption of surface- and ground-water resources (United Nations Environment Programme 1999).

Degradation of the quality of water resources is widespread and increasing with human population increases. Sources of contamination come primarily from human wastes, industrial and agricultural wastes, and various land uses. Water pollutants can be classified into four general categories: microbiologic contaminants, chemical contaminants, physical contaminants (sediments), and thermal pollution. Pollutants discharged from point and nonpoint sources can contribute to eutrophication, chemical contamination, acidification, dissolved oxygen depletion, thermal pollution, habitat simplification, sedimentation of surface water, and chemical contamination of ground water.

In the 21st century, human mortality from waterborne diseases arising from microbiologic pollutants will occur on an unprecedented scale (Davidson et al. 1992, USAID 1990). Currently, more than 1 billion people in developing countries lack access to safe, unpolluted drinking water, and about 3 billion live without access to adequate sanitation systems (Gleick 1999). Ninety-five percent of domestic sewage and 75 percent of industrial waste in developing countries is discharged untreated into surface waters (Carty 1991). The result has been an increase in enteric diseases such as cholera (Gleick 1993) and waterborne parasitic infections (e.g., schistosomiasis) in developing countries (Nash 1993). Currently, pollutants of this type occur rarely in the Pacific Northwest.

Industrial pollutants from point sources degrade surface and ground water, especially in urban areas of developing countries. Industrial discharges often contain complex chemical compounds that are known human poisons and carcinogens. Compounds such as heavy metals, PCBs, dioxins, and nuclear wastes are extremely toxic and persistent in the environment, and some, like mercury, tend to bioaccumulate in aquatic food chains (Lindberg et al. 1987). Industrialization in developing nations poses new threats to water quality from increased chemical contaminants discharge and increased likelihood of chemical spills.

The Pacific Northwest has effectively addressed many sources of industrial pollution, but persistent problems still occur in some areas with heavy metals (Fuhrer 1986), and nuclear wastes (Haushild et al. 1973, Hubbell and Glenn 1973). For example, a 161-km reach of the Clark Fork River, a headwater tributary of the Columbia River, is contaminated with heavy metals from abandoned copper mines (Ryan 1994). Also, the Hanford Nuclear Reservation, adjacent to the Columbia River in eastern Washington, is one of the most polluted places in North America. Ground water beneath more than 193 km^2 of the reservation is contaminated with various persistent toxic and radioactive chemicals (D’ Antonio 1993, White 1995).

Agricultural pollution is a growing problem in all nations where nitrate fertilizers and pesticides are used to increase crop yields. Nitrate contamination causes eutrophication of surface waters (Nash 1993) and algal blooms that can reach toxic levels (Day 1991). Contaminants in ground water, in agricultural areas, render it useless for human consumption. Many toxic herbicides and pesticides also bioaccumulate in aquatic food chains, causing long-term effects to both aquatic and terrestrial organisms (Carson 1962). Erosion and sedimentation are other problems associated with agricultural operations, and are especially severe in developing nations where marginal lands are converted for agricultural use. Water pollution from sedimentation (Clark 1997, Greene et al. 1996) and toxic chemicals (Clark et al. 1998, Wentz et al. 1998, Williamson et al. 1998) is a persistent problem in areas of the Pacific Northwest where intensive agriculture is practiced. For example, pesticides contaminated ground-water supplies in 51 out of 200 counties in the Pacific Northwest in 1992 (Ryan 1994).

Sedimentation and thermal pollution of surface waters from widespread changes in land use are persistent and growing global problems. Deforestation, conversion of grasslands and savannahs for agricultural use, and loss of wetlands have affected water quality and habitat for aquatic and riparian organisms. Extensive logging has resulted in erosion, sedimentation, turbidity, decreased dissolved oxygen, and increased temperatures in flowing waters on most continents (Nash 1993). This is also true in the Pacific Northwest area of the United States (Gregory et al. 1986, Meehan 1991), a major producer of softwood timber for the United States.

By 2025, the United Nations predicts that two-thirds of the world's population will live in countries with moderate (using more than 20 percent annual renewable water resources) to high water stress (using more than 40 percent of annual renewable water resources) (Turner 2000). Water tables are falling on every continent (Abramovitz 1996), and predictions are that global water-related problems will worsen on all continents in the 21st century. Economies are likely to be restructured around water availability (Brown and Halweil 1998), and increasing political tension may lead to wars fought over the control of water supplies (Hinrichsen et al. 1997).

North America is not exempt from 21st-century water shortages. For example, Mexico City, the cultural, industrial, and economic center of Mexico, is critically short of the water quantity and quality needed to supply its 20 million people. Nearly 72 percent of the city's water comes from the overexploited Mexico City aquifer that underlies the city. Decades of overdrafting (removing ground water faster than it can naturally be replenished) from the aquifer have caused the city center area to subside an average 7.5 m, damaging sewer and water lines and contaminating the city's water supply in many areas (National Research Council 1995).

Even Canada with its extensive water resources experiences problems with water supply. Uneven water distribution affects Canada's most populated areas. Approximately 60 percent of Canada's freshwater drains north to the Arctic Ocean, but 90 percent of the population lives within 300 km of the Canada-U.S. border (Environment Canada 1999). Many densely populated areas have restricted water supplies, and water availability constitutes a major concern for water management. Even in the Great Lakes Basin, some areas in southern Ontario experience periodic and even chronic water shortages. In these areas, underground aquifers are being depleted.

The resource-rich and technologically advanced United States is also subject to water-related problems, although major efforts are underway to conserve and more efficiently use water resources. Areas east of the Mississippi River generally have adequate water supplies for domestic, industrial, and agricultural use, but many areas suffer from periodic droughts. A recent 5-year drought in the Deep South (U.S. Drought Monitor 2000) has reduced agricultural production in that region, and although slow improvement is expected in the latter half of 2002 (Climate Prediction Center 2002), some water shortages are likely to persist in the area beyond 2002. Warm, dry weather in the Great Lakes basin from 1997 to 2001 reduced lake elevations to near record-low levels by 2000 (U.S. Army Corps of Engineers 2000a), and the effects have persisted through 2002 with the lakes currently at their lowest levels in 35 years (Great Lakes Environmental Research Laboratory 2002). The current water level in the Great Lakes is affecting waterborne commerce and the recreational boating industry, and is threatening the water intakes of some lakeside communities. Although short-term drought cycles have always affected the Eastern United States, their effects have become more apparent as human populations have increased across this region.

The analysis of global literature clearly indicates that the world's freshwater supplies are under stress from increasing human demands for water and extensive water pollution. Global water use will become more complicated in the coming decades. This is because of the heterogeneous distribution of water in juxtaposition with increasing global populations, global climate change and climate cycles, accelerating water pollution, and unsustainable use of ground water.

Water in Africa

Many African countries will experience severe water shortages in the 21st century. Predicted shortages in countries (e.g., Egypt) may be resolved through conservation and solar desalinization, but countries along the north African coast, the Horn of Africa, and South Africa will have a difficult time providing water for their growing populations (Gardner-Outlaw and Engelman 1997). Countries like Kenya have little opportunity to avert crisis. Kenya's population is projected to rise from 26 million in 1990 to 47 million in 2025. Water supplies will then be inadequate for domestic, industrial, and agricultural use, resulting in a high probability of economic disruption and famine (National Reporter 1999).

Water in China

China may face severe water problems within the next 30 years (Brown and Halweil 1998) despite large water developments like Three Gorges Dam on the Yangtze River. Water demand is expected to rise nearly five times as China's industrial base expands and the population increases by a projected 300 million people (Brown and Halweil 1998). Current conditions form the danger signs of future problems. For example, every year for more than a decade, the Yellow River has run dry in summer before it reaches the sea (Brown and Halweil 1998), and water levels are falling in many other Chinese river basins (Xinhua News Agency 1999). Between 1991 and 1996, overdrafting from the aquifer underlying the North China Plain, the area that produces nearly 40 percent of China's grain harvest, lowered the water table by an average of 1.5 m per year (Postel 2000b).

Water in Europe

Water shortages currently exist in several European countries. Germany, Belgium, Poland, and the Netherlands are in a state of mild water stress (using more than 20 percent of available resources), and Spain, Portugal, and Greece are in a state of moderate water stress (using more than 40 percent of available water resources) (Turner 2000). The European Commission is currently considering a controversial plan that would establish a European Water Network to combat Europe's heterogeneous distribution of water. This network would tap the resources of water-rich countries such as Austria to provide water-poor countries like Spain and Greece with increased water supplies (British Broadcasting Corporation 1998).

Water in Australia

Australia, the most arid inhabited continent on earth, developed most of its easily exploitable water resources during the past century to support the current population of greater than 19 million people. Over large parts of Australia the major rivers have been dammed or diverted to create new freshwater impoundments, wetlands have been drained, extensive watershed areas have been salinized by long-term flood irrigation, and rivers have been isolated from their flood plains (Day 1991).

The Murray-Darling River system in southeast Australia is a prime example of an overdeveloped river basin. Agricultural production in the basin accounts for 97 percent of the rice, 94 percent of the cotton, 97 percent of the grapes, and a large percentage of the fruit, wheat, wool, and vegetables grown in Australia. Agriculture consumes more than 80 percent of the river's annual flow, creating severe conflicts among water users, endangered species, and ecosystem health in the basin. The Murray-Darling Basin Commission is currently working on a resource plan for sustainable water use (Murray-Darling Basin Commission 1999).

The Australian population is predicted to grow at least another 30 percent by 2025 (Australian Bureau of Statistics 1992), adding more stress to the continent's limited water resources. Politicians, developers, and scientists are currently debating the merits of future population growth and the development of Australia's few remaining natural freshwater resources (Williams 1993).

Water in South America

The water resources of South America are highly variable, but some areas currently suffer from perennial droughts and water shortages. For example, chronic water supply problems occur in Brazil's Nordeste region (Robock 1980), especially in the area called the drought polygon where about one-third of the country's population lives (Smithsonian Institution and United Nations Environment Programme 1995). Quality of life and agricultural production in the area are tied directly to fluctuations in the annual water cycle.

Brazil also has acute water problems in some large cities like Sao Paulo (MacLeod 1994). Sao Paulo, the largest city in South America and home to nearly 20 million people, currently consumes about 75 percent of its potentially available surface water resources, and is said by some to be near collapse because of water shortages (Osava 1998). In response to recurrent problems with agricultural and domestic water supplies, Brazil passed a new water law in 1997. The law, approved amid a growing shortage of water in several regions of the country, requires that users pay for water and establishes new administrative structures for its implementation (United Nations Commission on Sustainable Development 1997).

Water Changes in the Western United States

The most acute U.S. water problems are in the West, especially in arid and semiarid regions of the intermountain West and the Great Plains. In this area, surface- and ground-water resources are in short supply given the current economic scenario for water allocation. Since the earliest days of settlement, cities, industry, and agriculture have depended on the development and redistribution of water resources in the West. A vast system of dams, diversions, canals, aqueducts, and pumping stations have stored and distributed surface waters for beneficial uses across an enormous area. But, the surface waters of the region, after more than a century of development, are currently inadequate in most areas to fully meet the needs of those holding water rights.

The Colorado River, one of the four great basins of the West, is a classic example of a fully used, overappropriated, river. In 1922, the Colorado River Compact was formed to divide the river's annual flow of about 20.4 billion m^3 among the seven Western States in the basin (Sibley 2000). Subsequently, during World War II an international treaty ceded 1.9 billion m^3 per year to Mexico. Since the compact was formed, 15 major storage facilities and eight major diversions have been built to impound and distribute the Colorado River's water. At the current rate of consumptive use, the river's flow is being fully consumed annually by the United States and Mexico, and strong demands exist for additional water. The Colorado River example is typical of many rivers flowing through arid sections of the Western United States.

Extensive exploitation of ground-water resources in the West has paralleled the development and use of surface waters. Much of the Western United States is underlain by aquifers that originally contained vast quantities of water accumulated over millennia. Extensive and uncontrolled pumping of ground water in the 20th century has exceeded the recharge rate for most aquifers and significantly dropped the water levels across broad geographic areas. For example, the High Plains aquifer underlies 450 000 km^2 of Colorado, Kansas, Nebraska, New Mexico, Oklahoma, South Dakota, Texas, and Wyoming. Irrigation water pumped from the aquifer has made the High Plains one of the Nation's most important agricultural areas.Pumping of ground water for irrigation, however, has dropped ground-water levels in excess of 30 m in parts of the High Plains aquifer in Kansas, New Mexico, Oklahoma, and Texas (Alley et al. 1999).

The Snake Plain aquifer in Idaho, one of the largest in the Pacific Northwest, is also showing the effects of overdrafting. Levels in the aquifer have receded as much as 100 m in some areas in the past three decades as farmers pump ground water and divert surface water to irrigate about 1.5 million ha of desert (Stuebner 2000). Agriculture is currently Idaho's largest industry, but most experts agree that the current rate of ground-water depletion is not sustainable.

Pumping of ground water for municipal and industrial use also is depleting water stored in some Western aquifers. For example, the aquifer that supplies industrial and municipal water for Albuquerque, New Mexico, has in some places dropped as much as 40 m in the past three decades (Selcraig 2000). Realization that Albuquerque's ground-water supply is being overused has resulted in a citywide water education and conservation program in an attempt to reduce water withdrawals. Most experts agree that continued overdrafting of ground water will eventually force changes in agricultural practices in much of the West (Kim et al. 1989) and curtail growth of some Western cities like Albuquerque (Selcraig 2000).

Although coastal areas of the Pacific Northwest receive large amounts of rainfall, the distribution of water in time and space across the region is uneven, creating geographic problems with water resource supply and distribution. Surface- and ground-water shortages for irrigation have emerged in the last decade, especially in the semiarid intermountain region. Water shortages are related both to changing demographics in the region and to increased demand for irrigation water. Since 1975, the population of the area has increased from about 6.6 million (Northam 1993) to about 10.6 million people in 2000 (Campbell 1997). The rapid growth in population has created sharply increased demands for consumptive uses of water for domestic, industrial, and agricultural applications, and also for instream uses such as recreation, hydropower generation, and recovery of threatened and endangered salmon stocks. The volume of water use for irrigation in southern Idaho, when viewed from a U.S. perspective, is currently second only to the massive use of water for irrigation in California (Stuebner 2000). Changing social values and heightened ecological awareness have been responsible for a recent increased emphasis on beneficial instream uses of water such as recreation and recovery of endangered and threatened salmon stocks.

According to Gleick (1998), water development is entering a new phase at the beginning of the 21st century. A new emerging global paradigm for development and management of water resources includes a shift away from developing new sources of supply, a growing emphasis on incorporating ecological values into water policy, a reemphasis on meeting basic human needs for water services, and an attempt to break the direct correlation between economic growth and water use (Gleick 2000). The new paradigm emphasizes small-scale, innovative, inexpensive water projects, and water conservation and efficiency of use, rather than the massive new construction and interbasin water transfers of the past.

The 2001 drought in the Pacific Northwest reduced water supplies in Washington for users on both sides of the Cascade Range. Seattle Public Utilities asked customers to voluntarily cut consumption by 10 percent in anticipation of short supplies in summer 2001 (Mapes 2001). In the Yakima Valley of eastern Washington, the drought intensified conflicts between power users, salmon recovery efforts, and irrigated agriculture (Lewis and Leff 2001), and unraveled attempts to balance water supplies among instream and offstream users. In 2001, a drought in the Klamath basin of Oregon was severe enough for the Governor to declare a “state of drought emergency” (State of Oregon 2001) and to cause civil disobedience among farmers who illegally diverted water to irrigate crops (Environment and Climate News 2001).

Columbia River Water Development

The chronology of development in the Sacramento-San Joaquin system in California (McClurg 2000), the Colorado River in the Southwest (Fradkin 1996), and the Columbia River in the Pacific Northwest (Harden 1996) historically followed a three-phase pattern of development that paralleled social changes in the United States in the 19th and 20th centuries. The Columbia River, possibly America’s most engineered river, provides a classic example of this pattern. The Columbia River ranks fifth in length at 1950 km (Shiklomanov 1993), and fourth in discharge (247 billion m^3) among North American rivers (Volkman 1997). The river and its major tributaries originate in the Rocky Mountains, traverse the arid but fertile intermountain region, and transect both the Cascade and the Coast Ranges before discharging to the Pacific Ocean. The river once produced between 10 and 16 million salmon annually (Volkman 1997), something for which the river has been noted since the 1805-06 journey of Lewis and Clark.

The first phase of water development (exploitation phase) consisted of relatively small, scattered efforts to provide water for irrigation, domestic and municipal use, and local electric power generation. This phase occurred during early settlement of the West (about 1850) when resources were plentiful, human population was low, and resource exploitation to facilitate settlement was the social norm. At this stage, water projects generally consisted of small diversions on tributary systems for irrigated agriculture (Volkman 1997). Although some diversions affected rearing and migration habitat of anadromous salmonids, the effects were individually small and generally ignored. By the early 1900s, many diversions were in place, but no attempt was made to assess their cumulative effects. Potential beneficial effects were maximized, whereas potential negative environmental effects were often ignored, or simply acknowledged and accepted as minor impacts.

Larger scale projects were typical of the second phase (reclamation phase) of water development. In the early 20th century, society generally accepted the premise that water resources could be controlled through engineering to maximize human benefits. Projects included dams and water storage facilities to reregulate river flows for irrigation, navigation, hydropower generation, and domestic and industrial use. Phase-2 developments were usually accomplished by federal agencies or private utilities, often with large-scale plans that included multiple projects that massively changed the hydrology and ecology of a river basin. Although project planning usually included analysis of environmental impacts, analysis of cumulative effects for multiple projects did not. Lack of understanding of these effects has led us to a legacy of water quantity and quality problems. Environmental concerns were often voiced by federal and state agencies and interest groups during this phase but were generally discounted or ignored by more politically powerful developers. Ecological consequences of developments were often difficult to predict, whereas the benefits of development could be readily demonstrated in economic terms. The developers expressed confidence that any environmental problems created by the projects could be mitigated through additional engineering solutions. The reclamation phase of development began on the mainstem Columbia River and its major tributaries, both in the United States and Canada, with planning for massive hydropower production and irrigation in the basin. Rock Island Dam, completed in 1933 by the Chelan Public Utilities District, was the first major U.S. project. Two massive main-stem U.S. dams followed, Bonneville and Grande Coulee, in 1938 and 1942, respectively. Development in the basin then matured rapidly with two additional dams completed in the United States in the 1950s, nine in the 1960s, and four in the 1970s. Benefits from these projects included slack water navigation from the Pacific Ocean to Lewiston, Idaho, additional water storage, and inexpensive hydropower, but the cost included the complete loss of the river's commercial salmon fishery, crippling of the Native American subsistence fisheries, the demise of various other fish stocks (e.g., steelhead (*Oncorhynchus mykiss* Walbaum)), and the listing of Snake River salmon stocks under the ESA.

Between 1922 and 1970, eight hydropower and storage facilities were built in the Canadian portion of the basin. Two major projects were completed in 1967 and 1968 as part of the Columbia River Treaty requirements. Four projects also were completed in Canada in the 1970s and 1980s. Two were built on the mainstem, one as a result of the Columbia River Treaty, and the others on tributaries. Despite the obvious benefits of inexpensive hydropower and massive volumes of water for irrigation, predicting the effects of Columbia basin dams on salmon and other species was difficult and uncoordinated.

Several U.S. public utilities districts, as well as the U.S. Army Corps of Engineers, Bureau of Reclamation, British Columbia Hydropower, and British Columbia public utilities built the dams, but the dam-building utilities and agencies completed no coordinated basin-scale analysis of effects. State and federal fisheries agencies voiced concern for salmon and steelhead stocks with each new project, and engineers attempted to mitigate problems, but commercial landings of salmon and steelhead declined precipitously with each decade of dam construction.

The reclamation phase of water development lost favor beginning in the 1960s as major social, political, and economic changes swept the United States (Ingram 1990). Included in this era of change was a slow shift in attitude from exploitation of the Nation’s resources to protection, conservation, and sustainable resource use. The reclamation phase of development resulted in major gains for farmers, cities, industry, and utilities but often caused environmental damage and serious losses, followed by resistance to further development by public interest groups, resource managers, and many politicians.

Consequently, the third and final phase (mitigation phase) of water development, which began in the late 1960s, seeks to mitigate or, in some cases, reverse negative environmental effects being caused by the reclamation phase. A gradual shift is occurring from engineering developments to protection and conservation of water resources and recognition that instream uses of water for recreation and species viability were beneficial. At this stage, developers and consumptive and nonconsumptive users alike are recognizing that the pace of development in the late 20th century and into the 21st century was unsustainable and has caused irreversible environmental and ecological changes that could not be mitigated through additional engineering. Resistance to further development, based on environmental concerns, is precluding construction of dams and other projects at the remaining feasible sites.

The mitigation phase in the Columbia basin began with the knowledge that upriver salmon stocks were moving toward extinction. Snake River stocks were listed under the ESA in the 1990s, and the Bonneville Power Administration (U.S. Department of Energy) began a massive salmon recovery program. More than $4 billion has been invested in salmon habitat restoration, changes in water releases at Columbia and Snake River hydropower facilities, and protection of upstream and downstream migrant salmon. This gave rise to serious discussions concerning removal of some of the Snake River dams to restore salmon runs. Currently, the dams remain in place.

A Brief History of Water Development and Conservation in the Pacific Northwest

Water development and use in the Pacific Northwest began during the early period of immigration into Oregon territory in the 1840s through 1850s. Initial developments consisted of impoundments and diversions from small tributaries for irrigated agriculture. Notable among these was the 1846 Doan Creek diversion constructed by Marcus Whitman to irrigate wheat fields near the Whitman Mission (Holbrook 1990). Water impoundments and diversions increased rapidly as settlement of the Pacific Northwest progressed. By 1902, the Yakima Valley had 500 irrigated farms that in total composed the largest irrigation project in the Northwest (Pisani 1992). Most available water in the semiarid areas of Oregon, Washington, and Idaho had been claimed by the beginning of the 20th century (e.g., Bastasch 1998).

The roots of Western water law were established during the California gold rush. In 1848, miners developed the doctrine of prior appropriation or “first in time, first in right” (Miller 2000) with regard to off-channel use of water for gold mining. The doctrine, which persisted nearly unchanged for more than140 years, was used almost exclusively to control allocation of water resources in the West during times of shortage. In the last decade, the doctrine has been successfully challenged in federal courts by Native American tribes who received water rights in treaties, or when reservations were established (Bishop 2000), but who had been denied water allocations to fulfill those rights for decades.

Water development in the Pacific Northwest continued aggressively in the 20th century. The 1920s ushered in the era of massive reclamation projects. Typical projects consisted of multipurpose dams and storage reservoirs for flood control, power generation, irrigation, municipal and industrial water supply, and recreation. About 2,540 dams at least 3 m in height or storing at least 12 300 m^3 of water were built in the Pacific Northwest by the end of the 20th century[1] (Oregon Department of Water Resources 2000, Washington Department of Ecology 2000). More than 128 facilities in the region produce hydropower with a generating capacity in excess of 30 000 MW (Foundation for Water and Energy Education 2000). Water from the storage reservoirs, and ground water from aquifers, is used to irrigate about 2.7 million ha annually in Oregon, Washington, and Idaho (Idaho Department of Water Resources 2000, Jackson 1993). Reservoirs on the main-stem Columbia River now provide deepwater navigation as far inland as Lewiston, Idaho.

The perceived need to protect and conserve the water resources of the Pacific Northwest lagged behind the development phase but was readily apparent by the beginning of the 20th century. Congress established the U.S. Forest Service in 1905 to provide the Nation with a sustainable supply of high-quality water and timber (Sedell et al. 2000). The National Forest System, which today encompasses 77.3 million ha of forests and rangelands, is located mostly in the Western United States. The 29 national forests in Oregon, Washington, and Idaho include most of the high-elevation watersheds in the region and are rich in both rainfall and runoff. Consequently, the national forests produce a disproportionately high share of the region's water resources. Approximately 81 billion m^3 of average annual runoff in the region is produced by national forests that occupy about 20 percent of the land area (Sedell et al. 2000).

The Bureau of Land Management also administers large areas of federal land in the Pacific Northwest. Their roots extend back to the 18th century, but the agency's current form dates back to 1946 when Congress merged the U.S. Grazing Service and the General Land Office (USDI Bureau of Land Management 2000). The agency primarily manages grazing lands, and some timberlands, in the intermountain region of the West. The Bureau of Land Management lands also produce a significant proportion of the Pacific Northwest's water resources, although the exact amount has not been quantified.

In combination, lands administered by the Forest Service and Bureau of Land Management, and other federal lands including National Parks and National Wildlife Refuges, account for a large proportion of the total areas of Oregon (48.2 percent), Washington (29.8 percent), and Idaho (63.7 percent) (Pease 1993). These lands (fig. 2), in aggregate, are critically important for maintaining a sustainable supply of high-quality surface and ground water for the region. The social and economic health of the Northwest is heavily influenced by the quantity and quality of water emanating from the federally owned landscape.

Although the yield of high-quality water from federal lands in the Northwest is great, most of the surface and ground water in the region is currently allocated to existing water rights (Bastasch 1998, Miller 2000). Consequently, most agencies and many

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[1] Hornbaker, S. 2003. Personal communication. Geologist, Idaho Department of Water Resources, 1301 North Orchard Street, Boise, ID 83706.

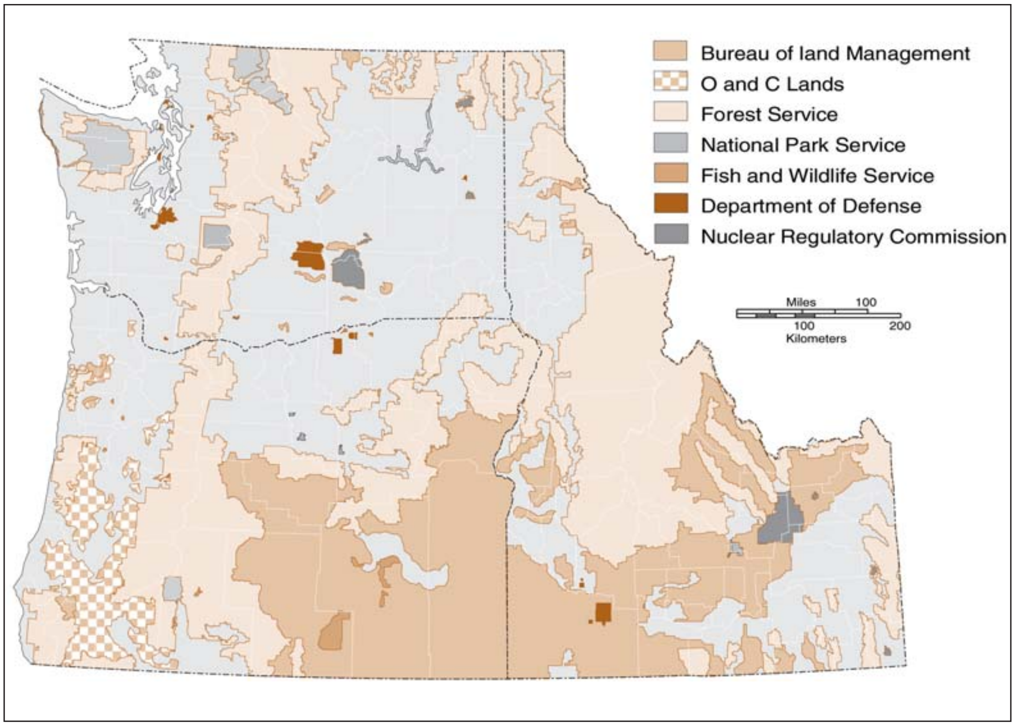

Figure 2—Lands under federal management in the Pacific Northwest (from Jackson and Kimerling). O and C LANDS are public lands in western Oregon that were granted to the Oregon Central railroad companies to aid in the construction of railroads.

industries recognize the need to both conserve water resources and protect the integrity of the region's watersheds and hence water supply.

Water conservation efforts in the region differ by type of water use. For example, agricultural water conservation is currently focused east of the crest of the Cascade Range. In parts of northeast, central, and south-central Oregon, a scientific irrigation-scheduling program initiated in 1998 (Oregon State Extension Service 2000) is capable of saving 30 to 50 percent of the water and energy required to irrigate various crops (Soltanpour et al. 1992). Irrigation systems are also slowly changing from flood and sprinkler systems to drip systems for crops with which the conversion is practicable.

Pacific Northwest industries noted for high water consumption, such as aluminum and paper industries (which use 1335 L kg^{-1} and 1250 L kg^{-1} per kg of product, respectively) (Oregon Department of Agriculture 2000), are actively participating in water conservation. For example, in the past decade, Reynolds Metals[2] has reduced water consumption at some of its U.S.-based aluminum plants by up to 80 percent through a number of related conservation efforts (AWARE 1995), and Weyerhaeuser has reduced water consumption at its pulp and paper mills in the Northwest by 65 percent over the past 20 years (Weyerhaeuser 1999). Domestic

[2] The use of trade or firm names in this publication is for reader information and does not imply endorsement by the U.S. Department of Agriculture of any product or service.

water conservation also is being practiced across the entire region through the federally mandated use of water-conserving toilets and faucets in all new residential and commercial construction.

The watersheds on federal land, and hence the integrity of water resources, is accomplished through a combination of national laws (app. 2), agency policies, and guidelines. Because the Forest Service and Bureau of Land Management are multiple-use agencies, riparian, wetland, and watershed management direction is primarily designed to reduce the land-disturbing impacts of resource extraction, such as timber harvest, grazing, and mining. National Park Service guidelines are directed toward preventing substantive human disturbances in the national parks, and relevant U.S. Fish and Wildlife Service guidelines are directed toward management of the National Wildlife Refuge system and recovery of threatened and endangered species.

Over the past 50 years, the application of measures to protect the integrity of federally managed watersheds in the Pacific Northwest has been variable and experimental. In the 1950s and 1960s, the effects of land-disturbing activities were poorly known. Measures designed to control or mitigate these effects remained inadequate to protect watershed health and habitats for terrestrial and aquatic species. Evolution of more stringent measures in the 1970s, often labeled “best management practices” (BMPs), was experimental, often based on the best judgment of technical experts, and then tempered politically to assure that the new practices were economically feasible for resource extractors. Land managers nevertheless effectively used BMPs for decades to assist with the development of standards and guidelines for land management, although BMPs were based on normative decisions and frequently changed. Toward the end of the period (1980s and 1990s), the natural resources research programs of many federal and state agencies and universities in the Pacific Northwest provided more comprehensive science-based information for management of forest and rangeland watersheds.

Despite slow progress on watershed and water protection measures on most public lands, advances have recently been made. In the last decade, scientific knowledge of the ecological consequences of disturbances caused by land management has proliferated. Land managers have recognized that watershed boundaries are coherent organizing units. Consequently, they have begun to design and apply ecosystem-based protective measures for water resources at the landscape scale. Examples include the Northwest Forest Plan (FEMAT 1993), the Tongass land management plan revision (Anadromous Fish Habitat Assessment Team 1995; U.S. Department of Agriculture, Forest Service 1997), the Interior Columbia Basin Ecosystem Management Project (Quigley and Arbelbide 1997), the Sierra Nevada Framework (U.S. Department of Agriculture, Forest Service 2001), and the Southern Appalachian Assessment (Southern Appalachian Man and the Biosphere 1996). These plans represent a new science-based paradigm for management of the land-water interface and water resources on public lands in the United States. The ecosystem-based and watershed-scale management practices described in these plans supplement the BMPs applied within the last decade, but their combined ability to protect watersheds and aquatic resources is unproven because insufficient time has elapsed for their evaluation.

Although water resources planning at the watershed scale is a commonly used procedure at the beginning of the 21st century, and a procedure that allows managers to address complex water-related problems in a coherent context, many emerging water resource issues remain to be solved.

Emerging Issues on Water Availability and Use in the United States and the Pacific Northwest

Global water problems, those in the United States, and even those in the Pacific Northwest, are exacerbated not only by the steady growth in human populations that increase demands on water resources, but also by the demands of the industrial and agricultural sectors, and by the lack of comprehensive and thoughtful policy and management structures. Although the population growth rate in the United States has been declining, 1999 estimates of population growth in the Pacific Northwest indicate rapidly increasing populations in Oregon, Washington, and Idaho. Oregon was the 10th and Washington was the 7th fastest growing state in the Nation in the 1990s, and 2025 census projections predict that the populations of all three states will grow between 31 and 43 percent in the next quarter century. The projected dramatic increase in the population of the Pacific Northwest, from both internal growth and migration, indicates that additional demands will be placed on the region's water resources in the near future. Other demographic changes in population, such as increasing numbers of older residents, whose numbers are expected to nearly double in the Northwest by 2025, and the projected 25-percent increase in the region's ethnic diversity in the next 25 years, could affect the way Northwest residents use water resources, especially recreational resources, owing to mobility and cultural differences.

Water withdrawals to cities, farms, and other offstream uses in the United States increased more than tenfold during the 20th century (Brown 1999), but the upward trend ceased in some categories in 1980. According to Stevens (1998), use of water in America declined by about 9 percent from 1980 to 1995, even as the U.S. population grew by 16 percent during the same period. Most of the declines were associated with increased efficiency in irrigated agriculture. Whether the observed national decline can persist in the face of a steadily growing U.S. population remains unclear.

Some declining trends in surface water use in the Western United States are also apparent, but less pronounced than for the entire United States. Estimates of withdrawals by source indicate that during 1990, ground-water withdrawals in the Western States were 73 billion m^3, or 5 percent more than during 1985, and surface-water withdrawals were 148 billion m^3, or 2 percent less than in 1985 (Solley 1997). During that period, the decline in surface water use resulted from more efficient water use by agriculture and industry, although water for domestic and thermoelectric use increased. Future trends are uncertain.

Brown (1999) projects that proportional increases in water withdrawals will be substantially lower than corresponding proportional increases in populations over the next 40 years. In the Pacific region, projected increases in withdrawals are lowest because increases in water for urban and industrial uses, recreation, and instream flow for ecological purposes are offset by decreases in irrigation withdrawals . Generally, improvements in water-use efficiency mean less water use than earlier studies projected (Brown 1999). Additional improvements are likely to follow the kind of influences that encouraged past improvements (e.g., environmental pollution regulations, price increases, reductions in government subsidies, and plumbing fixtures that restrict waterflow). In the West, the water needs of a growing population can reduce streamflows and lead to greater environmental challenges. Thus, instream flow will only be maintained by vigilant efforts by policymakers to stress the need for instream flow protection (Brown 1999).

Increased water demands will heighten the competition for available water resources. Consequently, the need increases for pricing policies that reflect the true value of water to different users, and water conservation and improvements in technologies that enable more efficient use of water may result. Managing demands for water in this way can potentially forestall new water developments and reduce conflict with instream uses (e.g., recovery of threatened and endangered aquatic species).

We need to better understand the causal factors that exacerbate water scarcity. Bromley (1999) suggests that causal factors for explaining many complex resource management problems (e.g., deforestation, global climate change, etc.) often fail to distinguish between the original intent of an action (e.g., timber harvest) and the broader outcome of that action. Water resource degradation does not happen by accident or by neglect; rather, it happens because there are purposes to be served by that degradation. “The analytical challenge,” Bromley (1999) writes, “is to search for those purposes.”

In the case of water resource management, to understand the purposes that account for degradation of water quantity or quality, we might conclude that it occurs (1) to make money and (2) to provide that water for other purposes. In the first case, the water is a source of income. In the second, the judgment is made that there is an unacceptably high opportunity cost associated with not using that water for other purposes, such as leaving unaltered streamflows for ecological aquatic functions as opposed to diverting it for agriculture or energy production.

An analysis that simply views increased water demand caused by population growth as a cause of water degradation misses other potential factors. This highlights weaknesses and gaps in institutional and policy structures and processes that govern water resource management. For example, government may be unwilling or unable to implement programs or policies that maintain instream flows for protection of certain species or ecological processes. This may reflect the failure of government and industry to recognize, and explicitly acknowledge, the real costs of water diversions for agriculture. It may reflect the failure to have a comprehensive and coordinated energy policy. Or, it may reflect the government’s unwillingness to confront the traditional doctrine of prior appropriation, which dramatically alters the political power in debates over water allocation.

To better understand why conditions detrimental for adequate waterflows and water quality occur, we need to look beyond simply attributing these problems to “too many people.” This requires increased attention to identifying the events that produce the intent and purposes underlying the conditions detrimental to water quality. It also requires critical examination of the institutional structures and processes that sustain these purposes and constrain change to more effective strategies and policies.

Pressing water resource issues during the next two to three decades are predicted to include the social and economic aspects of surface- and ground-water supply, water quality, flood control, sediment control, navigation, hydroelectric power generation, fisheries, biodiversity, habitat preservation and restoration, and recreation (National Research Council 1999). Another list of issues identified by the Western Water Policy Review Advisory Commission (1998) applies to the Western United

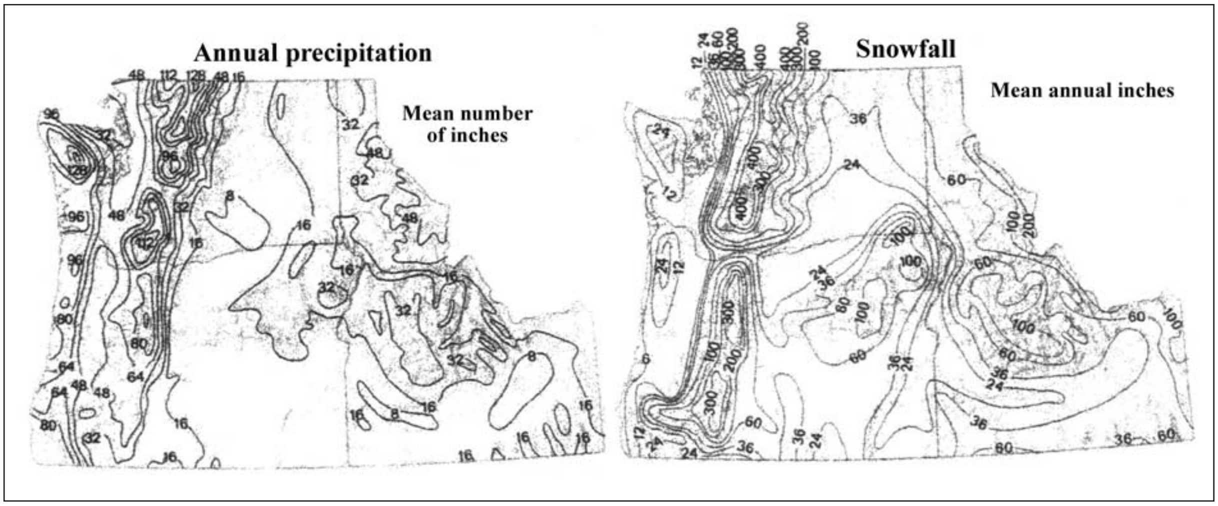

Figure 3—Mean annual inches of precipitation in the Pacific Northwest (from Jackson and Kimerling 1993).

States and includes sustainable use of existing water supplies, improved operation of existing federal water projects, improved mechanisms for governing water resources, meeting obligations to Native American nations, protecting and restoring aquatic ecosystems and water quality, and protecting productive agricultural communities. The primary societal issue identified in both lists is sustainable water resource use.

All the broad issues listed above are relevant in Oregon, Washington, and Idaho. The PNW Research Station, with the assistance of cooperators, used these issues to frame the principal priorities for a PNW Sustainable Water Research Initiative. The issues were categorized within the four following themes (also see "Preface"):

- Theme 1. The distribution of water affects the management of aquatic resources.
- Theme 2. Altered flow regimes and water quality affect water supply and use.
- Theme 3. Demands for water create conflicts over water use.
- Theme 4. New and existing tools and solutions for sustainable water use.

In the following pages, we review the scientific knowledge relevant to each theme and issue and identify the role of PNW Research Station in the resolution of these themes.

The Distribution of Water Affects the Management of Aquatic Resources

The Pacific Northwest has abundant water resources, but the spatial and temporal distribution of precipitation and runoff in the region is more variable than in any other comparably sized area of the United States (fig. 3). The uneven distribution of water at the regional scale is generally related to maritime influences of the Pacific Ocean west of the crest of the Cascade Range, continental influences east of the crest of the Cascade Range, arctic influences that enter the area from British Columbia, and orographic effects from the Coast, Cascade, and Rocky Mountains. Areas of the Olympic Peninsula and the northern Cascade Range receive >323 cm annual precipitation, the wettest locations in the conterminous 48 states. In the intermountain zone east of the crest of the Cascade Range, 50 percent of the area receives

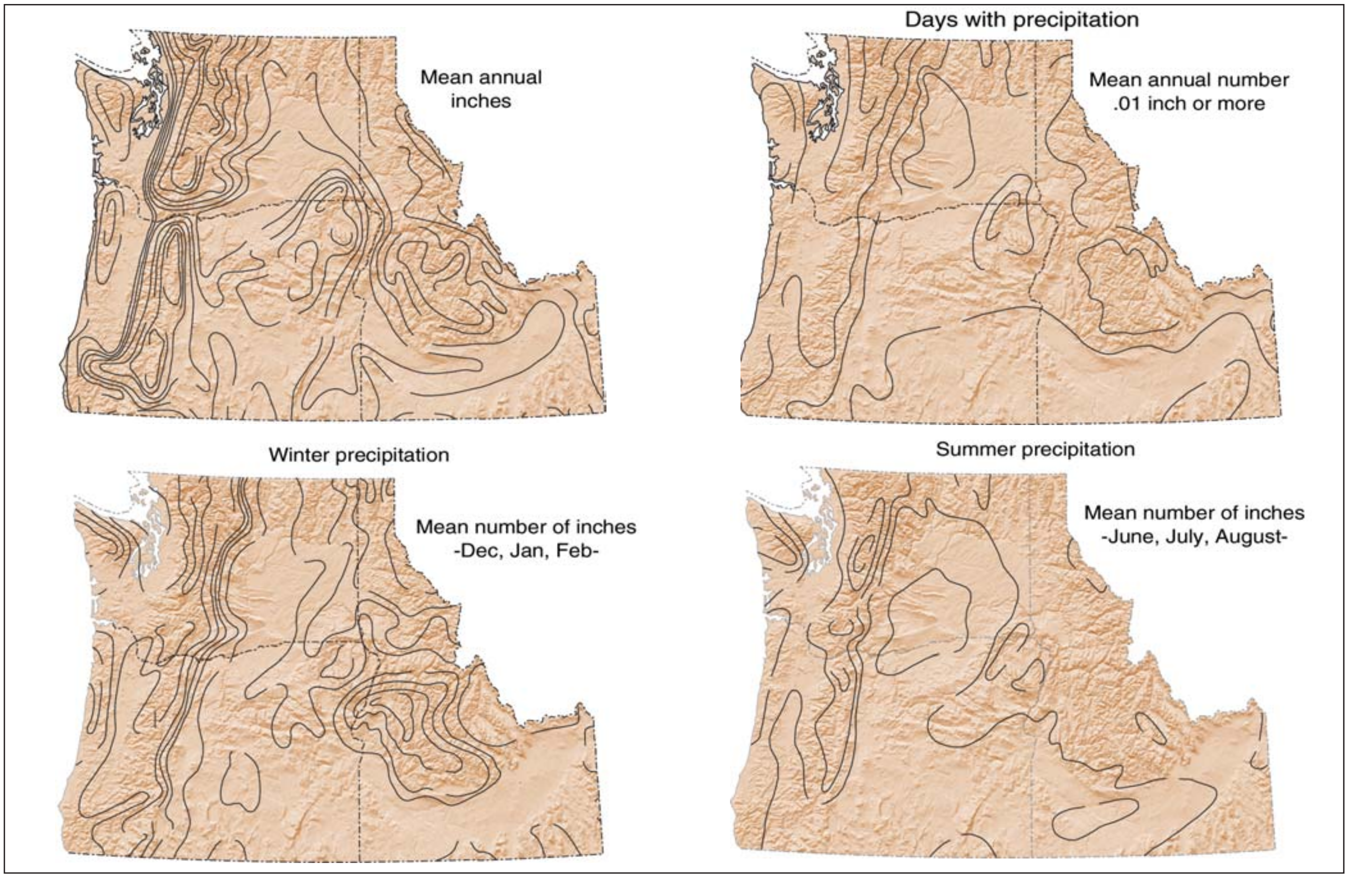

Figure 4—Mean annual winter and summer precipitation in the Pacific Northwest (from Jackson and Kimerling 2003).

<41 cm of annual precipitation, and a large area of south-central Washington and southeast Idaho, noted for agricultural production, receives <21 cm annually.

Although climatic factors strongly affect the distribution of water resources at the regional scale, other physical and biological factors operating in concert with the variations in regional climate may have greater influence at the watershed scale. Geology, topography, and climate can profoundly affect temporal and spatial production of water in individual watersheds within a regional climatic zone. Consequently, the complexity of water production in time and space is greater at the watershed scale than it is at the regional scale.

Superimposed atop an already complex and variable scale-related water regimen in the Pacific Northwest are periodic occurrences of the El Niño Southern Oscillation (ENSO), which affects the Pacific Northwest's climate on an interannual basis (Mantua 1998); the Pacific Decadal Oscillation (PDO), which affects Pacific weather patterns on cycles of two to three decades (Hare 1998); and emerging concerns that global climate change could shift weather patterns to new long-term equilibria (Drennen and Kaiser 1993).

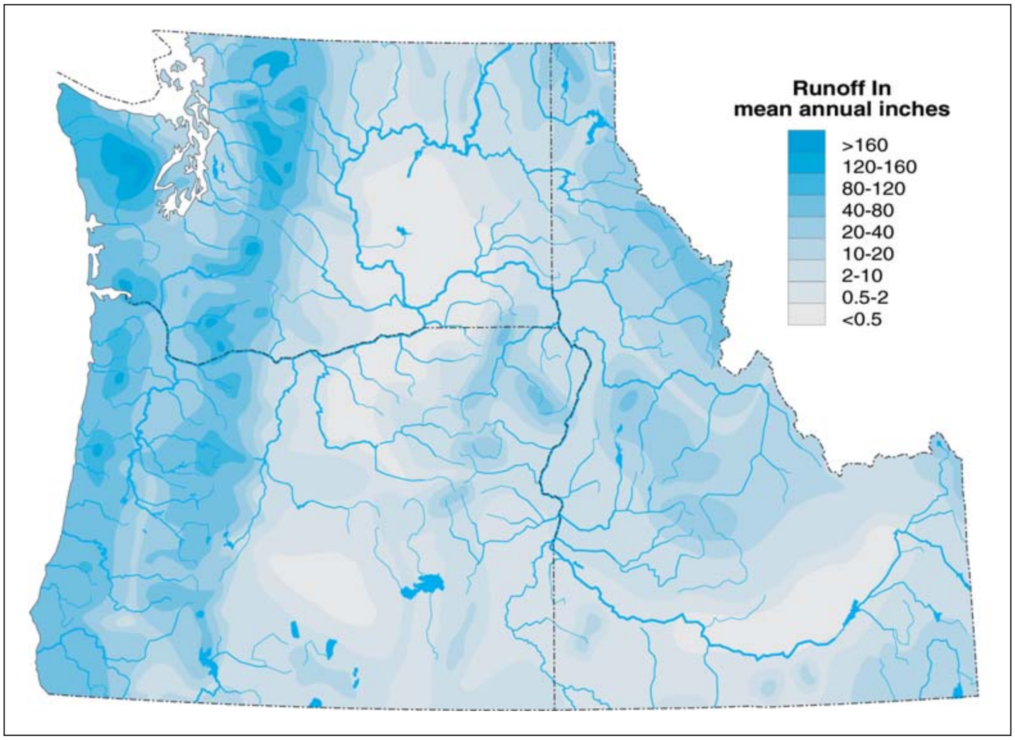

Figure 5—Mean annual inches of runoff in the Pacific Northwest (from Jackson and Kimerling 1993).

Spatial Distribution of Water Supply at the Regional Scale

Seasonal and spatial variability in precipitation (fig. 4) and runoff complicate management of the region's water resources and create persistent problems and conflicts in some geographic areas between offstream and instream water uses, and between user groups. Most precipitation falls in winter, and summers are generally warm and dry. Areas west of the Cascade Range receive 5 to 20 cm of summer rainfall, whereas areas east of the Cascade Range receive <2.5 to about 10 cm. Much of the intermountain area receives <5 cm during the average summer.

Variability of annual runoff parallels that of precipitation (fig. 5). Runoff west of the Cascade Range varies from >305 cm in the Olympic Mountains to <25 cm in valleys between the Coast and the Cascade Ranges. East of the Cascade Range runoff varies from >102 cm in high-elevation watersheds of the Cascade, Blue, and Rocky Mountains to <13 cm in some intermountain valleys. Large key agricultural areas of Washington, Oregon, and Idaho, where demand for water is greatest, have annual surface runoff of <13 cm.

Variations in the amount of runoff are related directly to amounts of precipitation and evapotranspiration, but timing of runoff is controlled largely by climatic and orographic factors. Three distinct hydrographs (fig. 6), dominated by rain, rain-on-snow, and snow hydrology, occur in the region. The type of precipitation affects the way water is stored on the landscape and the timing of its release as runoff. In watersheds dominated by rainfall, for example, in areas of the Oregon and Washington Coast Range, peak streamflows correspond with winter cyclonic storms moving onshore

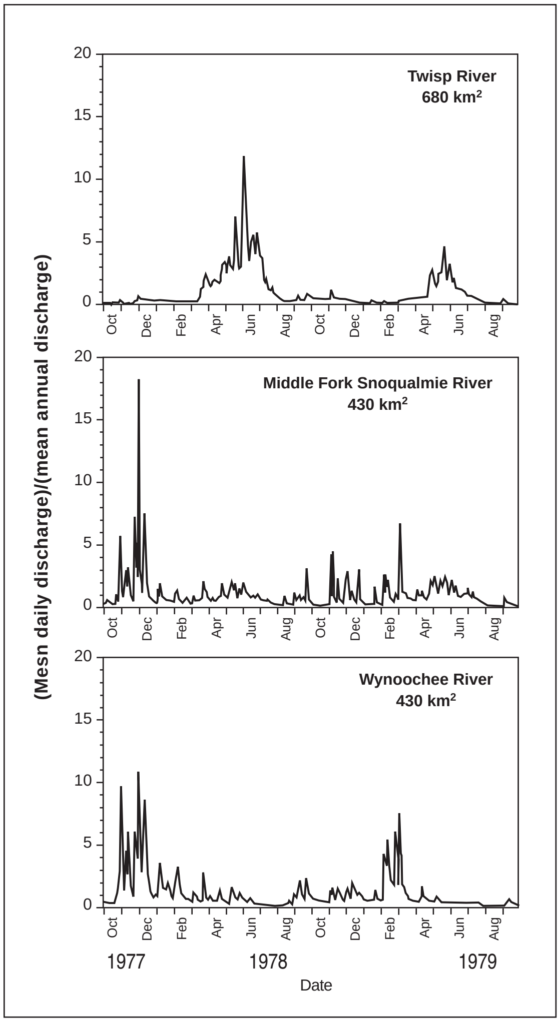

Figure 6—Hydrographs for representative watersheds dominated by rain (bottom), rain-on-snow (middle), and snow precipitation regimes (top) in Washington (from Ziemer and Lisle 1998).

from the Pacific Ocean. Low flows occur during the typically dry summers (fig. 6). In contrast, spring-driven systems (e.g., the Deschutes River) receive peak flows from snowmelt in May and June.

Watersheds in the transition snow zone (e.g., midelevation watersheds on the west slope of the Cascade Range) exhibit hydrographs similar to those of the rainfall zone, but with wider variations in peak winter flows (fig. 6). Extreme peak flows can occur when accumulated snow in watersheds melts rapidly owing to intense warm winter cyclonic storms. Such events often result in severe flooding. Rain-on-snow areas also exhibit low streamflow during the typically dry summers in the Northwest because most snowpacks have melted by early summer.

Watersheds dominated by snow hydrology (e.g., high-elevation watersheds in the Cascade and Rocky Mountains, and the Columbia River basin) exhibit hydrographs almost opposite those dominated by rainfall (fig. 6). Low streamflow occurs during winter when below freezing temperatures prevail in watersheds and winter precipitation accumulates as snow, and in late summer and fall after seasonal snowpacks melt. Snowmelt fuels peak flows in spring and early summer in these watersheds.

Spatial Distribution of Water Supply at the Watershed Scale

Detailed analysis of water yield at the watershed scale is generally lacking across the region. However, Grant (1997) studied the streamflow geography in the Willamette River basin (Oregon). This analysis revealed that wide temporal and spatial variations in streamflow occur within subwatersheds in the basin. Spatial variation, along an east-west gradient, results in seasonal changes in streamflow defined by the underlying geology and topography (Grant 1997). Streamflow in the basin and its tributaries is affected by drainage density, degree of landscape dissection, age of weathering of the underlying rocks, and topography (Grant 1997). Most summer streamflow in the Willamette River basin arises from lands managed by the National Forest System that are designated wilderness areas (Niemi and Whitelaw, in press). The greatest provider of municipal water supplies in the Willamette River basin is National Forest System lands. The study by Grant (1997) provides important watershed-scale surface-water information for water managers and planners. Data on both surface- and ground-water resources would complete the scientific information base needed to assist water managers with development of sustainable water use plans for this basin and most others.

Spatial Distribution of Water Use and Consumption in the Pacific Northwest

Four economic sectors—domestic, industrial, thermoelectric, and agriculture—exert the primary demands for consumptive water use in the Northwest. Regional demands, however, exceed supply. Water demands are greatest in late summer when water supplies across the region are generally at their lowest seasonal levels.

Drinking water in the Northwest is derived from both surface- and ground-water sources. In Washington, ground water provides more than 65 percent of the drinking water consumed by the state's 5.9 million inhabitants (U.S. Environmental Protection Agency 1999). Surface waters supply the needs of some major municipalities like the greater Seattle metropolitan area. Seattle's Cedar River and South Fork Tolt River watersheds provide drinking water from surface sources for more than 1.3 million residents (Seattle Public Utilities 2001). In Oregon, 30 percent of the residents rely solely on surface sources for drinking water and 50 percent rely solely on ground water (Oregon Department of Environmental Quality 2001). The remaining 20 percent derive drinking water from a combination of surface- and ground-water sources. The state's largest public water systems (e.g., serving the Portland metropolitan area) rely primarily on surface water from the Bull Run and Little Sandy River watersheds. Idaho relies more heavily on ground water than either Oregon or Washington. Ground water is the sole source of drinking water for about 95 percent of the state's residents (U.S. Environmental Protection Agency 1999).

Throughout the Northwest, drinking water from surface sources originates in forested watersheds and is stored in reservoirs to accommodate peak seasonal usage. Ground water originates in deep aquifers and is pumped from thousands of wells ranging in depth from a few meters to over 300 m. Although a large portion of drinking water in the Northwest is derived from aquifers, drinking water represents a small portion of the region's total use of ground water. Only about 4 percent of ground-water use in Idaho is for drinking water, as compared to 37 percent in Washington and 23 percent in Oregon (USDI Geological Survey 2001).

In the Northwest, the primary offstream use of water, agriculture, accounts for >80 percent of the region's water withdrawals. Idaho farmers annually use >20 million acre-feet (>24.7 billion $m^{3)}$ of surface and groundwater for irrigation, whereas

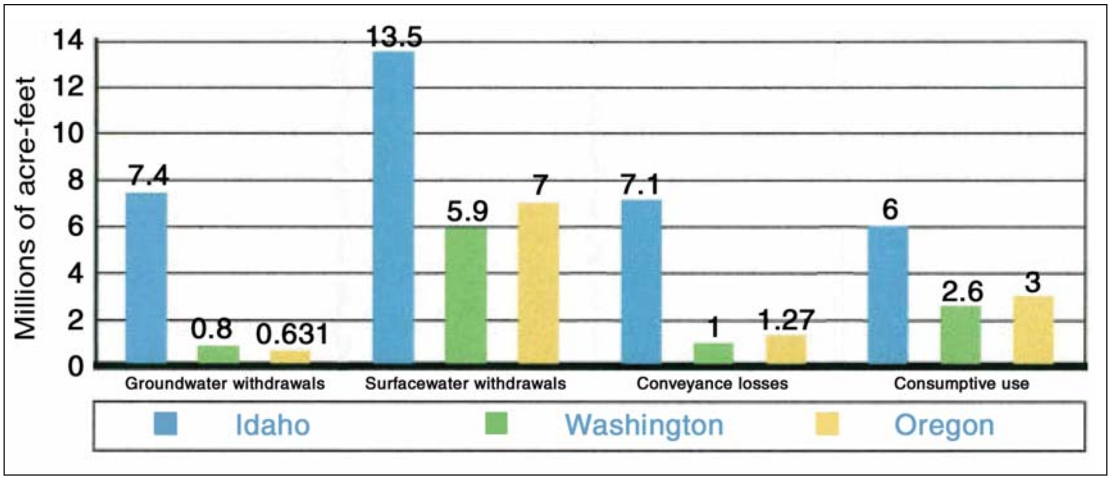

Figure 7—Annual irrigation water use in millions of acre-feet (1 acre-foot is the volume of water, 43,560 cubic feet, it would take to cover an area of 1 acre to a depth of 1 foot) in the Pacific Northwest (from Solley et al. 1993).

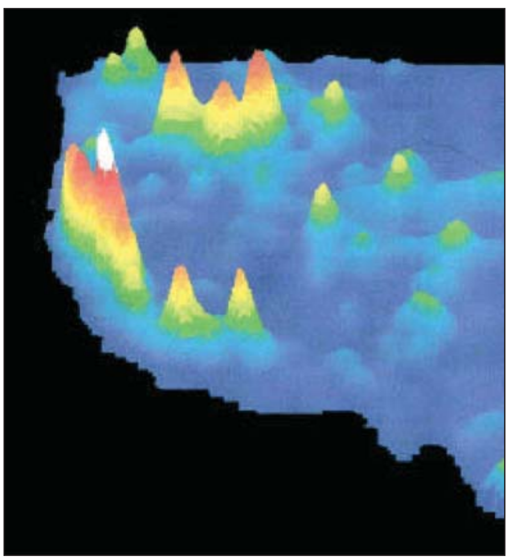

Figure 8—Total annual water withdrawals in the Western United States. Note high water use in the Snake River basin of southern Idaho and the Columbia River in east-central Washington (http://www.water.usgs.gov/watuse/graphics/wuto.fact.3d.gif).

Washington and Oregon use about 7.4 and 7 million acre-feet (9.1 billion and 8.6 billion m^{3}), respectively (fig. 7). Areas of high agricultural production in the intermountain regions of Oregon, Washington, and Idaho exert the greatest demand on water resources. Particularly high demands occur in the Snake River basin in southern Idaho and the Columbia basin of east-central Washington (fig. 8). Major reclamation projects in the intermountain area, mainly large dams and water conveyance facilities, have increased water availability for agriculture, but the quantity supplied in some areas, especially in the Snake River basin, is still inadequate to meet all demands. Irrigators currently supplement inadequate supplies of surface water (fig. 9) by pumping ground water from aquifers, in some cases at unsustainable rates (Stuebner 2000).

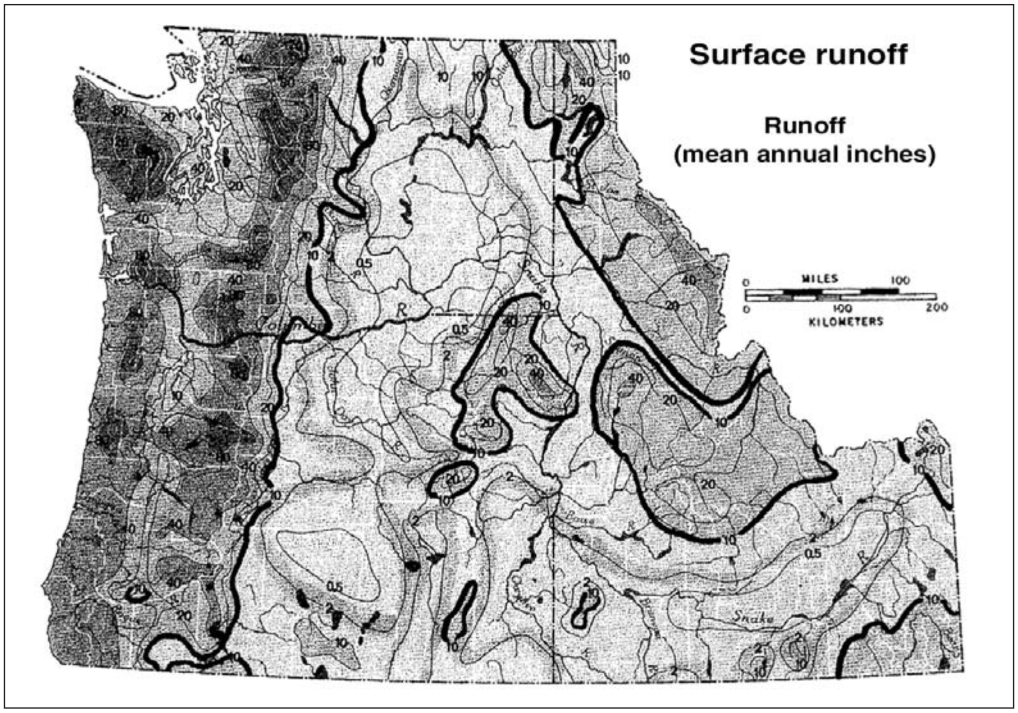

Figure 9—Geographic areas of the Pacific Northwest with <254 mm average annual runoff (light shaded areas in the intermountain zone) have the greatest potential for conflicts between instream and off-stream water uses (from Jackson and Kimerling 1993).

Offstream municipal and industrial demands for water differ with location. The Puget-Willamette lowlands, west of the Cascade Range, where most of the region's population resides, use the most water. The large metropolitan areas of Seattle, Washington, and Portland, Oregon, and the pulp and paper industry in the lower Columbia River basin consume significant volumes of water. However, in the area west of the Cascade Range, the current supply generally meets existing needs, except perhaps during extreme droughts. Offstream cooling of a nuclear reactor also uses water to cool reactors on the Hanford Nuclear Reservation. Water is drawn from the Columbia River, pumped through the reactor cooling system, and returned to the river as warm effluent.

The primary instream water uses include hydropower generation, navigation, pollution dilution and disposal, recreation, and aquatic and riparian habitat maintenance. In many areas of the Northwest, especially in the semiarid intermountain zone, beneficial instream water uses are compromised by offstream uses that dewater stream channels. For example, in the 1970s, Idaho's Big Lost River was a popular stream for recreational trout fishing. By 1995, surface- and ground-water withdrawals for irrigation had completely dewatered the lower portion of the river in summer.

The region's greatest nonconsumptive instream water use is for hydropower generation, with more than 1.7 trillion m^3 used annually to power turbines (Muckleston 1993). This volume exceeds the region's total runoff because the water is used repeatedly as it passes through successive powerhouses on large river systems.

Large volumes of water are stored at federal and provincial dams and reservoirs on the Columbia River in the United States and Canada, and released downstream for power generation as needed. Because the temporal and spatial distribution of water is uneven across the Northwest, water for hydropower generation must be stored to be available year-round. The region's dams and reservoirs also benefit navigation on the Columbia and Snake Rivers.

All rivers draining municipal, industrial, and agricultural areas in the Northwest and elsewhere are used to dilute, assimilate, and disperse various pollutants, including human wastes, complex industrial compounds, agricultural fertilizers and pesticides, radioactive materials, and waste heat. The capability of the region's rivers to assimilate or dispose of pollutants is compromised by offstream demands for water that diminish instream flows. The greatest conflicts occur in semiarid regions.

Aquatic recreation is currently one of the fastest growing instream uses of water throughout the United States. Recreational opportunities associated with water include both water-dependent and water-enhanced recreational activities. Water-dependent activities, where water is essential to conducting the activity, include fishing, boating, waterskiing, swimming, kayaking, rafting, canoeing, sailing, and most waterfowl hunting. Water-enhanced recreational activities do not require water in order to participate in the activity, but water greatly contributes to the overall recreation experience. These activities may include hiking and camping along bodies of water, viewing scenery, and nature study. These categories are rarely distinct. Instead, participants usually conduct several activities during a visit to a recreation site. For example, boating allows people to participate in other water-based recreational activities such as swimming, shoreline camping, or nature study.

Growing recreational demand in the Northwest is related to population growth and shifting regional demographics. The current trend in the United States has been for residents to migrate from the Northeast, Midwest, and Plains States to the South and West (USDC Bureau of the Census 1997). Both internal growth and migration, from within the United States and other countries, are expected to contribute to population increases in the Northwest. The projected increases in population in the Northwest in the next 25 years indicate that additional recreational demands will be placed on natural resources in general, and water resources in particular. Assuming that water resources remain relatively constant in the region, recreation pressure per unit of water area will increase substantially in all areas, affecting the quality of recreational experiences.

Shifting demographics in the region also will affect water-oriented recreation. In addition to general population growth, ethnic and racial diversity and the proportion of elderly residents in the population are expected to rise sharply by 2025 (USDC Bureau of the Census 1997). These demographic changes may have a profound effect on future recreation trends in the region owing to the differing ways older Americans and ethnic groups recreate. According to Murdock et al. (1991), older Americans tend to engage in lower intensity recreation activities than younger Americans, which could cause a shift in the preferred types of water-based recreation. Also, minorities may participate differently in water-based recreation. Hispanics, for example, tend to participate in sedentary recreational activities such as picnicking (Hutchison 1987, Hutchison and Fidel 1984). This may increase the pressure on the region's reservoir-oriented recreational facilities.

A unique feature of the Northwest is the concentration of federal wild, scenic, and recreational rivers, and state-designated recreation rivers that appeal to a national and international clientele. Across the region, Oregon has 2723 km of designated rivers, Washington has 285 km, and Idaho has 924 km (Zinser 1995). Classification of these rivers is based on their “outstandingly remarkable” characteristics. Land and water use are more tightly controlled on wild and scenic river corridors than on other streams.

Recreational activities are strongly affected by the distribution of water resources. In most of the areas where population and water resources co-occur west of the Cascade Range, water availability is sufficient to meet growing recreational demand. East of the Cascade Range, water availability can be insufficient to meet the needs of off-channel users while meeting demands for water-oriented recreation (e.g., trout fishing) (Stuebner 2000).

Maintenance and protection of aquatic habitat and biodiversity are critical instream water uses. For decades as surface waters were appropriated through individual and industry water rights, the beneficial use of instream water for aquatic habitat was not recognized. In 1993, the high-profile listing of Snake River salmon as threatened and endangered, however, provided both societal support and a legal basis for instream use of water for aquatic habitat and species protection. The need for instream flows for aquatic habitat is not limited to salmonid stocks in the Columbia basin. Other high-profile aquatic species, including many steelhead (*Oncorhynchus mykiss* Walbaum) stocks, bull trout (*Salvelinus confluentus* (Suckley)), and coastal stocks of coho salmon (*O. kisutch* Walbaum) have received threatened status under the ESA. Many other low-profile aquatic species or stocks also are listed, including 5 threatened and 7 endangered in Idaho, 15 threatened and 6 endangered in Oregon, and 12 threatened and 2 endangered in Washington (table 1). As demands for water increase in the region, it becomes essential for resource management agencies to coordinate their efforts to assure sustainable use of the region’s water.

Federal Land Management and Water Distribution in the Northwest

What is the potential role of federal lands in resolving water-related issues? The Forest Service manages lands that produce 38 percent of the region’s average annual runoff. The Forest Service and the National Park Service manage nearly all the high-elevation landscapes in the region that receive the greatest precipitation and provide the greatest runoff. Can these lands be managed to increase water yield, or change the timing of runoff to alleviate the region’s temporal and spatial problems with water supply?

The topic of increasing water yield through land management has been intensively studied during the latter half of the 20th century. Most research examined the potential of manipulating vegetation and snowpack to increase the quantity, or change the timing, of water yield from forested landscapes within the constraints of normal precipitation cycles. The results of hundreds of studies indicate that management can result in increases in water yield, but the magnitude and duration of potential effects are heavily influenced by the amount and timing of precipitation received by affected areas, and by social, economic, and legal constraints placed on the agencies managing those landscapes.

Table 1—Threatened (T) and endangered (E) aquatic animals in the Pacific Northwest (continue)

Status	Common name	Scientific name
Idaho:		
E	Limpet, Banbury Springs	*Lanx* sp.
T	Salmon, Chinook (spring/summer Snake River)	*Oncorhynchus tshawytscha* (Walbaum)
T	Salmon, Chinook (fall Snake River)	*Oncorhynchus tshawytscha*
T	Salmon, sockeye (Snake River)	*Oncorhynchus nerka* (Walbaum)
E	Snail, Bliss Rapids	*Taylorconcha serpenticola*
E	Snail, Snake River *physa*	*Physa natricina*
E	Snail, Utah *valvata*	*Valvata utahensis*
E	Springsnail, Bruneau Hot Springs	*Pyrgulopsis bruneauensis*
E	Springsnail, Idaho	*Fontelicella idahoensis*
T	Steelhead (Snake River basin)	*Oncorhynchus mykiss* (formerly [*Salmo gairdner*: Richardson])
E	Sturgeon, white	*Acipenser transmontanus* Richardson
T	Trout, bull (U.S. conterminous 48 states)	*Salvelinus confluentus*
Oregon:		
E	Chub, Borax Lake	*Gila boraxobius* Williams and Bond
T	Chub, Hutton tui (Hutton)	*Gila bicolor* ssp.
E	Chub, Oregon	*Oregonichthys crameri* Snyder
T	Dace, Foskett speckled (Foskett)	*Rhinichthys osculus* ssp. Girard
T	Fairy shrimp, vernal pool	*Branchinecta lynchi*
T	Salmon, Chinook (spring/summer Snake River)	*Oncorhynchus tshawytscha*
T	Salmon, Chinook (upper Willamette River)	*Oncorhynchus tshawytscha*
T	Salmon, Chinook (lower Columbia River)	*Oncorhynchus tshawytscha*
T	Salmon, Chinook (fall Snake River)	*Oncorhynchus tshawytscha*
T	Salmon, chum (Columbia River)	*Oncorhynchus keta* (Walbaum)
T	Salmon, coho (OR, CA pop.)	*Oncorhynchus kisutch* (Walbaum)
E	Salmon, sockeye (Snake River)	*Oncorhynchus nerka*
T	Steelhead (Snake River basin)	*Oncorhynchus mykiss*
T	Steelhead (lower Columbia River)	*Oncorhynchus mykiss*
T	Steelhead (upper Willamette River)	*Oncorhynchus mykiss*
T	Steelhead (middle Columbia River)	*Oncorhynchus mykiss*
E	Sucker, Lost River	*Deltistes luxatus*
E	Sucker, shortnose	*Chasmistes brevirostris*
E	Sucker, Warner	*Catostomus warnerensis* Snyder
T	Trout, bull (U.S. conterminous 48 states)	*Salvelinus confluentus*
T	Trout, Lahontan cutthroat	*Oncorhynchus clarki henshawi*

Table 1—Threatened (T) and endangered (E) aquatic animals in the Pacific Northwest (continued)

Status	Common Name	Scientific name
Washington:		
T	Salmon, Chinook (spring/summer Snake River)	*Oncorhynchus tshawytscha*
T	Salmon, Chinook (spring upper Columbia River)	*Oncorhynchus tshawytscha*
T	Salmon, Chinook (lower Columbia River)	*Oncorhynchus tshawytscha*
T	Salmon, Chinook (Puget Sound)	*Oncorhynchus tshawytscha*
T	Salmon, Chinook (fall Snake River)	*Oncorhynchus tshawytscha*
T	Salmon, chum (Columbia River)	*Oncorhynchus keta*
T	Salmon, chum (summer run Hood Canal)	*Oncorhynchus keta*
E	Salmon, sockeye (Snake River)	*Oncorhynchus nerka*
T	Salmon, sockeye (Ozette Lake and tributaries)	*Oncorhynchus nerka*
T	Steelhead (Snake River Basin)	*Oncorhynchus mykiss*
E	Steelhead (upper Columbia River)	*Oncorhynchus mykiss*
T	Steelhead (upper Willamette River)	*Oncorhynchus mykiss*
T	Steelhead (lower Columbia River)	*Oncorhynchus mykiss*
T	Trout, bull (U.S. conterminous 48 states)	*Salvelinus confluentus*

Source: U.S. Fish and Wildlife Service 2000.

Ziemer (1987) and Ziemer and Lisle (1998) examined the scientific literature on the effects of vegetation removal on water yield. In 94 watershed experiments worldwide, water yields either remained constant or increased after vegetation removal (Bosch and Hewlett 1982). The potential for increasing water yield by removing vegetation was greatest in areas having coniferous forests, less in deciduous hardwoods, and least in brush and grasslands. Water yield increases following vegetation removal were greatest in high-rainfall areas. Within a given area, yield tended to be greater in wet than in dry years (Ponce and Meiman 1983). When small, forested watersheds are cleared, either by clearcutting and silvicultural burning or wildfire, annual streamflow increases for a time (Bosch and Hewlett 1982, Rothacher 1971). Small watershed studies indicate that no potential exists for increasing water yield by manipulating vegetation in areas where annual precipitation is less then 40 cm, and marginal potential where annual precipitation ranges between 40 and 50 cm (Clary 1975, Hibbert 1983). Within the Pacific Northwest, relative to unmanaged forests, sustained increases in annual water yield related to forest practices in western Oregon and Washington would be about 2.7 percent under a 120-year rotation and 4.7 percent under a 70-year rotation (Harr 1983). Despite concerns about the negative effects of western juniper (*Juniperus occidentalis* Hook) expansion on water resources, Belsky (1996) determined that juniper control is unlikely to improve streamflows and aquatic habitats. Given the multiple-use sustained-yield guidelines and other legal frameworks of federal land management agencies, water yield (from forested watersheds) can only be increased by about 1 percent (in favorable high-precipitation and runoff zones) above current levels (Kattelman et al. 1983). Streamflow gauging records by the U.S. Department of the Interior Geological Survey have about 5 percent error (Rothacher 1970). Projected increases in water yield are so small relative to error that if they were achieved, they would likely go undetected.

These studies clearly show that water yield from small, forested watersheds in the Pacific Northwest could be slightly increased in some climatic zones through vegetation manipulation, whereas enhanced yield from arid areas is not feasible. To date, no controlled large-scale experiments to increase water yield have been conducted in the Northwest. Plans to increase water yield at landscape scales in other areas of the West have been proposed (Barr 1956a, 1956b; Fox 1977), but implementation was never completed because of inadequate scientific design, political resistance, and funding problems.

The potential of manipulating snowpacks to increase water yield and improve timing of runoff from high-elevation forests and alpine zones also has been reviewed by Anderson (1963), Kattelman et al. (1983), Ponce (1983), and Ziemer and Lisle (1998). They identified four promising proposals. First, forest cutting patterns can be modified to maximize and protect snow accumulation (Anderson 1956). Second, various configurations of snow fences have been created to maximize accumulation and delay snowmelt (Martinelli 1975, Tabler and Sturges 1986) to modify water yield and timing of runoff. Third, chemicals can be used to suppress melting and sublimation of snowpacks (Slaughter 1970). Fourth, weather can be modified (e.g., cloud seeding) to increase snowpack (Kattelman and Berg 1987). After reviewing these proposals, Ziemer and Lisle (1998) concluded that although some of the proposals have technical merit, serious constraints prevent their implementation. An overriding constraint is that much of the high-elevation land is in national parks, wilderness areas, or other areas reserved from active land management. Another constraint applies to areas where manipulation of snowpack is possible. In these areas, protection of old-growth forest stands, scenic values, wildlife and fish habitats, water quality, and other resource values often preclude water yield improvements. Given existing administrative boundaries and management constraints, there appears to be little potential to improve water yield and timing of delivery from snowpack zones of the Pacific Northwest.

Providing additional surface storage could alter the timing of water yield from forested landscapes and balance the distribution of water resources across the region. Additional storage capacity would allow managers to impound excess winter flows for subsequent release during summer when water is in short supply. Providing additional storage, however, is now a complex social, economic, and ecological proposition.

Increasing storage and delivery capacity is largely the responsibility of individual states that have acknowledged the need to provide additional water (Western States Water Council 1995) to sustain the rapid growth within their boundaries (Case and Alward 1997). However, most of the socially acceptable and economically and environmentally feasible major storage projects in the region had already been built by the early 1980s. Accordingly, the states have indicated that additional storage projects are likely to be smaller and more environmentally compatible than previous water developments (Western States Water Council 1995). Any new storage is likely to be used at least partly for ecological purposes, or to meet the needs of rural communities and the water rights of Native American nations (Western Water Policy Review Advisory Commission 1998).

New water developments could be constructed on federal or private lands, but in either case, stringent, interorganizational and individual planning and examination of social, economic, and environmental concerns would be required. As with manipulation of vegetation and snowpack, it is doubtful that significant gains in water supply through additional storage can be made in the Pacific Northwest, although acute needs at specific locations might be met in this way.

Despite the fact that the Forest Service administers the most water-rich landscapes in the Pacific Northwest, it is often overlooked as a federal water management agency. Little opportunity exists to increase water yield from national forests; however, under existing laws and management guidelines that emphasize multiple use, land management activities can affect water quality and water delivery downstream. Forest management can affect sediment yield, water temperature, nutrient loading, and toxic contaminants (Sedell et al. 2000). It also can marginally affect peak streamflows and the duration of dry-season streamflows in downstream waters. The potential consequences of management can affect the value of national forest water for both instream and offstream uses.

If national forest managers maintain water yield and water quality within the long-term historical range of natural variation, predictable levels of water quality and water supply, whether impounded or free-flowing, will be available for water users and consumers downstream. Conversely, management that reduces water quality could result in significant social, economic, and ecological consequences downstream.

The Need for Improved Water Conservation in the Northwest

Because the prospects of increasing water supplies from forested landscapes of the Pacific Northwest are minimal, continued improvements in conservation and efficient use of existing supplies become essential in meeting the region’s growing water needs. Economic incentives can be used as a management tool to encourage both water conservation and improvements in water quality (Baumol and Oates 1988). These include taxes, subsidies, tiered pricing, low-interest loans, and market-based mechanisms such as tradable water rights or discharge permits.

Water law in the Western United States is slowly changing to provide incentives for wiser use of water in arid regions, in part, by acknowledging a greater variety of water’s “beneficial uses.” Historically, Oregon law required that a water rights holder had to use their allocated share of water at least once out of every 5 years to prevent its forfeiture or cancellation (Oregon Department of Water Resources 2001). Leaving the water in the stream could result in the loss of the water right. Recently, however, Oregon water law included instream flow as a “beneficial use” (Oregon Water Resources Congress 2000). This change allows irrigators to sell or lease their water rights to augment instream flows to benefit water quality, fish and wildlife habitat, and instream recreation. In some cases, federal agencies buy water to increase instream flows for fish and wildlife habitat, recreation, and improve water quality.

Other conservation measures, including some mentioned earlier, have the potential to conserve large volumes of water in the Northwest. Agricultural efficiencies are being achieved by leveling fields and by using low-head sprinklers, drip and surge irrigation, enclosed conveyance pipes, and low-water-use crops (Western Water Policy Review Advisory Commission 1998). Federal and local governments subsidize many of these investments in water-saving technologies. Municipal and industrial conservation also can be achieved through water-saving plumbing codes. Diligent interagency and user-group cooperation in water conservation holds great potential for meeting the water needs of the Northwest.

Research Needs on Water Distribution

How can the PNW Research Station assist in improving understanding of the spatial distribution of water on national forests and other forested landscapes in the region? Fruitful areas to apply research efforts in the Pacific Northwest include (where priorities are defined as H = high, M = moderate, L = low):

- Establishing information on natural spatial and temporal historical and current variability in water yield and water quality from the region's major basins and subwatersheds. (H)
- Biological research to improve understanding between outcomes of land management and influence on aquatic and riparian habitats. (H)
- Developing improved understanding of the hydrologic and ecologic role of headwater catchments and small stream channels in the context of river basins. (H)
- Developing improved understanding of water management impacts on recreational opportunities, including the displacement of recreationists from one location to another. (M)
- Defining the historical distribution and abundance of salmonids in large watersheds. (M)
- Hydrologic and biological research to improve understanding of the relationship between land management and water yield and water quality. (M)
- Studying the effects of Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco) and true fir (*Abies* species) removal on water yield from ponderosa pine (*Pinus ponderosa* Dougl. ex Laws.) sites in the intermountain region of the Pacific Northwest. (L)
- Providing a better understanding of the options for and consequences of additional water storage on federal lands. (L)

Altered Flow Regimes and Water Quality Affect Water Supply and Use

Some of the most endangered rivers of the United States, according to the American Rivers Council, are located in the Pacific Northwest (Sonner 1998). The 82-km Hanford Reach of the Columbia River is listed as the most endangered river in North America because of chemical and nuclear pollution entering the river from the Hanford Nuclear Reservation. The lower Snake River is ranked eighth on the list because of the threats that dams pose to threatened and endangered salmon stocks. The Rogue and Illinois Rivers in southwest Oregon, ranked 13th, are threatened by dams and mining, and the Walla Walla River, ranked 18th, is threatened by agricultural pollution, low flows, and channelization. Many streams and lakes in the region, and the aquatic ecosystems they support, also are affected by alterations in streamflow and water quality.

Table 2—Effects of El Niño (El N.) events on temperature and precipitation in the Pacific Northwest by climate divisions[a]

	Temperature, Dec.-Feb.			Precipitation, Nov.–Dec.		
Division	**Ave.**	**El N. ave.**	**El N. diff.**	**Ave.**	**El N. Ave.**	**El N.**
	---------Degrees celsius---------			*---Centimeters---*		*Percent normal*
Coastal Washington	4.9	5.8	+.9	71.07	69.19	97
Interior W. Washington	3.1	4.1	+1.0	4.64	37.59	93
Central Washington	-1.1	.2	+1.3	16.48	14.22	86
N.E. Washington	-2.4	-.9	+1.3	15.42	14.48	94
Idaho-Oregon-Washington	-.4	.8	+1.2	13.74	11.25	82
Coastal Oregon	6.7	7.4	+.7	61.04	57.12	94
Int. W. Oregon	3.5	4.3	+.8	41.50	37.03	89
Central Oregon	-1.1	-.3	+.8	14.81	12.01	81
Central Idaho	-5.6	-4.6	+1.0	14.94[b]	11.46[b]	77[b]
S.W. Idaho	-1.2	-.2	+1.0	9.47[b]	8.15[b]	86[b]
S.E. Idaho	-4.4	-3.4	+1.0	8.79[b]	6.99[b]	80[b]

[a] Temperature and precipitation averages are based on 102 years of record, including nine El Niño (El N.) events between 1940 and 1995 (from NOAA 2000).

[b] Idaho precipitation data are for the period December through February.

Climate Fluctuations

The cyclic climatic effects of the ENSO and the PDO complicate the variability of water availability and flow in the Pacific Northwest. El Niño is a recurrent interannual climatic event characterized by unusually warm ocean temperatures in the equatorial Pacific. These events typically occur every 2 to 7 years and generally have durations of 12 to 18 months (Hare et al. 1999). As El Niños recede, ENSO's opposite extreme, La Niñas, which are characterized by unusually cold ocean temperatures in the equatorial Pacific Ocean, follows. 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 (table 2), 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. Between 1895 and 1989, La Niñas generally produced cooler temperatures in coastal areas of the Pacific Northwest and in some areas of the western slope of the Cascade Range of Oregon, while much of the region experienced higher than normal precipitation (fig. 10).

The PDO also affects Northwest weather but in a more widely variable way than ENSO. The PDO is a long-lived Pacific climate pattern with profound effects on the North Pacific and terrestrial environments of the Pacific Northwest (Mantua et al. 1997). Two main characteristics distinguish the PDO from ENSO. First, 20th-century events 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, which affect temperature, precipitation, and runoff patterns in western North America as well as the productivity of anadromous salmonid-rearing areas in the North Pacific.

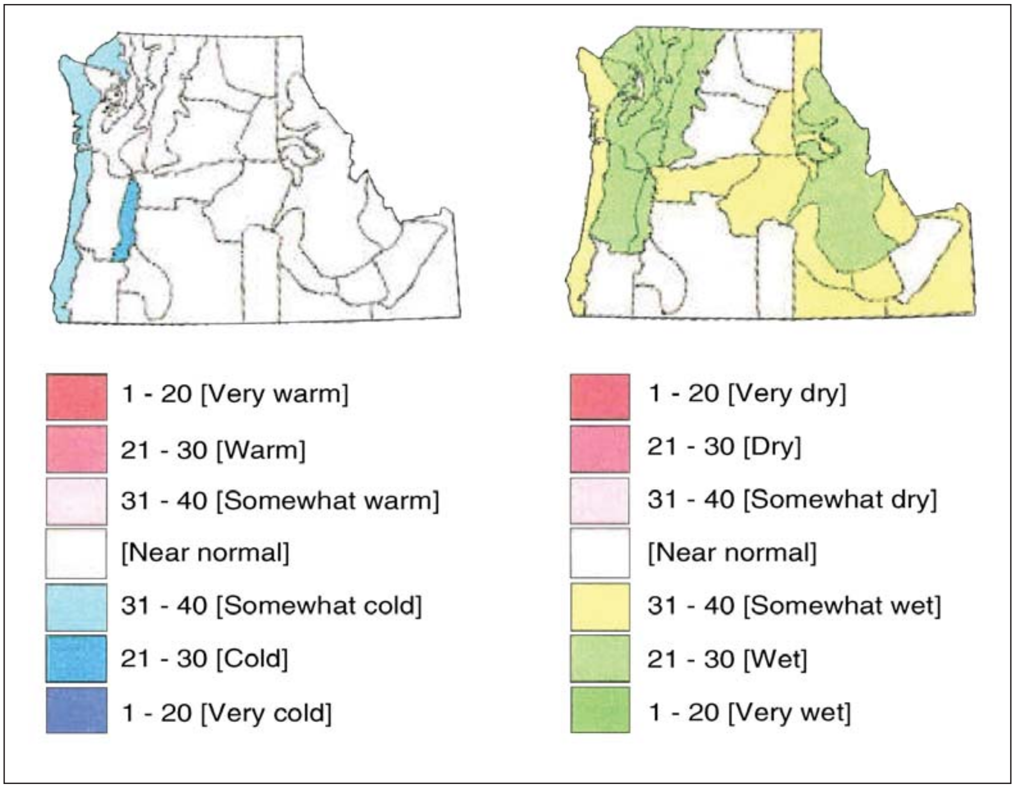

Figure 10—Average temperature and precipitation ranks for Pacific Northwest climate zones based on seven La Niña events, 1985-89 (from NOAA 2000).

The PDO from 1925 to 1946 and from 1977 to at least 1995 favored salmonid production in the Alaska Gyre, increased storm activity and precipitation in Alaska, and produced calmer, warmer, and drier weather in the Pacific Northwest. Ferguson (1999) reported highest winter precipitation in all areas of the interior Columbia basin in the mid-1970s (just prior to the last PDO shift), and since then, precipitation decreased 30 to 80 percent over most of the interior basin. In a study of the relation between streamflow and logging in 23 western Washington watersheds, Bowling et al. (2000) found significantly decreasing trends in annual streamflow minima (uncorrected for climatic influences) that are apparently dominated by the 1977 shift.

In contrast, in the Pacific Northwest and California, anadromous salmonid production is highest from 1890 to 1924 and from 1947 to 1976. Weather patterns tended to be the reverse of those during years when salmon production is strongest in Alaska. Neither the exact causes nor the predictability of the PDO are currently known. However, the positive phase of the cycle has the potential to cause decades of below-normal precipitation in the Northwest and greatly complicate management of water resources.

Global climate change may complicate future water management in the Northwest. However, the exact nature of the extent and consequences of global warming in the region and world are not yet clear. Some predict warmer and drier summers resulting in less water available for drinking, irrigation, hydropower, recreation, and even

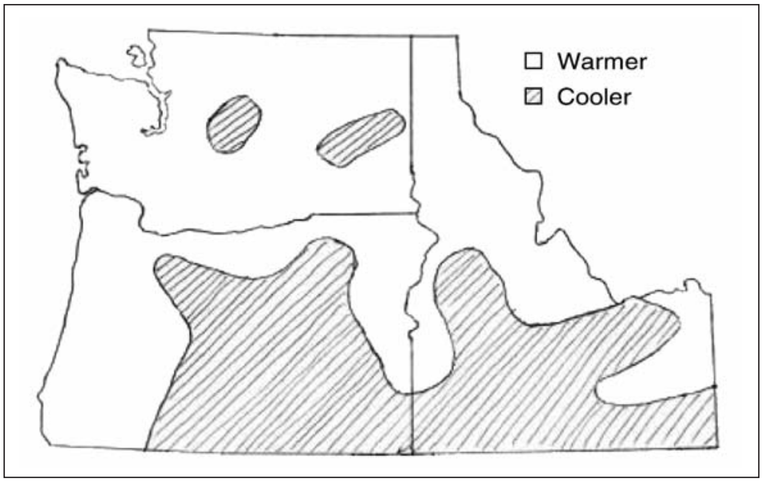

Figure 11—Areas of the Pacific Northwest that appear to have warmed (unshaded) and cooled (shaded) during the 20th century based on mean annual temperature data from 112 Pacific Northwest weather stations.

salmon. The science community is working to improve our understanding of the likely climatic and environmental consequences. Evidence indicates that the earth is in a gradual warming phase, and climate change models predict temperature increases in the Northwest of 1.1 °C by 2020 and 2.5 °C by 2050. For the Pacific Northwest, predictions indicate warmer, wetter winters and warmer, drier summers.

Temperature changes over the past century, however, appear to be inconsistent across broad geographic areas of the Northwest. Twentieth-century temperature data from 112 stations in the region with recording periods ranging from 58 to 138 years do not indicate a warming trend (fig. 11) (Center for the Study of Carbon Dioxide and Global Change 2000). Most of Washington, coastal Oregon, and the Columbia and lower Snake River basins of Oregon and Idaho are warmer. Conversely, during the same period, areas of the Great Basin in Oregon and southern Idaho, some southern tributaries of the Columbia River in Oregon, and portions of the upper Snake River basin in Idaho have cooled. Narrowing the temperature change analysis to the past 70 years of record from all sites would remove some variability from the analysis but would not likely change the interpretation. The data have a low-elevation bias because most temperature stations are located in populated areas in valley locations (Ferguson 1999). Despite this bias, water distribution reflects the effects of warming and cooling over the past century across the region. How future global climate change will affect the temperature and precipitation in the region is not yet known.

The Northwest climate cycles have created variable and complex intrawatershed precipitation and runoff patterns that produce natural events like floods and droughts that influence the frequency of fire and landslides. The ecosystems of the Pacific Northwest have, over approximately 10,000 years since retreat of the last ice age, developed under the influence of the climatic cycles of the region. Aquatic, wetland, and riparian biota are adapted to the natural variability of streamflow, sediment, turbidity, water temperature, and nutrients associated with the region's climatic and runoff patterns or regimes. Any changes in these natural regimens, caused by human activities, can affect the ability of aquatic biota to cope, potentially risking long-term population viability.

The impact of climate change on water resources could be significant because water use is so strongly linked to factors like human population growth, ecological health, wild salmon, and quality of life. The region's capacity to grow food and timber, produce power, protect wild salmon runs, manufacture aluminum for the aircraft and aerospace industries, and many other related activities depends directly on stewardship of available water resources.

Altered Flow Regimes

Natural flow regimes in the Pacific Northwest have been intentionally altered to enhance human benefits from available water resources and to reduce the risks of floods associated with natural flow regimes. Flow regimes also have been altered unintentionally by land management activities and utilization of the region's natural resources. Development of Pacific Northwest water resources has facilitated population growth, hydropower production, agriculture, industrial production, flood control, and slack-water navigation. It has enhanced some forms of water-oriented recreation, reduced others, and fundamentally changed the ecology of many Northwest waterways and the composition of aquatic communities that reside there.

Human activities further complicate the natural variability in water distribution across the Northwest because they have altered natural flow regimes in two ways over large areas with documented consequences for both natural ecosystems and human populations. First, human activities can change the natural spatial and temporal distribution of the quantity of surface waters. Use of water, both instream and offstream, can significantly alter normal physical flow patterns. Activities that retard or accelerate downstream movement of surface waters (e.g., stream channelization, changes in vegetative cover, loss of beaver (*Castor canadensis*) dams and wetlands, or reservoir construction) can dramatically affect natural flow regimens. Second, activities that reduce water quality have widespread impacts on aquatic ecosystems and human uses of water.

Hundreds of dams and reservoirs located on Pacific Northwest main-stem rivers and tributaries have altered natural streamflows. Generally, reservoirs tend to delay downstream movement of stormflows and thus reduce both the height and duration of peak flow for a given storm (fig. 12) (Ziemer and Lisle 1998). Over 2,500 small dams and reservoirs and many large multipurpose reservoirs alter the natural flow regimes of large and small streams throughout the region. The Columbia River is perhaps the region's best example of a major river system whose hydrograph has been permanently altered by reservoir storage. Prior to construction of most major multipurpose reservoirs on the river (1885 to 1964), peak flows occurred in June, followed by minimum flows in December or January (Volkman 1997). By 1985, construction of major dams and reservoirs was completed, resulting in reduced peak flows in May, followed by low flows in September (fig. 13). The annual hydrograph is now much flatter, and streamflow is more consistent throughout the year than the historical norm. Other major systems notably affected by reservoir storage include the Rogue, Willamette, Deschutes, Skagit, Yakima, Clearwater, and Snake Rivers.

Development of the hydropower potential on many of the region's large rivers has made the Northwest the national leader in hydroelectric power production. Nearly half the energy consumed in the Northwest and more than 90 percent of the power generated in the region comes from hydropower facilities (Kale and Sifford 1993).

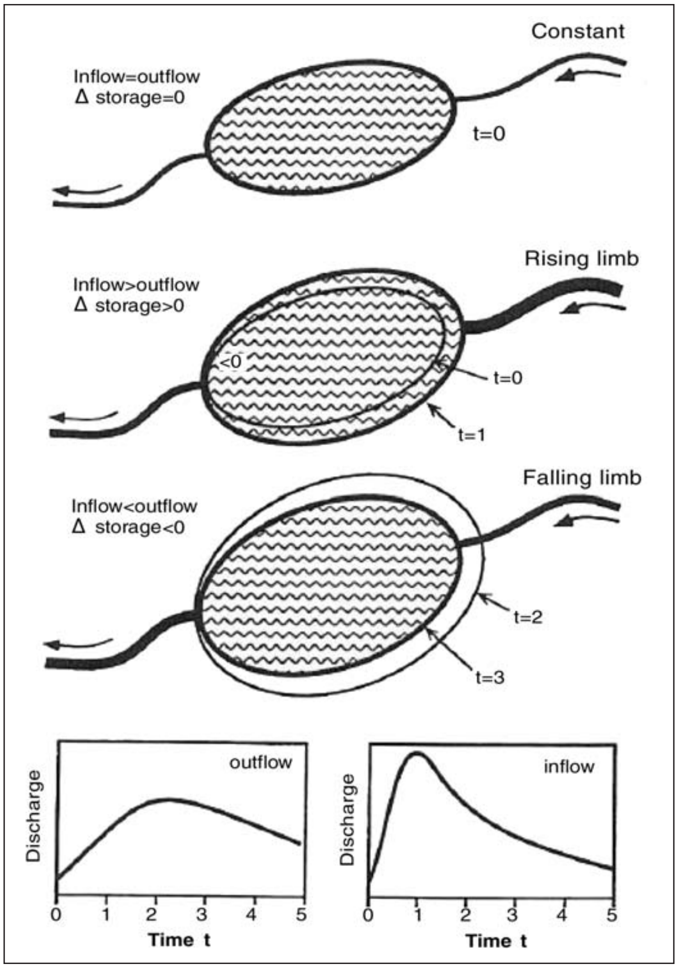

Figure 12—Flood routing in a channel with a reservoir during constant flow (t = 0) and the rising (t = 1) and falling (t = 3) limbs of a peak flow event. Volumes of storage in the reservoir during three time periods are represented by oval size; finer lines outline the water surface area in the reservoir during the preceding time interval. The patterned oval depicts reservoir level at corresponding inflow and outflow rates (from Ziemer and Lisle 1998).

The region has about 30 000 MW of hydroelectric generating capacity (Foundation for Water and Energy Education 2000), including about 19 000 MW produced at 11 generating plants on the main-stem Columbia River between the Grande Coulee and Bonneville Dams (Muckleston 1993). Hydropower sales by public and private utility companies, which are more than $1 billion per year, are marketed within and outside the region through firm contract sales, nonfirm sales of temporary excess power, and direct industry sales, for example to Columbia basin aluminum industries (U.S. Army Corps of Engineers 1995). Low-cost hydropower has facilitated many aspects of regional development, but the generating facilities have substantially changed the natural physical and ecological characteristics of the rivers on which they occur.

Water development in the Northwest also has facilitated specific types of industrial activity. Most notable is the aluminum reduction industry with seven plants in Washington and two in Oregon. These plants, located in the Pacific Northwest, account for 40 percent of the U.S. smelting capacity for primary aluminum (Beyers 1993). Because smelting of aluminum requires large quantities of electricity, nine plants are located near inexpensive federal hydropower from Columbia and Snake River Dams.

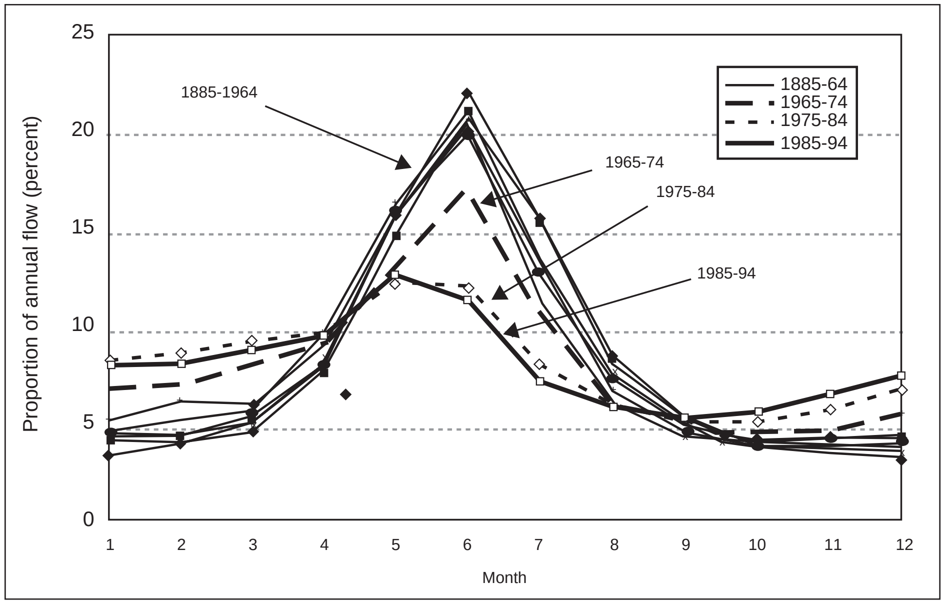

Figure 13—Annual distribution of monthly streamflows on the Columbia River at The Dalles, Oregon, by 10-year increments (from Volkman 1997).

Construction of dams and storage reservoirs on many major rivers in the Pacific Northwest reduces the frequency of flood damage in populated areas. The dampening effect of upstream reservoirs tends to reduce the height of flood flows in agricultural, residential, and urban areas downstream for all but the most severe floods. Thus downstream flood plains are protected from most floods, saving billions of dollars of private and commercial developments from potential flood damage, and at the same time encouraging additional settlement and development within the boundaries of seemingly “safe” flood plains. The potential consequence of flood control is that reservoir capacity cannot always protect against large, infrequent floods. When such floods do occur, the damage can be extensive owing to human encroachment onto flood plains. Major floods that occurred in 1964 and 1996 through 1997 caused extensive damage in the Northwest despite reservoir buffering capacity.

Altered flow regimes on the Columbia and Snake Rivers have enhanced commercial transportation in the region. Multipurpose dams and reservoirs, and navigation locks, allow slack-water navigation from the mouth of the Columbia River to Lewiston, Idaho. Six barge companies operate about 40 towboats and 175 barges on the rivers (U.S. Army Corps of Engineers 1995). Fifty-four port facilities and shipping operations provide transportation primarily for timber products and grains, from the intermountain region to Portland, Oregon, for national and international distribution (Northam 1993).

In the past, and to a limited extent now, beaver trapping affected flow patterns in small streams of the Pacific Northwest (Naiman et al. 1994). The loss of beavers and their dams is associated with wetland loss and water chemistry changes on small streams throughout the intermountain West. Prior to 1800, beavers were major ecosystem modifiers in the waterways of the Pacific Northwest, and a natural part of the region’s aquatic ecosystems. Beavers built and maintained many small dams that stored water and created extensive wetland habitats in the low-gradient valleys of headwater streams in summer (Swanston 1991), especially in the otherwise semiarid landscapes of the intermountain region. Trappers decimated beaver populations in the Northwest by the 1840s (Johnson and Chance 1974), ending their substantive effects on water storage and streamflow. Beaver populations are currently estimated at less than 2.5 percent of their numbers prior to European settlement.

Altered flow regimes result from streamflow diversions and pumping of surface water for offstream uses. The largest offstream water use in the Pacific Northwest, irrigated agriculture, has a profound effect on natural flow regimes. Twenty-nine percent of the Northwest is classified as farmland (Jackson 1993), 50 percent is cropland, and less than 20 percent is irrigated from surface- and ground-water sources. Farm sales in the Northwest totaled over $7 billion per year in the early 1990s, with more than 50 percent of the sales coming from less than 3 percent of the region's farms (Jackson 1993). Irrigated lands generally produce the greatest value of farm products.

Examples of dewatering for irrigation occur throughout the semiarid intermountain region. In one case, water withdrawals for irrigated agriculture in the Upper Snake River basin exceed 9.9 billion m^3 per year (Clark et al. 1998), most occurring from April to October (Maret 1995, 1997). In another case, irrigated agriculture in the Yakima River Basin uses about 3.1 billion m^3 per year, or nearly 65 percent of the mean annual flow (Morace et al. 1999, USDI Geological Survey 2000). Six reservoirs store more than 1.2 billion m^3 of water from headwater sources to supplement agricultural needs during the irrigation season. In addition to the reservoirs, the irrigation system in the basin consists of 669 km of canals, 2737 km of laterals, 232 km of drains, 15 major return flow channels, and 2 small hydroelectric plants (USDE Bonneville Power Administration 1985). Flow in the main-stem river is heavily altered by withdrawal and return of irrigation water (fig. 14). During the low-flow periods, return flows account for about 75 percent of the water in the lower river (USDI Geological Survey 2000). Generally, the quantity and quality of streamflow in most major streams in the basin is highly altered between the upstream reservoirs and river mouth.

Overdrafting of aquifers also can reduce summer streamflows in the Northwest. Water is regularly pumped from aquifers under large areas of Oregon, Washington, and Idaho for domestic, industrial, and agricultural uses. When aquifers are well connected to streams and water withdrawal exceeds recharge rate, water tables decline (fig. 15), more surface water infiltrates streambeds for aquifer recharge, and less is available for in-channel flow (fig. 16). Perhaps the greatest impact from pumping water occurred in Idaho where the level of the Snake Plain Aquifer receded significantly during an 8-year drought in the 1980s and 1990s, reducing surface flow in some of the area streams. Significant lowering of aquifer levels also has occurred in the Columbia River basalt aquifers of north-central Oregon, and the sand and gravel aquifers of Oregon's Willamette Valley.

Links between land uses and altered streamflow patterns have been intensely studied to identify effects on annual flows, peak flows and floods, minimum streamflows, and water yield. The effects of land uses differ with basin size and the magnitude of flows, and recovery processes, which vary in time and space, depend on the type of disturbance and the hydrologic processes affected (Ziemer and Lisle 1998).

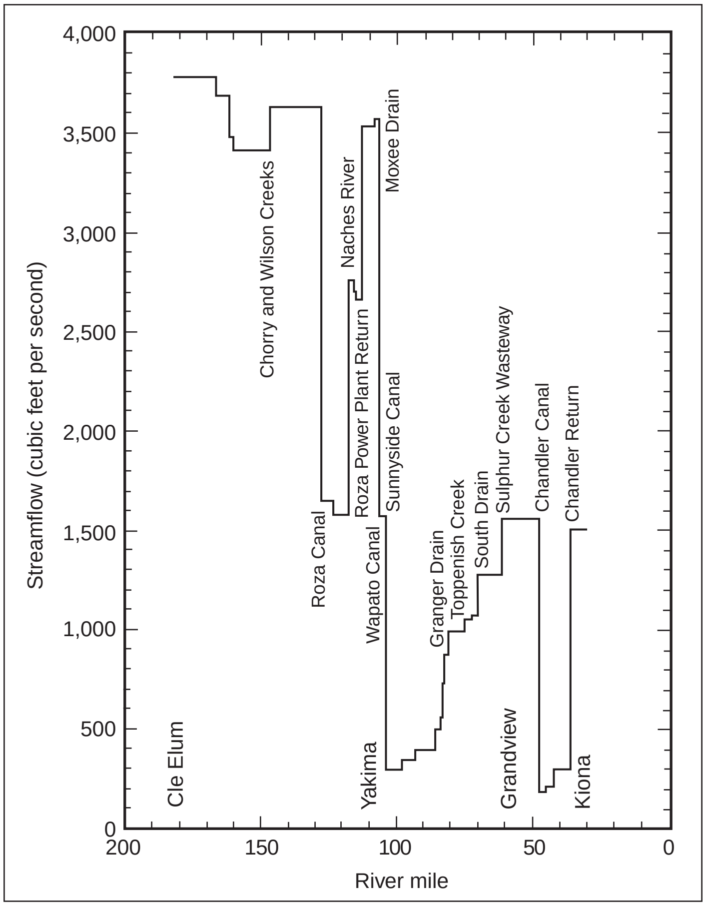

Figure 14—Instantaneous streamflow in the Yakima River as influenced by reservoir releases, tributary contributions, and canal diversions, Yakima River basin, Washington, June 25-30, 1989 (from Morace et al. 1999).

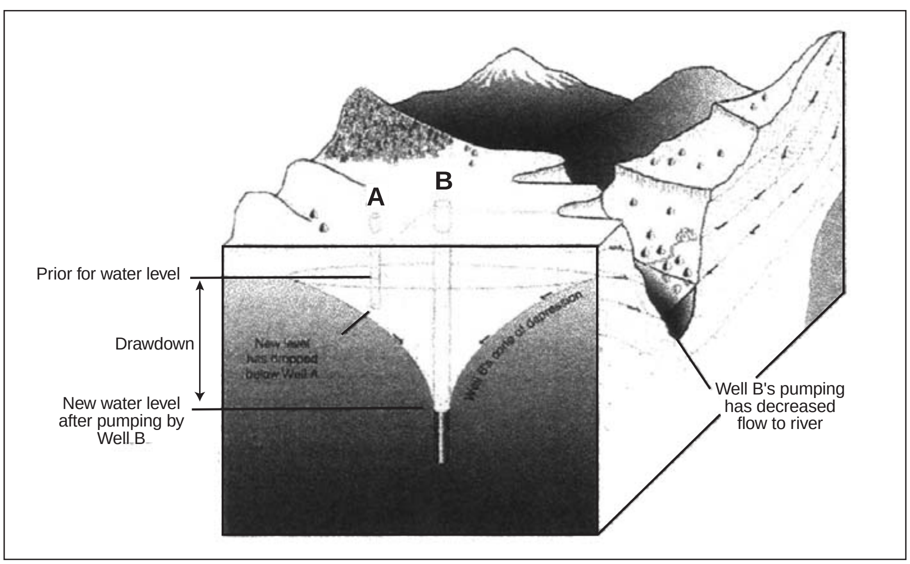

Figure 15—Groundwater dynamics around major wells. As groundwater is pumped, the cone around wells such as B expands, intercepting water bound for streams (from Bastasch 1998).

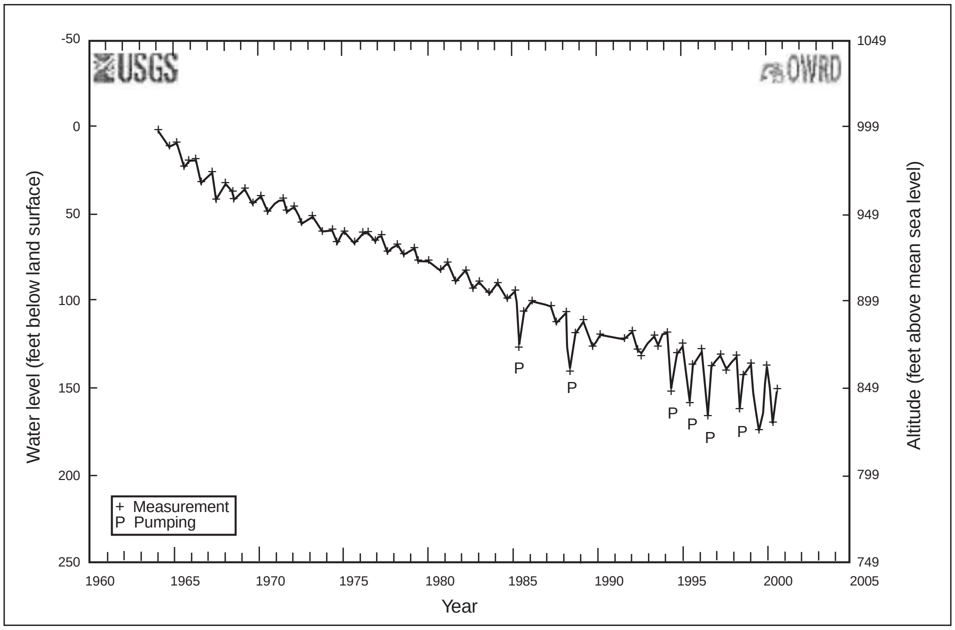

Figure 16—Water-level decline in Well 502 in Linn County, Oregon. Water level has declined 150 feet in 30 years owing to pumping of groundwater (from Orzol et al. 2000).

Activities (e.g., logging, road building and use, grazing, and urbanization) that alter vegetative cover, cause extensive soil compaction, or generally modify surface runoff also can alter natural flow regimes. Widespread flooding and sedimentation after logging and fire in forested landscapes were among the primary reasons for establishing the national forests (Sedell et al. 2000). But, the debate over the beneficial influence of forests in maintaining natural flow regimes and providing flood protection in large watersheds has continued for the past century in the United States (Ziemer and Lisle 1998).

At the river-basin scale, of the factors affecting the freshwater phase of salmonid populations, the flow-altering effects of dams, reservoirs, and agriculture have had the greatest impacts. Many of the negative effects resulted from hydro-power, flood control, and irrigation developments during the past 30 years. Flow altering activities have had the greatest effect on rearing habitat and migration routes in the region's major river basins. In the Columbia basin, dams, reservoirs, and turbines cause direct mortality of migrating salmonid adults and juveniles and delay upstream and downstream movement of survivors. Hundreds of kilometers of free-flowing main-stem rearing habitats have been inundated by slack-water reservoirs that are now occupied by salmonid predators. The net effect of these flow-altering human actions, coupled with habitat simplification in forested landscapes, overfishing, and changes in the PDO, has been a reduction of wild salmonid numbers to about 5 percent of their historical levels in the Columbia River basin. In the highly developed Yakima River basin, annual anadromous salmonid runs numbered more than 500,000 prior to 1880 (Rinella et al. 1992b) but by the 1980s had declined to less than 1 percent of historical numbers (4,000 fish per year) (USDE Bonneville Power Administration 1988).

Currently, most of the productive salmonid habitats that are least disturbed by flow alterations in Northwest river basins occur in forested landscapes managed by the federal government. Those areas, located primarily in the uplands or upper portions of Northwest river basins, are currently valuable refuge habitats for remnant stocks of anadromous salmonids. Historically, greater salmonid production often occurred in larger downstream waters that are now poor salmonid producers because of dams, reservoirs, agricultural activities, and various types of pollution (Clark et al. 1998). Because productive anadromous salmonid habitats still exist on many upstream, forested landscapes in the region, agencies and interest groups have focused intense preservation efforts on protecting those few remaining refugia.

Nationwide, urban and developed areas expanded by more than 285 percent between 1945 and 1992 (USDA Economic Research Service 1995). Increasing urbanization also has reduced the area of private forests in the Pacific Northwest (Kline and Alig 2001). Forests, the largest source of land for development in the Northwest, can be influenced directly through conversion, and indirectly through forest fragmentation (Alig et al. 2000). As the human population of the Pacific Northwest increases, the subsequent reductions in private forest areas will result in increases in water runoff from urban areas.

Major reviews summarizing what is known about the influence of forests on floods and peak streamflows have been completed for the Eastern United States (Lull and Reinhart 1972) and for the world's major forested regions (Hewlett 1982). Together these papers summarized hundreds of papers and concluded that forestry activities have minor effects on flood flows in large basins. But scale is important in interpreting the effects of forest harvest on peak flows.

Results of hydrologic studies from the Pacific Northwest and other regions differ by basin size. In small watersheds in the intermountain West, Coleman (1953) established a relation between vegetative ground cover and streamflow following high-intensity storms (fig. 17). In locations where up to 75 percent of the ground surface was vegetated, flood peaks and sedimentation were substantially reduced when compared to areas with less ground cover.

A Tennessee Valley watershed rehabilitation study (Smallshaw and Ackerman 1951) demonstrated how changes in land use could affect stormflows. Prior to its purchase in 1934 by the Tennessee Valley Authority, the small 695-ha White Hollow watershed was burned, grazed, had intense agriculture, and had timber cutting for about 150 years. After purchase, the watershed was no longer cultivated, and watershed rehabilitation began by reforestation and check dam installation. Following treatment, runoff from peak flows decreased for comparable storm events after rehabilitation (fig. 18).

Paired watershed studies in western Oregon and Washington indicate that land use activities that reduce vegetation cover increase peak discharges resulting from small storms in small watersheds. Small storms with low recurrence intervals ($\leq$1 year) resulted in the largest differences in peak flows (Beschta et al. 2000, Bowling et al. 2000, Thomas and Megahan 1998). As recurrence intervals increased, differences in peak flows between control and treatment watersheds decreased.

An analysis in paired watershed studies of the relation between land management activities and the largest peak flows (flood flows) is less definitive. Rothacher (1971, 1973) reported that clearcut logging and burning in the Douglas-fir region of western

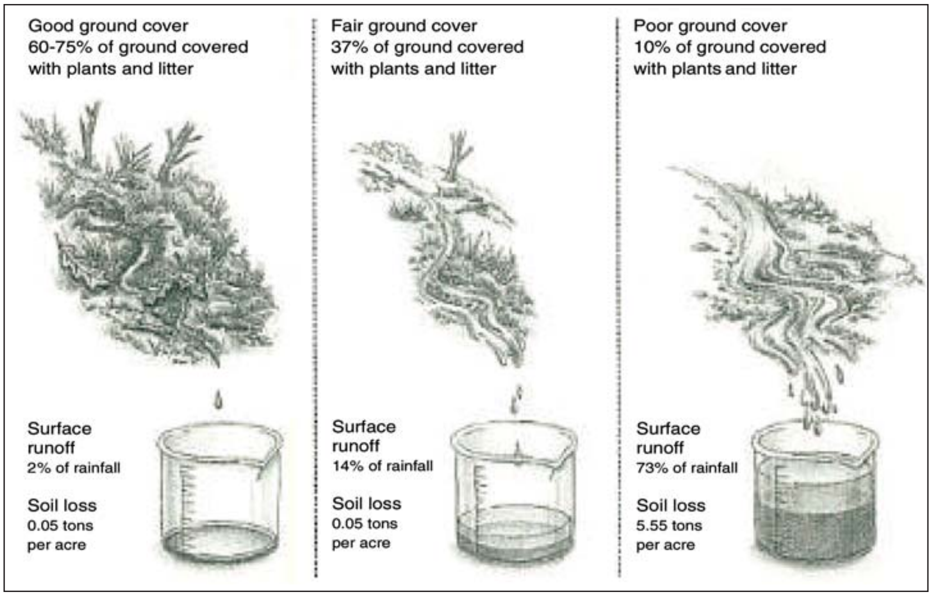

Figure 17—Experimental results of the effects of watershed condition on rainstorm runoff and erosion (from Sedell et al. 2000).

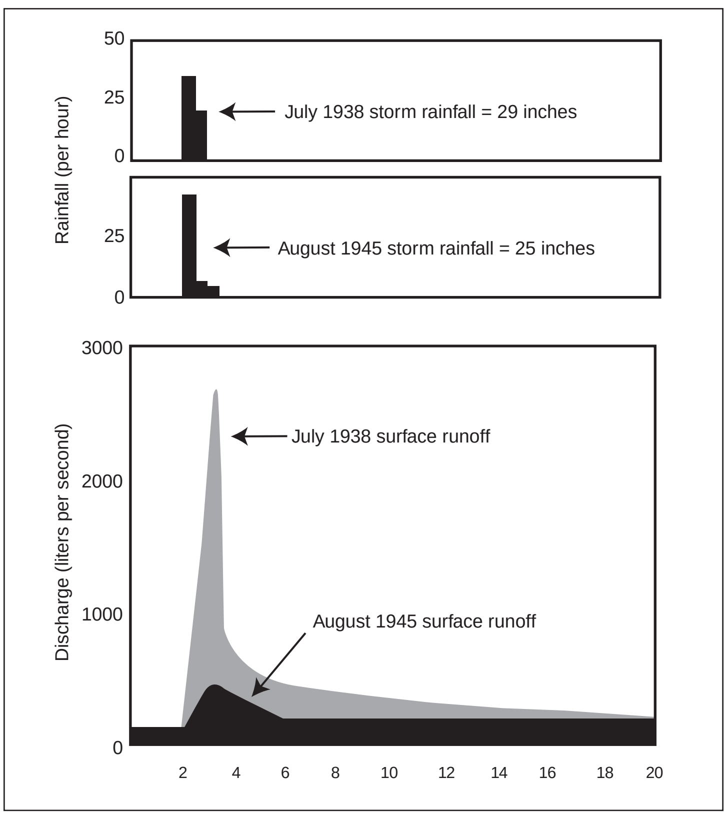

Figure 18—Rainfall and runoff hydrographs for the White Hollow, Tennessee, watershed before and after watershed rehabilitation (from Smallshaw and Ackerman 1951).

Oregon did not appreciably increase the largest peak flows in the affected watersheds. Also, studies in the Cascade Range (Harr et al. 1979), the Coast Range (Harr et al. 1975), and the northern California coast (Wright et al. 1990, Ziemer 1981) indicated that logging did not increase large floods when soils were saturated. More recent analyses of paired watershed studies in western Oregon (Beschta et al. 2000) and western Washington (Bowling et al. 2000) provide more evidence that statistical differences between large storm events in large treated and untreated watersheds are difficult to demonstrate.

Although increases in peak flows related to logging have been observed in small watersheds, such changes are more difficult to detect in larger basins. Jones (2000) examined the relation between peak discharge and forest removal and regrowth in 10 small watersheds in the western Oregon Cascade Range. Even with 50 years of record, he concluded that extreme floods and large rain-on-snow events are so rare that it is difficult to assess the statistical significance of changes in flow. According to Ziemer and Lisle (1998), it is difficult to determine if forest practices increase the size (i.e., magnitude and extent) of large floods; this is because forest practices usually affect only a small portion of large basins and large floods.

The inability to demonstrate a statistically significant link between flood peaks and harvest and timber access roads does not preclude controversy. Extensive timber harvest on National Forest System lands in the Idaho Panhandle in the 1970s and 1980s, followed by major floods in 1990 and 1995-96, caused residents and some scientists to accuse the Forest Service of exacerbating the floods by overharvesting timber in nearby watersheds (Associated Press 1992; Foster 1993; Olsen 1995, 1996; Prager 1996; Titone 1993, 1996).

Much of the Pacific coastal ecoregion is within a climate zone where logging might be expected to result in an increase instreamflow during summer (Ziemer and Lisle 1998). An example from the H.J. Andrews Experimental Forest in western Oregon showed an increase in annual streamflow of 53 cm after clearcut logging of a small watershed (Rothacher 1971). Similar results were observed in a paired watershed study in Caspar Creek in north coastal California. Selective logging of 67 percent of the stand volume in the 484-ha South Fork watershed in the early 1970s increased the summer low flow by about 125 percent (Keppeler and Ziemer 1990). Summer flows returned to prelogging levels within 8 years. Subsequently, when 12 percent of the North Fork watershed was clearcut in 1985, summer streamflow increased by about 150 percent for 1 year before returning to prelogging levels. When an additional 42 percent of stand volume was cut 3 to 5 years later, summer streamflow again increased by 200 percent (Ziemer et al. 1996). Similar patterns have been reported elsewhere in which summer water yield has been reported to increase after forest harvest and then return to precutting levels within a few years (Hewlett and Helvey 1970, Hicks et al. 1991a, Stednick 1996, Ursic 1986). Although the evidence indicates that removal of vegetation increases late summer streamflow in small watersheds (Hibbert 1967, Hicks et al. 1991a), the increases are often so small that even doubling normal flows does not represent a large absolute increase.

In addition to research examining the relation between logging and mean, peak, and minimum flows in small watersheds, other aspects of forest management altered streamflows in the Pacific Northwest. Splash dams and log drives, which were the prevalent means of getting logs to mills in the 1870 to 1920 period (Sedell et al. 1991a), simplified stream and river channels to the extent that they have not yet returned to the predisturbance condition (Sedell 1991b). Use of major splash dams for log transportation was extensive in western Washington and Oregon at the turn of the 20th century. Over 150 major 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. 1991a). Flow in the affected streams was consolidated into a single channel, increasing water velocity and stream energy over long reaches, and causing long-term alteration of natural flow patterns (Sedell et al. 1991a).

For decades, timber harvest was conducted in the Northwest with little regard for streamside vegetation. From the 1940s to the 1970s, all commercial streamside timber was regularly removed during logging of stream-adjacent areas. The loss of riparian timber, and thorough removal of large wood from stream channels made long-term alterations in the characteristics of waterflow and the structure of associated habitats. As with splash damming, loss of channel structure simplified and consolidated channels and reduced channel roughness, resulting in shallower water and faster-than-normal water velocities in the affected areas. Also, loss of root strength at the channel margins after removal of riparian trees often initiates accelerated channel erosion (Ziemer and Lisle 1998). The altered flow characteristics can persist for a century or more while riparian timber is regenerating.

Livestock grazing can alter the physical characteristics of streamflow. Livestock use in riparian areas can aggrade stream channels and lower water tables (Platts 1991). Streams modified by livestock grazing may have less streamflow in summer, or changes in depth and flow velocity (Duff 1983, Platts and Nelson 1985). In many parts of the West, heavy livestock grazing over the past 100 years has increased surface runoff and erosion (Platts 1991), contributing to floods and increased erosion (Coleman 1953, Platts et al. 1985).

Alterations in the volume of flow in rivers and streams in the Northwest have significantly affected water-oriented recreation in the region in two ways. First, temporal and spatial changes in streamflow affect the types of recreation that can be conducted on rivers and streams. The altered flows may range from daily changes in reservoir releases for generating power to seasonal changes resulting from dewatering of streams for irrigation. Second, dams and reservoirs have created long reaches of standing water where rivers once ran freely.

Shelby and Whittaker (1995) reviewed the literature describing the effects of altered streamflow on recreation. Flow variations strongly influence a variety of recreational experiences including fishing (Loomis et al. 1986), rafting and floating (Shelby and Whittaker 1995), and hiking along rivers (Shelby et al. 1997). Many water-based recreation activities require a minimum level of streamflow for the activity to occur. For example, whitewater rafters are particularly limited by streamflow in their attempts to find suitable rivers for their recreational experiences (Shelby and Lime 1986). But, streamflow volume also can affect the safety of recreational experiences (Shelby et al. 1992b), perception of crowding at recreation sites (Tarrant and English 1996), and overall satisfaction of recreational experiences on rivers and streams (Whisman and Hollenhorst 1998).

Flow evaluation curves have been used to quantitatively assess the quality of recreational experiences. Research reveals that the acceptability of river-based recreation experiences follows a bell-shaped curve (fig. 19) that defines marginally acceptable high and low flows, and optimum flows, for a given experience (Shelby et al. 1992a).

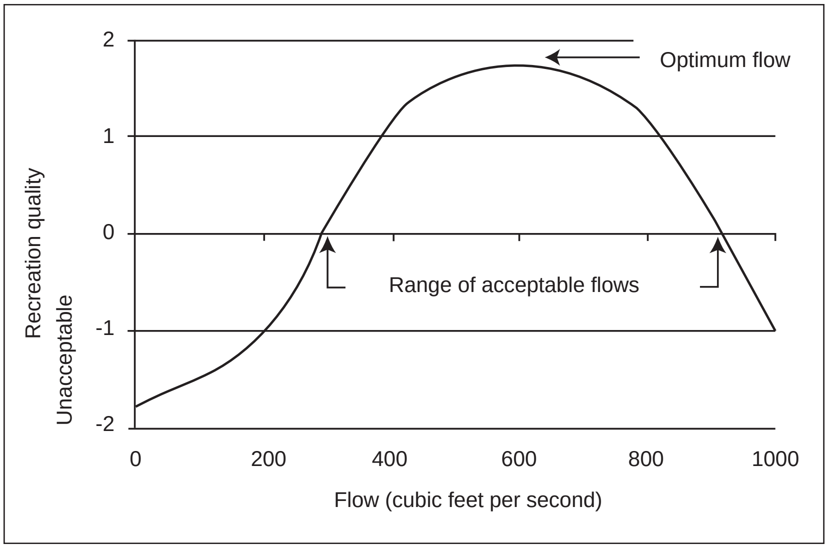

Figure 19—Relation between recreation quality and streamflow (from Shelby and Whittaker 1995).

The optimum flow often varies by recreation activity, although the flow evaluation curves often have similar shapes. For example, the acceptable level of flow for hikers may be too low for boaters, thereby indicating that different activities have different “niches” of acceptable flow.

Construction of dams for hydropower production, flood control, and slack-water navigation also has altered recreation by replacing hundreds of kilometers of free-flowing rivers and streams in the Pacific Northwest with human-made lakes and reservoirs. The change from flowing water to standing water has caused corresponding changes in recreational opportunities. Rivers and streams, for example, provide opportunities for specific types of boating (e.g., kayaking, rafting, and drift boating), fishing (e.g., fly fishing and spin fishing in flowing waters), and other activities that are different from those associated with lakes and reservoirs. Recreationists who previously used free-flowing waters for activities might not find the reservoir environment an acceptable substitute.

Because of a long history of involvement with a particular place, people often form strong bonds with specific landscapes over time (Brown and Perkins 1992). The existence of strong place attachments often is sufficient to mobilize people into challenging management decisions thought to be harmful to a valued location. Although place-based sentiments are often overlooked in natural resource management decisions, the strength of the meanings and ties that people have with particular places within the natural environment are an important consideration for water management (Mitchell et al. 1993).

Water Quality

Any human activity that causes changes in water clarity, suspended and bedload sediments, temperature, inorganic chemicals, nutrients, or pathogens alters the characteristics of streams and lakes and affects water supply. Changes in water quality can be independent of changes in the quantity of streamflow, but the two processes are often linked and may operate synergistically.

Sediment and turbidity—Sediment is the Nation's most common surface water contaminant by weight and volume. The Environmental Protection Agency has identified sediment as the primary problem threatening America's waterways (Koltun et al. 1997). Land management activities can contribute to accelerated soil erosion and sedimentation in water.

Suspended and bedload sediments are natural characteristics of flowing waters. Surface and mass erosion in undisturbed watersheds vary widely in time and space because of large variations in erodibility and slope stability between watersheds and large infrequent natural events. Human actions (e.g., timber harvest) contribute to more frequent and noticeable changes in events. Human activities in watersheds can alter natural erosion and sediment export processes and sediment production and transport. If sediment delivery from human actions significantly exceeds natural levels, and results in sediment deposition and excessive turbidity (Nelson et al. 1991), major alterations in ecosystem functions can occur (Platts and Megahan 1975). Sediment and turbidity are most often increased by human actions, but decreases can sometimes be achieved through watershed rehabilitation and restoration.

Exposure of mineral soil (especially clays) by land management activities, and resulting erosion and sediment delivery, can cause chronic increases in stream turbidity with biological, social, and economic consequences. Agricultural practices, especially production of annual crops that require frequent soil tilling, often contribute to suspended sediment loads in streams (Coleman 1953). Many guidelines for forest and agricultural practices have been developed to control suspended sediment production, but persistent increases after land disturbances still occur (Chamberlin et al. 1991). Suspended sediment of fine particle sizes is slow to settle; sediment that results from management in upstream watersheds can affect water clarity for long distances downstream.

Dams and reservoirs on regulated rivers have variable effects on natural sediment and turbidity regimes. Reservoirs delay downstream movement of sediment-laden inflow water, impounding bedload sediments, and allowing some portion of fine sediment to settle. Streams carrying high sediment loads reduce reservoir storage capacity (Dasmann 1959), affecting their ability to function as designed. A national survey of 1,819 reservoirs and lakes in 1994 revealed an average 5-percent loss of storage owing to sediment deposition, but 40 percent of the reservoirs had lost half or more of their storage capacity (Atwood 1994). In reservoirs designed for irrigation use, recent sediment surveys (post-1978) indicated that storage capacity was reduced by an average of 15 percent. The higher rate of sedimentation in these reservoirs was attributed to intense agriculture and population growth and their associated impacts (Reckendorf 1995).

Sediment retention in reservoirs can alter water quality and the sediment regime and geomorphic characteristics of stream channels below dams. Reservoirs trap much or most of the transported sediment and release clear water (Koltun et al. 1997), changing the natural regimen of both suspended and bedload sediments in downstream channels. Downstream effects, in addition to flow alteration, include channel instability, channel bed armoring, and alteration of aquatic habitats (Collier et al. 1996).

Accelerated erosion from forest and rangeland management as well as agriculture is well documented, and varies with geology, soil, climate, vegetation, dominant geomorphic processes, and the type of land use in the affected watersheds (Anderson 1971). In forested watersheds, the quality of management planning (Reinhart et al. 1963) and the amount of bare soil exposed by an activity strongly influence surface sediment production (Chamberlin et al. 1991, Everest and Harr 1982). Anderson (1971) demonstrated that detailed management planning that reduced surface erosion could reduce surface sediment production from skidder logging by three orders of magnitude.

Silvicultural activities such as controlled burning also can expose bare mineral soil and increase surface runoff and surface erosion (Swanston 1991). Even when effects do not expose mineral soil, a water-repellent layer can form and reduce the ability of water to infiltrate the soil after fire (Bockheim et al. 1973, Krammes and DeBano 1965), increasing the runoff energy available for surface erosion. Fire also increases the potential for landslides for at least 5 years after the event owing to the decay of reinforcing root systems (Swanston 1974, Ziemer and Swanston 1977).

Roads represent the primary source of accelerated sediment production in many 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). Surface erosion originates from roadbed surfaces, drainage ditches, and cut and fill surfaces (Brown and Kyrgier 1971, Burns 1972, Larse 1971, Weaver et al. 1987). Roads commonly accelerate mass erosion (i.e., slumps and earthflows, debris avalanches, debris flows, and debris torrents) in steep forested watersheds (Wolfe 1982). Studies on the H.J. Andrews Experimental Forest, and in Alder Creek on the western slope of the Cascade Range of Oregon, quantified the rate of debris flow occurrence associated with undisturbed forest, clearcuts, and roads (Morrison 1975, Swanston and Swanson 1976). Roads accelerate debris torrents by factors of greater than 40 to greater than 100 times that observed in undisturbed forest (table 3). Other studies in the western slope of the Cascade Range in Oregon showed that mass erosion caused by roads is 30 to 300 times greater than in undisturbed forests (Sidle et al. 1985), especially in areas prone to landslides.

Two examples in the Pacific Northwest illustrate how severe soil erosion and sedimentation after road construction and logging can affect forest lands. Two decades of intense roading and logging on the Payette National Forest in the granitic geology of the Idaho batholith, followed by an intense flood in 1964, inundated the channel of the South Fork Salmon River with fine granitic sediments (Platts and Megahan 1975). Stream channel substrates changed from gravel and cobble to sand, pools filled up to 3 m of fine sediment, and in some places, riparian vegetation was buried. The severe effects on the South Fork Salmon River resulted in a decade-long moratorium on future logging and road construction on federal lands in the basin and initiation of a major watershed rehabilitation program. Recovery of the stream channel took more than a decade (Megahan et al. 1980, Platts and Megahan 1975).

The second example is from the Mapleton District of the Siuslaw National Forest in the Coast Range of west-central Oregon. The district is located in steep terrain in highly erosive sandstone geology. Extensive road building and timber harvest in the 1960s and 1970s, followed by severe storms in the late 1970s and early 1980s, caused accelerated surface and mass erosion throughout (Swanson and Roach

Table 3—Debris torrent occurrences in selected areas in western Oregon

Area	Period of record	Area	Triggered by debris avalanches	With no associated debris avalanche	Total	Annual number	Rate of debris torrent occurrence relative to forested areas
	Years	*km^2*	-----------------*Number*	-----------------		*Per km^2*	
H.J. Andrews Experimental Forest, western Cascade Range, Oregon							
Forest	25	49.8	9	1	10	0.008	1.0
Clearcut	25	12.4	5	6	11	.036	4.5
Road	25	2.0	17		17	.340	42.0
Alder Creek drainage, western Cascade Range, Oregon							
Forest	90	12.3	5	1	6	.005	1.0
Clearcut	15	4.5	2	1	3	.044	8.8
Road	15	.6	6		6	.667	133.4

Source: Swanston and Swanson 1976.

1986, 1987; Swanson and Swanson 1977). Severe effects on stream channels resulted in a temporary injunction on future logging in 1984 (Simmons 1984). This injunction remained in effect until land use planning complied with both the National Environmental Policy Act (NEPA) and the National Forest Management Act (NFMA). In both examples, the primary causes of accelerated erosion was mass failure associated with road cuts and fills and surface erosion from road subgrades and ditches.

Heavy livestock grazing on many Western rangelands over the past 100 years caused increased surface erosion and contributed to rapid sedimentation of reservoirs (Coleman 1953). In the Pacific Northwest intermountain region, livestock grazing increased sediment and turbidity in many natural stream systems. Stream channels in grazed areas generally contain more fine sediment and have more trampled and unstable streambanks than channels that have not been subjected to grazing (Platts 1991). The increased sediment loads alter depth and flow velocity in affected reaches.

Agricultural activities in the Pacific Northwest contribute significant turbidity and sedimentation to surface waters. Croplands that are tilled and planted for annual harvest, contribute the highest levels of sediment and turbidity to streams. For example, the Palouse prairie, a major wheat-growing area of eastern Washington and north-central Idaho, has high erosion rates in late winter and early spring (Coleman 1953) and high levels of turbidity and sedimentation in streams. Erosion control measures applied in the 1980s and 1990s have reduced erosion on the Palouse by 1.5 million Mg annually (Ebbert and Roe 1998). However, turbidity and sedimentation problems persisted in the Palouse River drainage and its tributaries. Sediment loads altered historical water quality and flow characteristics of the area's streams from the historical characteristics.

Low-gradient streams in the Willamette Valley, Yakima Valley, tributaries of the upper Snake River, and Klamath basin show effects of turbidity and sediment from agricultural practices. The Yakima Valley is one of the most intensively farmed and irrigated areas in the United States (Morace et al. 1999). Suspended sediment concentrations and turbidity in the basin are positively correlated with agriculture and are 27 or more times higher in streams draining agricultural lands than in streams draining forested watersheds (Bramblett and Fuhrer 1999). Agriculture alters water quality over long reaches of midsized and large low-gradient valley streams.

Mining activities in the Pacific Northwest affected natural levels of sediment and turbidity in streams but less so than forest practices or agriculture. More than a century of mining in the three-state area altered water quality in many lakes and streams. Historically, hydraulic mining and dredging for gold increased sediment transport and deposition. The legacy of those activities still exists in streams like Bear Valley Creek and Crooked River in Idaho where channels and flow characteristics were permanently altered by dredge mining (Nelson et al. 1991). When mining ceased, more than 500 000 m^3 of sediment had been deposited into Bear Valley Creek and into habitats occupied by spring chinook salmon (*O. tshawytscha* Walbaum) and steelhead trout. The Shoshone-Bannock Tribe completed an extensive rehabilitation there during the 1990s (Platts 1991).

Mining sediments affect a large part of the Coeur d'Alene River valley in northern Idaho. A century of mining for silver and other metals in the area resulted in deposition of 3 to 6 m of mining sediment in active and abandoned channels in the 100-year flood plain of the upper river valley (USDI Geological Survey 2000). More than 68 million Mg of sediments (laden with heavy metals) were deposited on the bottom of Coeur d'Alene Lake (Wood 2001). Because sediments raised the riverbed and changed the flow characteristics of the river, recent floods caused more damage for a given river stage than floods that occurred there in the 1970s (Titone 1996). Most mines are closed and cleanup of sediments and mine wastes continues (U.S. Army Corps of Engineers 2000b).

Other major mining operations left a legacy of sediment problems in the region's lakes and rivers. The now-closed Anaconda mining complex between Butte and Missoula, Montana, released tons of sediments and mining wastes into the Clark Fork River (upper Columbia River basin). This changed substrate and flow characteristics of a 225-km reach of the river. Stormflows carried large amounts of the materials downstream to Pend Oreille Lake (Clark Fork-Pend Oreille Coalition 2000). Cobalt mining operations at the Blackbird Mine in central Idaho released more than 2 million m^3 of mine tailings in the Blackbird Creek basin (Agency for Toxic Substances and Disease Registry 2000). Some of the highly erodible tailings were placed directly into the creek and along its banks and have since been transported by stormflows into downstream waters. Cleanup of sediments at the two sites continues.

Recreation activities, such as motor boating and camping, also can affect sedimentation and turbidity in lakes, as well as streams and rivers in the Northwest. Turbulence from propellers and wakes can create erosive stress, causing erosion of shorelines and increasing sedimentation and turbidity, changes of particular concern in fish spawning areas (Kuss et al. 1990). All lake sizes can be affected, but the greatest effects occur on small lakes where boat wakes create the dominant wave sizes on the water body. Sedimentation effects from camping are usually limited in extent.

The relative contribution of turbidity and sediment from various human actions in a river basin can be difficult to predict. Oregon and Idaho report about 6 percent of total stream length is impaired by sediment, siltation, and turbidity. About 40 percent of the impaired stream length is on lands managed by the Forest Service and Bureau of Land Management (Quigley et al. 1997). The remaining 60 percent is in other ownerships affected by mining, agriculture, industry, and urbanization. Most of the affected streams on federal land are small in relation to affected waters in other ownerships downstream. Affected stream length alone does not reflect the magnitude of the problem, so distinctions between ownerships are not very meaningful. Agriculture and mining have introduced millions of metric tons of sediments that are sometimes contaminated with various toxins (see following section on chemicals). These sediments and toxins operate synergistically in the region's aquatic ecosystems. Forest management activities also introduce large quantities of sediments into streams of forested watersheds, but the sediments almost always lack the toxic component associated with agriculture and mining.

Water temperature—All anthropogenically undisturbed freshwaters have variable water temperature regimes based on the physical and climatic characteristics of their watersheds. Natural ranges of water temperature vary with annual seasonal cycles and longer term cycles of ENSO, PDO, and other trends. Human activities can temporarily or permanently alter natural water temperature regimes. Removal of streambank vegetation, withdrawal and return of water for irrigation, release of water from deep reservoirs, and waste heat from nuclear power plants (Bjornn and Reiser 1991) can alter stream temperature. Depending on the type of human activity, seasonal water temperatures can be either increased or decreased.

Land management activities (principally timber harvest and grazing in the Northwest) that remove streamside vegetation allow more solar radiation to reach water surfaces, thereby increasing water temperature and light available for photosynthesis (Brown and Krygier 1970). Brown (1969) has developed models to predict thermal loading from removal of riparian vegetation. Opening the vegetative canopy along small streams (first to third order) also has been observed to increase daily temperature fluctuations (Beschta et al. 1987, Bisson et al. 1988, Meehan 1970). A summary of studies of stream temperature changes associated with canopy removal over small streams in Pacific coastal watersheds found a latitudinal gradient in increases of daily maximum temperatures in summer that ranged from less than 1 °C in Alaska to over 10 °C in Oregon (Beschta et al. 1987). Removal of streamside vegetation also can alter winter temperature regimes, but the changes are small (Beschta et al. 1987, Hicks et al. 1991b).

Water withdrawals for irrigated agriculture alter the natural temperature regimes of streams and rivers. The effects can be complex because during major irrigation withdrawals, the flow in streams is often supplemented by cool water released from upstream reservoirs. Nevertheless, dewatering stream channels exposes the remaining low streamflow to accelerated heating by warm air temperatures and solar radiation. Studies in the Yakima River basin from 1986 to 1991 measured water temperatures at 192 sites and found that 12 percent of 1,152 measurements exceeded state water quality standards (Morace 1999). Eighty percent of the high temperatures occurred in agricultural areas of the lower Yakima River valley at main-stem, tributary, irrigation canal, and irrigation drain (return water) sites. Much of the summer heating of river water was associated with low streamflows downstream of two major irrigation canals (Wapato and Sunnyside), other canal diversions, low stream velocities and gradients in the lower river, and low streamflows below Prosser Dam. Similar effects of irrigated agriculture on water temperatures have been noted in the Upper Snake River basin (Clark et al. 1998), the Willamette River Basin (Cude 2000a, 2000c; Wentz et al. 1998), the Klamath River basin, and other areas in the Northwest where irrigation diversions dewater streams (Cude 2000b). In all areas, irrigated agriculture reduced streamflow and increased water temperatures in valley tributaries and main-stem rivers.

Large storage reservoirs throughout the Northwest influence the normal temperature regimes of streams and rivers. A major consideration in operation of the reservoirs includes the effects of reservoir releases on downstream water temperatures. In winter, stored water can be warmer than natural flows, and in summer, water stored in the depths of reservoirs can be cooler than natural flows. How a reservoir is managed (drafted and filled) plays a significant role in how solar radiation and atmospheric temperatures affect the temperature of stored water (U.S. Army Corps of Engineers 1995).

The reservoir type influences the potential effects on downstream water temperatures. Thermal characteristics of large storage projects are potentially very different from run-of-the-river projects. Shallow run-of-the-river reservoirs, like Bonneville on the Columbia River, have short flow-retention times and more uniform stored water temperatures than deep storage reservoirs where the stored water column is thermally stratified. When surface water is released, increased solar heating of reservoir surface waters in summer can result in elevated outflow temperatures, causing abnormal heating of downstream waters (Petts 1980). Conversely, in deep storage reservoirs, abnormal cooling of downstream waters in summer, and heating in fall and winter, may occur if dam operators release water from the depths of a reservoir. It is the latter case that has caused the greatest change in water temperature regimes in large rivers of the Northwest.

Projects on the Santiam River provide good examples of the effects of deep release reservoirs on downstream water temperatures (for other examples, see box on page 54). Studies by the U.S. Department of the Interior, Geological Survey (Hansen and Crumrine 1991, Laenen and Hansen 1985) indicate that the Detroit/Big Cliff project on the North Santiam River caused water temperatures 69 km downstream to be cooler (x = 134 days) in summer and warmer (x = 71 days) in fall and winter than preproject river temperatures. Maximum temperature effects were 4.7 °C warmer in November and 8.7 °C cooler in August (fig. 20).

Similar studies on the South Santiam River indicated water temperatures 57 km downstream of the Green Peter/Foster projects to be cooler (x = 91 days) in spring and summer and warmer (x = 66 days) in late fall and winter. Maximum temperature effects were 4.2 °C cooler and 5.7 °C warmer (fig. 20). The operation of Lost Creek

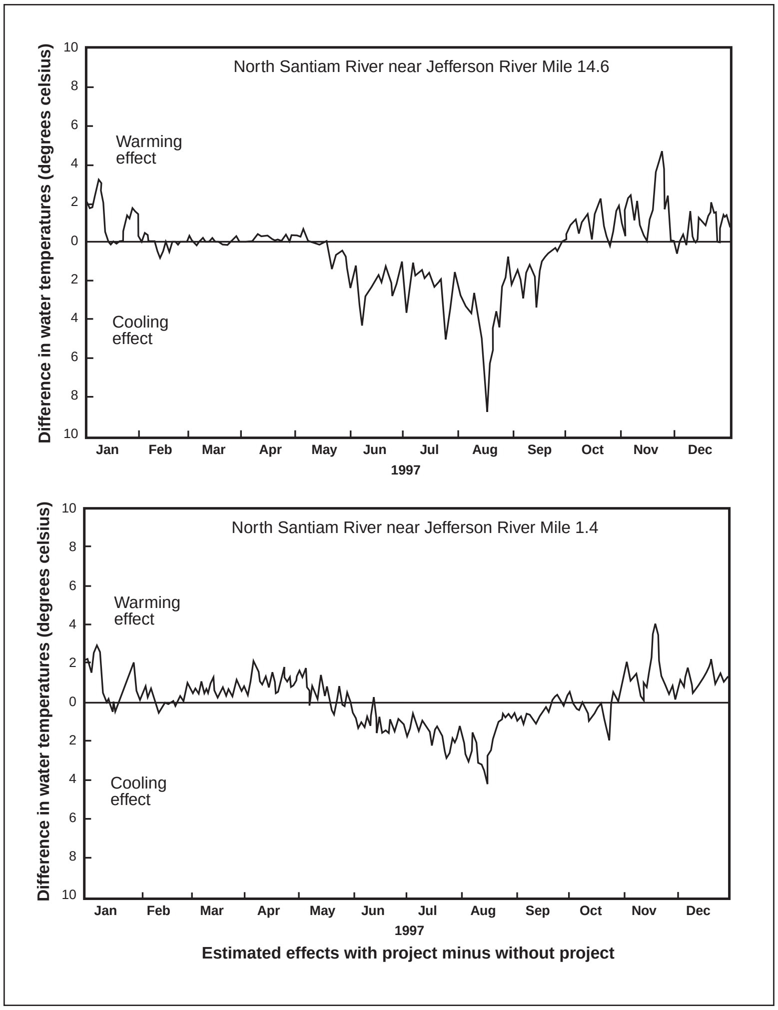

Figure 20—Simulated water temperatures with, and without, U.S. Army Corps of Engineers' reservoirs at selected sites on the North and South Santiam Rivers, 1977 (Hansen and Crumrine 1991).

Northwest Waters With Altered Thermal Characteristics

Dam/reservoir	River
Hungry Horse	Clark Fork River
Dworshak	N. Fork of the Clearwater River
Libby	Upper Columbia River
Detroit/Big Cliff	North Santiam River
Green Peter/Foster	South Santiam River
Lookout Point/Dexter	Willamette River
Blue River and Cougar	McKenzie River
Lost Creek	Rogue River

Reservoir on the Rogue River in southwest Oregon provides another example. Operation of the reservoir reduces summer temperatures in the river by more than 3 °C and increases winter temperatures by about 1 °C at Marial, about 160 km below the reservoir (Oregon Department of Fish and Wildlife 1994). Large storage projects of this type have caused seasonal changes in normal water temperature regimes of many major Pacific Northwest river systems.

Chemicals—Inorganic and organic chemicals and dissolved gasses in natural waters can be altered by various human activities. Changes in land use in forested watersheds, coupled with agricultural, mining, industrial, and military activities in the Pacific Northwest have extensively altered the chemical composition of natural waters. Many of the chemical changes resulting from human activities persist without precedent in Pacific Northwest waters.

Forest chemicals, consisting primarily of herbicides, fungicides, insecticides, rodenticides, nematocides, fertilizers, fire retardants, and biological agents (e.g., *Bacillus thuringiensis* and viruses) have been historically used to protect and enhance various forest resources. Concerns for the environment, human health, and intense public controversy terminated extensive use of herbicides for silvicultural purposes on the national forests in 1989. A court order temporarily stopped all herbicide use on forest lands in the Northwest the same year (Norris et al. 1991) pending full NEPA analysis and documentation of their use. Herbicides are currently used sparingly on private, state, and federal forest lands to enhance forest production in the region, as are other pesticides and fertilizers.

Most forest chemicals have historically been applied through aerial spray techniques. Private forest managers and local and state governments still use aerial sprays for various forest applications, but ground-based applications are now more common on federal forest lands. Control of large-scale outbreaks of forest defoliators on federal forest lands with aerially applied insecticides is an exception. Aerial application poses the greatest threat to contamination of streams because of wind drift and application logistics.

Current application of forest chemicals is minimal on federal forest lands in the Pacific Northwest. About 19 000 ha (0.2 percent) of national forest lands in Oregon and Washington were treated in 120 separate ground applications of insecticides, rodenticides, herbicides, fungicides, fumigants, and repellents in 1999.[3] On 50 treatments, herbicides were used to control noxious weeds on about 3200 ha of land.[4] Nearly 15 000 ha were treated with strychnine as the active ingredient for animal damage control.

Aerial spray applications to control Douglas-fir tussock moth (*Orgyia pseudotsugata* McDunnough), spruce budworm (*Choristoneura occidentalis* Freeman), and other defoliators on national forests in the region are conducted as needed. In 2000, 16 000 ha were treated with TM Bio-control, a natural virus to control tussock moth.

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[3] Smith, G. 2000. Personal communication. Integrated pest management specialist, USDA Forest Service, Region 6, 333 SW First Avenue, Portland, OR 97204-3440.

[4] Forsgren, H. 2000 (June). Letter to Forest Supervisors and Directors. Annual report on vegetation management for fiscal year 1999. On file with: USDA Forest Service, Pacific Northwest Region, P.O. Box 3623, Portland, OR 97208.

From 1995 to 1999, no aerial spray programs were conducted on the national forests of the Pacific Northwest. Tribal governments also conduct aerial spray operations to control forest defoliators. In 1999 and 2000, the Yakama Indian Nation treated 15 000 ha and 2000 ha, respectively, to control tussock moth. On private and local government forest lands in Oregon, requests are made for chemical treatment of about 162 000 ha of harvest units and 764 km of roadsides annually,[5] although not all of the land is actually treated each year.

Washington and Oregon have monitored the effects of aerial application of pesticides on stream water quality for the past 16 years (Dent and Robben 2000). Three studies in two states reveal little water contamination from forestry activities. Oregon Department of Forestry monitored aerial pesticide applications from 1980 to 1987 to assess the effectiveness of forest practice rules (in effect at that time) in protecting Oregon waters (Oregon Department of Forestry 1992). Eighty-six percent of the water samples analyzed revealed no detectable level of pesticide; in no samples did detectable levels exceed 1 part per billion (PPB). A second Oregon study in 1989 to 1990, to assess the effects of herbicide applications, reported similar results. Eighty-three percent of water samples indicated no detectable herbicide levels. The Washington Timber, Fish, and Wildlife Program monitored six herbicide treatments in 1991 (Rashin and Graber 1993). All samples analyzed contained either no detectable level or <1 PPB of herbicide. Results of these studies indicate that even decade-old forest practice rules and actual practices as implemented in Oregon and Washington were effective at maintaining acceptable water quality.

A more recent study to examine the effects of changes in aerial pesticide application (Dent and Robben 2000) made in Oregon Forest Practice Rules in 1997 (OAR 629-620), tested the effects of 26 pesticide operations on fish-bearing streams and streams used as sources of domestic water in western Oregon. No pesticide contamination levels >1 PPB were found in any postspray samples taken immediately after application. Also, no detectable levels were found in water samples at three sites where rainfall and runoff occurred within 72 hours of application. Results of these four studies indicate that pesticide contamination >1 PPB from forest practices is rare under normal circumstances.

Although use of pesticides for silvicultural purposes is widely distributed in time and space across the Northwest, the most concentrated use of pesticides and other organic compounds occurs on agricultural lands. Extensive studies conducted in the Yakima River basin from 1987 to 1991 reveal the extent and magnitude of pesticide use, and movement of pesticides into streams and rivers from nonpoint sources in the basin (Rinella et al. 1992a, 1999). Estimates of pesticide use indicate that about 3 million kg of active ingredients, representing about 180 pesticides, were applied in the basin in 1989 (Rinella 1999). From 1987 to 1991, 100 sites in the basin were sampled to assess the potential effects of pesticides and other organic compounds on streams. Fifty-four compounds were analyzed in the study, and 43 (80 percent) were detected in streambed sediments, suspended sediments, water, or aquatic biota at one or more of the sampling sites. The highest concentrations of pesticides occurred in dewatered sections of the lower river and lower main stem as the proportion of agricultural return flow increased. Many samples had concentrations of

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[5] Peck, J. 2000. Personal communication. Oregon Department of Forestry, 2600 State Street, Salem, OR 97310.

compounds that exceeded chronic-toxicity water-quality criteria for the protection of aquatic life (National Academy of Sciences and National Academy of Engineering 1973, U.S. Environmental Protection Agency 1986b). Most of the high concentrations occurred in irrigation water returns and in the main-stem river below the city of Yakima.

Pesticide contamination of other Northwest streams and rivers is also well documented. A 148-km reach of the Snake River below Milner Dam is degraded, in part, from pesticide accumulation from agricultural operations (Clark 1997). Although detailed analyses of pesticide problems in the basin have not been completed, polychlorinated biphenyls (PCBs) and organochlorines have been detected in water, sediment, and fish tissues at sites downstream from agricultural and urban areas (Clark et al. 1998). Fish tissues had high concentrations of PCBs, dichloro diphenyl trichloroethane (DDT), and the breakdown products of DDT; these values exceeded criteria for aquatic life (Maret and Ott 1997).

Streams in agricultural areas of the mid and lower Willamette basin also are contaminated with pesticides. According to Rinehold and Witt (1992), about 2 million kg of pesticides are used annually in the Willamette River basin. A study of water quality in the basin from 1991 to 1995 (Wentz et al. 1998) found 49 pesticides in streams draining predominately agricultural land; criteria for the protection of aquatic life were exceeded for 10 pesticides found. All sites with high levels drained primarily agricultural and urban lands, with the highest concentrations in agricultural basins. Herbicides were detected at twice the rate of insecticides in streams draining agricultural lands. A study by the Oregon Department of Environmental Quality (2000a) found that levels of mercury, PCBs, various pesticides, and dioxins were sufficiently high in four fish species in the Willamette River between Willamette Falls and Salem to pose a long-term cancer risk to subsistence anglers (Oregon Department of Environmental Quality 2000a). In general, agriculture was the primary land use upstream from the most highly impaired water quality sites in the basin.

Fish communities in small agricultural and urban stream sites included high abundances of pollution-tolerant fishes with low levels of external abnormalities (deformities, tumors) and low abundances of introduced species (Wentz et al. 1998). These sites had small riffles, moderately open riparian canopies, relatively high maximum water temperatures, lowest minimum dissolved oxygen saturation, and highest nutrient and pesticide concentrations. In contrast, large agricultural sites were characterized by relatively high numbers of pollution-tolerant sculpins, minnows, and introduced species, such as carp, with moderate levels of external abnormalities. Habitat characteristics included small riffles, open riparian canopies, high maximum water temperatures, and intermediate nutrient and pesticide concentrations (Wentz et al. 1998). These results indicate that the best remaining salmonid habitats in the Willamette River basin are located on forested lands upstream from urban and agricultural areas. The study, however, did not attempt to compare the current productivity and structure of fish communities at the sample sites with historical productivity and community structure.

Clark et al. (1998) conducted a similar study of fish communities in the Upper Snake River basin including large rivers, streams dominated by agricultural activities, and least-disturbed streams and springs in forested and rangeland watersheds (Maret

1997). Overall, 26 native and 13 introduced fish species were collected in the basin indicating that the quality of fish communities in the Snake River and its tributaries deteriorates from the headwaters near Yellowstone National Park to the basin outlet near King Hill.

The upper reaches of Henrys Fork and the Snake River upstream from its confluence with Henrys Fork is mostly forested, largely free of agricultural activities, and contains some of the best stream and large river trout fishing in the Nation (Clark et al. 1998). In contrast, in the agricultural reach downstream from the confluence of Henrys Fork and the Snake River to Milner Dam, fish communities are composed primarily of cutthroat trout (*O. clarki* Richardson) and other native and nonnative species (Maret 1995). However, according to Maret (1995), fish communities in this reach are degraded by irrigation return flows, grazing, and irrigation diversions.

Historical records indicate that prior to hydroelectric and agricultural development, the reach of the Snake River between Shoshone Falls and King Hill was productive habitat for chinook salmon, steelhead, Pacific lamprey (*Lampetra tridentata* Gairdner), and white sturgeon (*Acipenser transmontanus* Richardson). Of these, only white sturgeon is still present and its numbers are declining. Because of degraded water quality, trout have been nearly eliminated from this reach of the Snake River. The national water-quality assessments in the upper Snake River (Clark et al. 1998, Maret 1995) and Yakima River (Morace et al. 1999) basins showed similar results. Forested landscapes in these basins had high water quality and unimpaired fish communities, whereas fish communities in downstream areas influenced by agriculture and urbanization were often moderately to severely impaired.

Nuclear isotopes and associated chemicals have minimal impact on most Northwest waters. The exception is chemical contamination of 82-km Hanford Reach of the Columbia River from the Hanford Nuclear Reservation. The U.S. government manufactured plutonium for nuclear bombs at Hanford from the early 1940s to the 1980s (White 1995). Columbia River water was used to cool the nuclear reactors and then returned with radioactive contaminants to the river, which in the 1960s was believed to be the world’s most radiologically contaminated river (Oregon Department of Energy 2000). Plutonium manufacture also produces various toxic chemicals and radioactive by-products. By 1985, more than 757 billion L of contaminants had been stored in surface tanks and underground vaults on the reservation (Ryan 1994, White 1995). Leaking tanks and vaults have contaminated ground water beneath 310 km^2 of the reservation with toxic and radioactive wastes that are slowly moving into the Columbia River (Bastasch 1998). In 1995, chromium concentrations lethal to fish were detected in nearby salmon spawning areas (Connelly 1997, Hanf et al. 2000).

Mining in Northwest river basins also can change the natural chemical content of the region’s waters. Mining activities are widely scattered spatially across the three states, with the most concentrated activities in northern and central Idaho. The primary effects of mining on water chemistry include addition of toxic sediments and acid mine discharge that also contains toxins resulting from sulfite oxidation of mine tailings exposed to air and water (Hinkle 1999). Several hundred abandoned mine lands across this region, and others, present some potential risk to water quality, and only a few have become Superfund[6] cleanup sites.

Examples of the most heavily polluted areas occur in Idaho. A century of mining for silver and other metals in the Coeur d' Alene basin in northern Idaho have contaminated both the Coeur d'Alene River and Lake with millions of metric tons of sediments laden with lead, cadmium, mercury, and other metals (Horowitz et al. 1993). In addition to release of contaminated sediments into the waters of the valley, operation of the smelters at the Bunker Hill Mine from 1917 to 1982 contaminated lands and waters around the smelter with lead and zinc in sufficient quantities to kill livestock and endanger human health in the area (Aiken 1998). A 54-km^2 area around the site of the Bunker Hill smelters is now a Superfund cleanup site supervised by the U.S. Army Corps of Engineers. Another site contaminated with mining pollution is a 225-km reach of the Clark Fork River downstream from copper mines near Butte, Montana. The reach, which drains to Lake Pend Oreille, is polluted with heavy metals from mine tailings (Ryan 1994). The area comprises one of the largest Superfund cleanup sites in the United States.

The mines mentioned above and others, for example, the Thompson Creek molybdenum mine (Langston 1998) and Blackbird cobalt mine (Agency for Toxic Substances and Disease Registry 2000) in Idaho, the Riddle nickel mine (Hinkle 1999), and the White King and Lucky Lass uranium mines (U.S. Environmental Protection Agency 1995) in Oregon, all produce acid mine discharges containing heavy metals and other chemical pollutants. Water quality at these sites and others in the three-state area are being addressed by state and federal cleanup plans.

Some recreation activities cause extensive chemical contamination of water. The greatest chemical impacts result from motorboats powered by two-stroke engines. A study on the effects of motor boating by Jackivicz and Kusminski (1973) found that, depending on the engine design, two-stroke outboard motors discharged an average of 10 to 20 percent of their unburned fuel into the water—with some engines discharging as much as 55 percent. The high variability in the amount of engine discharge results from differences in the size of motor, intake and exhaust design, size of crankcase, speed of operation, tuning of the engine, and recycling of crankcase drainage. In 1970, it was estimated that 380 to 600 million L of raw fuel were discharged into U.S. waters owing to the inefficiency of outboard motors (Jackivicz and Kusminski 1973). The discharge typically contained raw fuel, nonvolatile oil, volatile oil, lead, and phenols that have been found to negatively affect plant and animal species within riparian environments (Stewart and Howard 1968) and the quality of drinking water (Dissmeyer 2000).

Nutrients—Nitrogen and phosphorous are essential plant nutrients in natural waters, but large concentrations can be pollutants that alter the characteristics of water. The natural nutrient composition of waters in the Northwest can be altered by fertilizers used in forestry and agriculture, discharge of domestic sewage, animal wastes, and runoff from urban landscapes. Land use activities that affect the quality of fish habitat and commercial fishing that reduces returns of anadromous fish, also can affect the natural range of nutrients in fresh water.

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[6] Congress established the Superfund Program in 1980 to locate, investigate, and clean up the worst hazardous waste sites nationwide. The U.S. Environment Protection Agency administers the Superfund program in cooperation with individual states and tribal governments.

Both nitrogen- and phosphorous-based fertilizers are used rarely in forestry to enhance tree growth. In 1980, about 54 500 Mg of fertilizers were applied to forest lands nationwide (Bengtson 1979, Norris et al. 1991), an amount representing about 0.5 percent of fertilizer products used in agriculture. Much of the product was applied to private forest lands in the Eastern and Southern United States. Use of fertilizer is rare on federal forest lands in the Pacific Northwest, with most use occurring on nurseries and seed orchards. Use on private forest lands is more common but is still used on only a small proportion of these lands. Water quality sampling programs in the Yakima, Snake, and Willamette River basins indicate that nitrogen and phosphorus concentrations in waters flowing from forested watersheds are similar to those observed at national benchmark sites on streams minimally disturbed by human activities (Clark et al. 1998, Pogue et al. 1999, Wentz et al. 1998). Median values for nitrite plus nitrate nitrogen, and total phosphorous at national benchmark sites are 0.24 mg/L and 0.03 mg/L, respectively. By comparison, values from forested sites in the Yakima River basin in 1987 to 1991 were 0.01 mg/L total phosphorous and 0.02 mg/L nitrite plus nitrate nitrogen. Thus, overall concentrations remain low.

Fire retardants for air-delivered fire suppression activities on forested lands have a small potential to increase nutrient loads in forest streams and lakes. Common chemical fire retardants are primarily ammonium phosphate or ammonium sulfate and small amounts of several other chemical compounds (Norris et al. 1991). A large number of aerial drops in a restricted area, or an accidental drop directly into surface water, can potentially add nitrates, phosphates, or sulfates to streams and lakes, but the duration of increase is usually brief. Such occurrences are rare because use of air-delivered fire retardants is usually widely scattered in time and space across forested landscapes.

One of the greatest sources of nutrient enrichment in streams of the Northwest is agriculture. For example, in the Willamette Valley in 1991, 57 200 Mg of nitrogen and 18 200 Mg of phosphorous were applied to agricultural lands (Rinella and Janet 1998). Water-soluble fertilizers are sometime applied as additives to irrigation water in the Northwest (Clark et al. 1998), so runoff from rainfall or irrigation return flow often carries nutrients directly to streams. Median total nitrogen and total phosphorous concentrations in the Yakima River basin were 8 and 19 times higher, respectively, at sites on agricultural lands than at sites on forested lands (Pogue et al. 1999).

Similar relations occurred in the Willamette and upper Snake River basins. A study of nutrients in the Willamette River basin in 1993 revealed that nitrate concentrations in streams increased as the percentage of drainage area in agriculture increased (fig. 21) (Wentz et al. 1998). Also, 68 percent of streams where phosphorous exceeded 0.1 mg/L (nuisance level for aquatic plant growth, U.S. Environmental Protection Agency 1986a) occurred on agricultural lands. The lowest nitrate concentrations (0.054 mg/L) were in streams draining forested basins, while tributaries of the predominantly agricultural Pudding River basin had nitrate concentrations exceeding 10 mg/L, violating the level established by the Environmental Protection Agency for safe drinking water (U.S. Environmental Protection Agency 1996a).

Drainage and treated wastewater from urban areas also alters natural nutrient loads in surface waters of the Northwest. Treated wastewater and runoff from urban landscapes are major point sources of nutrient enrichment from cities in the region. Most receiving waters occur in downstream locations in major river basins that already

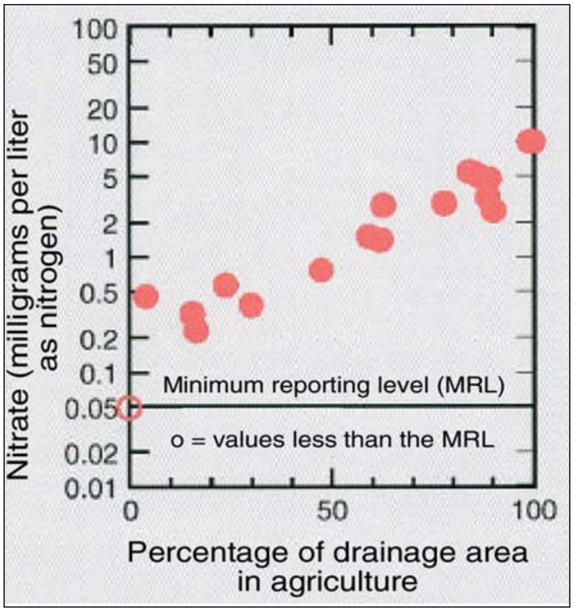

Figure 21—Nitrate concentrations in Willamette basin tributary streams Pudding and Mollala increased with percentage of drainage area in agriculture, April 26-29, 1993 (from Wentz et al. 1998).

receive nutrient enrichment from upstream agricultural areas. Oregon and Idaho discharge more than 1.14 billion L of treated wastewater daily into Northwest waters (Rivercare 2000). The pollution control performance of treatment plants varies considerably across the region. For example, modern plants like those located at Hillsboro and Tigard, Oregon, release effluents low in biochemical oxygen demand, nutrients, and toxins, whereas older plants in the region like those located at Tillamook and Newport, Oregon, produce effluents with higher concentrations (Rivercare 2000).

Most cities in the region have dedicated sanitary sewers that collect only wastewater from domestic and industrial sources. Some, however, still have combined sewer and storm drainage systems that can overtax water treatment facilities during periods of storm runoff, and release raw sewage into the region's waterways (U.S. Environmental Protection Agency 2000). Three cities in Oregon (Portland, Corvallis, and Astoria) (Oregon Department of Environmental Quality 2000b), and 15 in Washington, including many in the Puget Sound area, have combined collection systems that discharge effluent directly into saltwater (U.S. Environmental Protection Agency 2000).

Commercial and recreational fishing and fish habitat degradation have reduced anadromous salmonid populations in the Pacific Northwest by changing the natural nutrient loads of surface waters. Pacific salmon annually ascend rivers of the Northwest to spawn, where they die and leave nutrient-rich carcasses to decompose. Historical runs in the Columbia River that once exceeded 16 million fish (Volkman 1997) have been reduced to about 5 percent of that number. Similar statistics can be cited for most major river systems in the Northwest. The reduction in fish runs results in a corresponding decrease in stream nutrients derived from decomposing salmon carcasses. The result is nutrient impoverishment in salmon streams, the opposite of nutrient enrichment, and loss of natural nutrient regimes of Northwest streams that historically supported anadromous salmonid runs.

Pathogens—Increases in human pathogens in Northwest waters can arise from several sources. Discharge of untreated domestic sewage from urban areas, or untreated leachates from septic tanks in rural areas can contaminate water with coliform bacteria and other human-infecting pathogens. Modern sewage treatment facilities minimize pathogen pollution during most periods, but combined sewer and storm drainage systems may be overtaxed in winter by high stormflows. Although raw sewage overflows are diluted by rain and river water, they still pose health and environmental hazards, especially for water-contact recreation activities (Oregon Department of Environmental Quality 2000b).

Recreation activities, such as swimming and camping, can change the natural level of pathogens in water, although the scale of effects is usually small. The effects accrue either through direct contact with water or through indirect means. Direct impacts result from human and pet contacts with water such as swimming. Indirect impacts result when land-based recreation activities such as camping or hiking occur near streambanks or the shores of lakes and reservoirs (Kuss et al. 1990). These distinctions also have been described as water- and shore-based activities (Liddle and Scorgie 1980). Camping sites along water bodies also can result in increases in human-infecting pathogens; and increased soil compaction, runoff, and erosion; lower soil moisture; reduced flow of air, water, and nutrients through the soil; higher pH; lower number of roots in the soil; a loss of vegetative cover; and increased eutrophication of nearby water bodies (Green 1998, Lockaby and Dunn 1984). A study in the Pacific Northwest that examined the effects of recreation at two camping sites on water quality in the Mount Baker-Snoqualmie National Forest in Washington (Christensen et al. 1978) found that densities of total coliforms, fecal coliforms, and fecal streptococci downstream of campsites increased over weekends, when 90 percent of the recreation occurred. Another study in the Snoqualmie National Forest also found high levels of certain indicators (total coliforms, fecal coliforms, and fecal streptococci, *Salmonella* and *Shigella* species) downstream from heavily used motorized camping sites (Varness et al. 1978).

Swimming can increase human pathogens in two ways. First, as a body-contact recreational activity, it has the potential to introduce pathogens into water through direct contact. Second, swimming may increase bacteria loads by disturbing bottom sediments that may contain higher concentrations of bacteria than surface waters (Hendricks 1971, Kuss et al. 1990). The potential for recreational impacts from swimming are particularly important to consider in reservoirs built primarily as a source of drinking water. In a study examining the potential impact of body-contact recreational activities on reservoir drinking water, Anderson et al. (1998) found that their model predicted possible high levels of *Cryptosporidium*, rotavirus, and poliovirus during the summer high-recreation-use months. In another municipal water supply reservoir, Wagenet and Lawrence (1974) observed a highly localized increase in fecal coliform densities associated with peak recreation use exceeding standards for recreational waters. Because increased coliform densities were so localized and far removed from the location from which water was extracted for municipal purposes, Wagenet and Lawrence (1974) believed that the reservoir could still be used for dual recreational and drinking water purposes. Thus, swimming can increase pathogens both directly and indirectly and have potential effects on water quality and health.

Changes in water quality—Domestic water supplies in the region derived from surface waters can be degraded by sediment and turbidity or excess nutrients that cause undesirable growths of algae. When these conditions occur, it becomes more expensive to maintain water treatment compliance with federal water quality standards, and the aesthetics of drinking water may be reduced. Many domestic water sources on forested federal lands in western Oregon and Washington are seasonally affected by sediment and turbidity. One of the most visible examples is the Bull Run Watershed, which supplies potable water for the city of Portland, Oregon. Three times since 1996, Portland's primary water source has been shut down owing to turbid water in the Bull Run Reservoir (Learn 2000). The city was forced to use alternate ground-water sources until Bull Run cleared sufficiently to resume use. Water for many other urban areas in the region also is derived from surface waters that carry the cumulative effects of human activities upstream from their intakes. Extensive treatment and purification of those waters can be necessary to render them potable, and chronic turbidity can necessitate construction of filtration plants.

Research Needs on Altered Flow Regimes and Water Quality

What is the potential role of the PNW Research Station in solving unanswered questions about how altered flow regimes and water quality affect water supply and use? Several potentially fruitful areas of research include (priorities are H = high, M = moderate, L = low):

- Evaluating economic tradeoffs between the causes and consequences of altered flow regimes. (H)
- Learning how to manage forested landscapes with fewer roads. (H)
- Establishing the comparative productivity of the best remaining salmonid habitats today with the historical productivity of salmonid habitats at the large watershed scale. (H)
- Defining the effects of forest management on flow regimes at large scales through watershed studies. (M)
- Improving understanding of how subsurface and surface flows may be affected by roads, and their significance to downstream flow regimes. (M)
- Improving understanding of the consequences and implications of altered flow regimes on social uses and values of water, including outdoor recreation, subsistence use, and sense of place, and developing methods for mitigating adverse impacts. (L)
- Water quality research to assess the effects of recreation on drinking water, especially with respect to pathogens. (L)

Demands for Water Create Conflicts Over Water Use

The array of policies, doctrines, laws, and traditions that regulate and govern water use and allocation commonly create conflict over water management. Although such conflicts often are viewed as dysfunctional, counter-productive, and costly, conflict can be useful in defining problems and potential solutions. Conflict often is an inevitable consequence of competing interests and demands over the allocation of scarce resources. Although there is no agreed-on definition of conflict, in the context of water management, the term can be used to describe conditions when incompatible goals of different user groups or individuals come into direct contact over the management and allocation of water, the scarce resource. Conflict over water might occur between different sectors, such as between municipal use and ecosystem restoration, or within a particular sector, such as between kayak and motorboat users. Often, differing norms and conceptions of appropriate uses, conditions, and behaviors about water are simultaneously involved. Some users may perceive that the differences are inadequately addressed by economic and scientific analysis and remedies. When two or more value systems come into direct contact, or when the resource in question becomes more scarce, or when one party can only gain at another's expense, the potential for conflict grows.

Water Rights

Conflicts typically occur between and among instream and offstream uses of water. Offstream use of water resources in the Pacific Northwest began with initial settlement of the region in the mid-19th century. The "first-in-time, first-in-right" use doctrine is still used, with some recent modifications to govern allocation and adjudication of most surface water rights by states west of the 100th meridian. Water rights awarded under the doctrine have a priority date that allows permanent access to a specified water amount as long as the water use is beneficial on a regular basis. The priority date remains important because it determines who receives water when supplies are inadequate to meet the needs of all holders of valid water rights. For more than a century the doctrine has been the primary legal basis for allocation of water and generally facilitated orderly development of Western water resources. Because water allocated under the doctrine was free to the holders of valid water rights, most Western waters were quickly appropriated (Bastasch 1998, Western Water Policy Review Advisory Commission 1998).

The doctrine of prior appropriation governed the allocation and use of water in the Northwest for more than 140 years (Miller 2000), but its ability to meet the changing needs and values of society diminished with time. As populations in the Northwest grew and the economic base of the region diversified, the simplicity of the doctrine became inadequate to resolve the increasing variety and magnitude of demands for water resources. In the 19th century, the doctrine was used effectively to resolve water-related conflicts, but in the 20th century, it began to generate more conflicts than it solved.

The doctrine has at least two major flaws. First, its definition of "beneficial use" of water was not comprehensive. The definition initially focused on off-channel uses of water such as irrigation, and in-channel uses such as hydropower production. Maintenance of instream flows to maintain societal values such as, recreation, aquatic ecosystems protection, and production of aquatic species (e.g., salmon) were not recognized. Second, the doctrine has been unable to accommodate priority-date water rights established by law that are out of sequence with the initial filing dates for water rights. At issue here are Native American water rights recognized by the 1908 Supreme Court decision (U.S. v. Winters) that established the Winters

Doctrine and awarded water rights to Native American nations on federal reservations. Those water rights date to the signing of treaties that established the reservations, most about 1855, and therefore pre-date, and are senior to, most non-Native American rights. When the Winters Doctrine was established, most Western waters were already fully appropriated, and for the next 80 years, legally established tribal water rights were largely ignored.

The shortcomings of the doctrine of prior appropriation resulted in many conflicts over sustainable water use in the Northwest in the latter decades of the 20th century. Because most Western waters are fully appropriated, and because beneficial use of water was historically focused on consumptive off-channel uses such as agriculture, industry, mining, and municipal needs, and production of hydropower, recognition that free-flowing water could be left in channels for beneficial uses was slow to evolve. In the last two decades, the states of Oregon, Washington, and Idaho have recognized that instream uses of water, such as protection of fisheries, aquatic ecology, and recreation for example, are beneficial uses. These states have established minimum flows on many streams to protect instream values. The problem is that under existing Western water law, instream flows have the status of junior water rights, and in times of shortage are the first to be usurped by more senior water rights. Strict legal interpretations of water law do not favor instream flow needs (Oregon Water Resources Congress 2000).

Historical Western water law conflicts with some more recent state and federal laws related to management and use of water resources (see app. 2). As demands for water resources have become more intense, especially in semiarid areas, the conflicts between water-related laws also have intensified. For example, overappropriation of surface water for consumptive uses, or water pollution associated with consumptive uses like irrigated agriculture, can impose viability risks on aquatic species, and thereby come into conflict with the ESA [16 USC 1531-1544] and the Clean Water Act (P.L. 95-217). Provisions in the ESA, for example, can legally require maintenance of minimum flows in specific streams for recovery of listed salmonid populations. The dilemma is that the same water may have previously been allocated and adjudicated to a water right holder for offstream use. Conflicts of this type are common across the region and may affect maintenance of aquatic biodiversity, recovery of threatened and endangered aquatic species, and some types of water-oriented recreation. Conflicts between offstream and instream uses of water urgently need resolution for equitable and sustainable development of the region's water resources.

Conflicts, however, are not limited to these issues. Conflicts among instream uses are also common. The interaction between dams and reservoirs and anadromous salmonid populations in the Northwest is a case in point. Several factors, including hydropower operations, overfishing, hatcheries, and loss of freshwater habitats, have contributed to the decline and eventual listing of several stocks of anadromous salmonids (Nehlson 1997). But alterations of instream conditions related to the construction and operation of hydropower facilities on the Columbia and Snake Rivers have had the greatest effects on Idaho stocks (Ford 2000, White 1995, Volkman 1997).

Conflicts between user groups over scarce water resources occur in nearly every river basin in the Northwest. The Deschutes basin in north-central Oregon provides a typical example. A coalition of user groups in the basin has identified current and emerging water-related conflicts and is working toward resolution. The conflicts revolve around a rapidly increasing population; social values that no longer fully support current water use; impacts from agriculture, ranching, and forest management; emerging interests 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). Topics on this list closely parallel the current and emerging water-related issues in the Northwest.

Sustainable development of water resources in the Northwest requires a new balance between off-channel consumptive uses of water and nonconsumptive instream uses to solve current and emerging issues over water allocation. This balance must include definition, maintenance, and legal standing for minimum instream flows necessary to maintain viable aquatic ecosystems, and at the same time, include plans to accommodate expanding consumptive uses of water in the region. To date, the states have been unable to define and maintain this balance.

Equitable allocation of water resources is arguably the largest issue currently facing water managers in the Northwest, but it is not the only issue. Timber management and roads on forest lands create potential conflicts with water quality, especially turbidity and sedimentation. These can in turn affect the health of aquatic habitats, recovery of threatened and endangered aquatic species, water-oriented recreation, and downstream domestic and industrial water use.

The needed resolution of legal tribal claims to water in the Northwest further complicates the establishment and maintenance of minimum streamflows for ecological needs. Resolution of conflicts over Native American water rights in the West is in progress. Since 1982, Congress has ratified at least 15 Native American water rights settlements. Two of those were in the Pacific Northwest. The first, and largest to date, was a 235 122-ha allocation to the Shoshone/Bannock Tribe on the Fort Hall Reservation in Idaho (National Research Council 1996, Western Water Policy Review Advisory Commission 1998). The second is the final settlement of the treaty and aboriginal water claims of the Warm Springs Tribes in central Oregon.

The agreement with the Warm Springs Tribes did not allocate a specific amount of water, but instead included the following key points (Environmental Defense 1998). First, it creates a framework for cooperative water management to protect freshwater supplies for salmon survival and other ecological purposes. Second, the agreement sets aside the entire flow of all streams on the reservation to "sustain or enhance the aquatic ecosystem," except for specified quantities that the tribes are entitled to consume. Third, it establishes minimum streamflows needed for survival of salmon and other life in the Deschutes basin and other major rivers. Fourth, even greater minimum streamflows may be established in the future under federal or state law. Fifth, it protects existing and future tribal uses of water. And last, the tribes are authorized to market and sell a block of their water off the reservation.

Negotiations for water rights settlements with other Pacific Northwest tribes, including the Paiute-Shoshone, Lummi, Nez Perce, and Klamath, are in progress. With completion of these settlements, a new baseline for priority use of water will be established in the Northwest. However, the issue of minimum flows remains unresolved.

The most acute water-related conflicts in the Pacific Northwest are related to the habitat, production, and status of anadromous salmonid populations. Many of these conflicts have been discussed in previous sections of this synthesis and have been reviewed by others (see for example, Meehan 1991, Murphy 1995, Stouder et al. 1997, Volkman 1997). Instream and offstream water uses have created irreversible changes in the biological, social, and economic characteristics of salmonid resources, and the once-abundant salmon fisheries. Alternative uses of water have led to extinctions of many stocks, and the decline of many others has led to ESA listings (Nehlson et al. 1991). Sport, commercial, and Native American fisheries in many Northwest rivers have collapsed as a result of salmon- and water-related conflicts.

Many of the conflicts stem from 19th-century laws. Beginning in the mid-1800s, dams were built with little control over their attributes. Although fishery impacts on fish were noted before the turn of the 20th century (Smith 1895), fish passage at dams was rarely provided. Even Bonneville Dam on the Columbia River, constructed in 1933, was originally designed without fish passage facilities (Gregory and Bisson 1997). Currently, 30 100 km of streams are blocked by dams. This represents 38 percent of historical habitat that was formerly accessible to anadromous salmonids in the Columbia basin (Volkman 1997). Portions of major coastal rivers in the Northwest, like the Rogue, Lewis, and Skagit Rivers, also are dammed and inaccessible to anadromous fish.

Major sources of mortality for anadromous fish include the reservoirs created by dams, associated turbines for hydropower generation, and ladders for fish passage. Slack water reaches behind dams on the Columbia and Snake Rivers slow downstream passage of ocean-bound salmonid smolts, increasing mortality as a result of unfavorable water temperatures and predation in the reservoirs. Large numbers of smolts are likely killed passing through penstocks and turbines. As a result, many of the downstream migrants are currently either trucked or barged from the Snake River to the ocean. Fish ladders for upstream passage of adult salmonids cause mortality of fish moving to spawning areas. Estimates are that >5 percent of adults are killed at each of the eight major dams on the Columbia and Snake Rivers (Ford 2000).

Dewatering of rivers and streams for irrigated agriculture, and agricultural, domestic, and industrial pollution that degrade water quality create additional conflicts between water management and fisheries. Conflicts arise between anadromous fish and land management activities such as forestry, livestock grazing, and mining because of alteration in streamflows and water quality in salmonid habitats. Although additional ecological knowledge of salmonid biology would help to guide restoration of anadromous salmonid stocks, current conflicts between salmon and other uses of water will likely only be resolved through socially acceptable economic and political actions.

Recreation

Potential conflicts between water use and recreation activities center around human-caused changes in streamflows, changes in the characteristics of water bodies, and the effects of crowding on water quality, with potentially negative feedback on either recreation or domestic uses of water. Knowledge of the relation among water-based recreation, water body characteristics, and temporal and spatial distribution of water is important to understanding the types of conflicts associated with water-based recreation. Some conflicts might not affect the level of participation in an activity even if individual satisfaction may decrease. But other conflicts can lead to coping behaviors that attempt to minimize the source of the conflict and maintain the desired level of satisfaction, and some may be so severe that participants pursue substitute recreation activities. Conflicts for individuals have been defined as "goal interference attributed to another's behavior" (Jacob and Schreyer 1980). The perceived conflict level is not constant among all recreationists but instead differs in response to a variety of factors. An individual's sensitivity to conflict is influenced by activity style (i.e., personal values associated with a recreational activity), resource specificity (i.e., the importance placed on a particular resource such as a swimming hole), lifestyle tolerance (i.e., willingness to share resources with members of other lifestyle groups), and mode of experience (i.e., preferred ways of experiencing the environment) (Jacob and Schreyer 1980). For instance, many individuals have expectations that a recreational experience will not involve encounters with other people. Consequently, the presence of others can detract from the recreationist's experience (Stankey 1973).

Recreation conflict has been classified into three main categories: (1) recreation versus other uses of the water resource, (2) interactivity recreation conflict, and (3) intra-activity recreation conflict (Schreyer 1990). These three forms of conflict are described below.

Recreation versus other uses of water—Many studies have examined the link between recreation and land use (e.g., how different logging practices impact the visual quality of camping sites [Brunson and Shelby 1992, Langenau et al. 1980]), but much less research has been conducted on conflicts between water-based recreation and water management for other uses. Water conflicts can occur when alternative water uses are incompatible. For example, water appropriated for out-of-stream uses (e.g., irrigation) reduces the flow of water available for recreational opportunities.

Under certain circumstances, recreationists might be able to find an acceptable substitute by modifying a particular aspect of the experience, such as timing or access to the activity or resource setting (Brunson and Shelby 1993). Shelby and Vaske (1991) have created a typology of alternatives for recreation substitutability. In their scheme, four outcomes are possible: (1) the recreationist substitutes a different time for conducting the activity or a different means of gaining access to the resource, thereby retaining the same activity and resource setting; (2) the recreationist can substitute an activity in the same place; (3) a recreationist moves to a new setting yet continues participating in the same activity; and (4) a recreationist can change both the setting and activity.

Research on recreation substitutability has revealed that activities grouped by similar activity types (e.g., waterfowl hunting and deer hunting) are not necessarily perceived as equivalent substitutes by participants (Baumgartner and Heberlein 1981). Consequently, recent studies place greater emphasis on understanding the factors that make acceptable substitutes for specific recreation experiences. In particular, research suggests that instead of altering activities, participants in specific types of recreation typically attempt to substitute a different setting, time, or access method (Manfredo and Anderson 1987, McCool and Utter 1982). For example, if a free-flowing river was converted to a reservoir, river recreationists are more likely to seek equivalent recreation on other rivers than to begin boating on a newly created reservoir. As a result, changes in the management of any one area can have profound consequences on other similar, nearby areas to which recreationists may become displaced.

Reservoirs may not be suitable recreation substitutes for rivers, but because reservoirs have greater surface areas than the streams they inundate, they should represent a net overall gain in recreation opportunities. Two reservoirs in Washington have been designated national recreation areas because of the extensive and unique recreational opportunities they offer, and the recreational use they receive. The most prominent is Coulee Dam National Recreation Area, a 40 500-ha park that centers on 209-km Franklin D. Roosevelt Lake in the mid-Columbia basin (Nolan 1993). The second is Ross Lake National Recreation Area on the Skagit River. High mountains surround the reservoir that lies between the scenic north and south units of North Cascades National Park. Both developments appear to provide greater, but different, recreation opportunities than the preproject environment.

Reservoirs, because of unique site characteristics, also can provide new forms of recreation for a region. A classic example is Bonneville Dam reservoir on the lower Columbia River that created a world-class site for wind surfing. The geomorphology and climatology of the Columbia River Gorge, and the broad reservoir area at Hood River, Oregon, combine to create ideal conditions for wind surfing that are used by a national and international clientele.

The net effect of the addition of numerous large reservoirs in the Northwest has been an increase in opportunities for water-oriented recreation. Campers place high importance on setting their campsites near accessible bodies of water (Bumgardner et al. 1988, Lucas 1970), and correlate this with increased scenic value of an area (Zube et al. 1975). Fishing opportunities also increase in concert with increased surface area of human-made lakes and reservoirs. More than 2 million anglers spend about 20 million days fishing the waters of the Northwest annually (USDI and USDC 1996). Much of the fishing effort centers on the region’s lakes and reservoirs.

Robertson (1989) noted both direct and indirect impacts on recreation from competing uses of urban waterways. Some direct impacts include private ownership of waterfront properties and subsequent development and problems associated with the navigation of large ships in commercial ports. Indirect impacts to recreationists include reduced opportunities to view wildlife, a reduction in the visual quality of a recreation site, or increased noise (Clark 1986, Robertson 1989).

The quality of recreation experiences can be altered by competing demands for water resources. Using a survey of park visitors to an urban waterway, Robertson (1989) found that two-thirds of recreationists felt that poor water quality, odors from treated wastewater, and increased siltation detracted from their recreational experience. In another study examining the impact of commercial and industrial uses of water on recreation in a Midwest urban river corridor, Robertson and Burdge (1993) found that impacts to water quality associated with commercial navigation and water withdrawals (e.g., siltation, turbidity, and water pollution) significantly reduced recreationists’ satisfaction.

The effect that other uses of water have on recreation depends on the extent to which the public perceives negative impacts to the water regime. Studies of public perceptions of water quality suggest that people make determinations about water quality based primarily on visual aspects (Smith et al. 1991), and secondarily on smell and touch (Lant and Mullens 1991). In a survey of adults in Wisconsin, David (1971) found that people identify polluted water by the presence of algae, suds and foam, and murky, dark water.

Public perceptions of pollution influence the decisions of recreationists. Some impacts to the water regime from other uses may be so great that they eventually displace recreationists to other locations or convince recreationists to stop conducting the activity altogether. Water clarity has been found to be important for swimming suitability. David (1971) noted that the presence of green scum or algae would prevent 80 percent of recreationists from swimming, whereas the presence of cans or glass in the water would prevent 70 percent of respondents from swimming.

Interestingly, although recreationists use visual cues to determine the level of water pollution, water quality measures for gauging public health traditionally include nonvisual indicators such as bacteria levels or toxicity of organic compounds. On the Salt River in Arizona, Nelson and Hansen (1984) found no relation between water clarity and fecal coliform levels in recreation sites. These findings suggest that efforts to improve water quality for recreationists will have to include improving visual indicators from the recreation site such as the amount of litter and water clarity. Otherwise, water that is considered of good quality by toxicity or bacterial standards may still be perceived as unclean by recreationists (Dinius 1981).

Incompatible or noncomplementary uses of water, such as fisheries and hydropower production, or agriculture and recreation, require an accurate analysis of tradeoffs before informed policy decisions can be made. In such cases, a comparison of the value of alternative water uses can help identify socially and economically beneficial water allocation between competing offstream and instream uses (Colby 1989). Determining the most economically or socially advantageous way to allocate water supplies among users in time and space depends on an accurate representation of the value of water to different users and the impact each water user has on other users. Once economic values have been determined, tradeoffs can be evaluated to examine social, political, and economic ramifications of different water allocation scenarios. One way of estimating the marginal utility each user has for water, and thus allocate water optimally, is to evaluate what tradeoffs water users are willing to make. To make meaningful comparisons, it is important to define the quantity of water used for both instream and offstream purposes, assure comparability of use in terms of time, location, and quality, and distinguish between long- and short-run uses (Young and Gray 1972). Such economic-based analyses of tradeoffs of water resources rarely have been attempted.

Interactivity conflicts—Most studies on recreational conflict have examined interactivity conflict—the conflict occurring among recreationists participating in different activities. Empirical research on water-based recreation has observed problems between fisherman and water-skiers (Gramann and Burdge 1981), fisherman and canoeists (Driver and Bassett 1975), and particularly between motorized and nonmotorized boaters (Shelby 1980). For example, jet skiers have been found to be a disturbance to people engaged in other recreational activities such as fishing or swimming (Burger 1998).

A common finding in these research studies is an asymmetrical aspect to interactivity conflict. Although some people participating in a certain recreational activity may not mind the presence of recreationists participating in another activity, others do mind. For example, studies have clearly documented an asymmetric conflict between motorized boaters and nonmotorized recreationists such as canoeists. Although motor boaters are typically indifferent, or even have positive associations with their encounters with canoeists, canoeists dislike encounters with motorized recreationists (Lime 1977, Shelby 1980). Furthermore, these motor-craft users typically were unaware that other recreationists were disturbed by their activities. Over 85 percent of these motor craft users believed that they seldom or never disturb paddling canoeists, although 79 percent of paddlers felt they were occasionally or frequently disturbed by motor-craft users. This asymmetrical aspect to recreation conflict complicates management of water resources for recreation.

Intra-activity conflicts—Intra-activity conflicts are those conflicts that arise between recreationists who are participating in the same activity (Schreyer 1990). The literature on crowding is a well-researched example of this form of recreation conflict. For example, in a study of boating on the Cheat River in West Virginia, Whisman and Hollenhorst (1998) found that 64 percent of commercial boaters and 84 percent of private boaters experienced higher-than-normal levels of crowding. Crowding is defined as a "negative evaluation of a certain density or number of encounters" (Shelby et al. 1989). Crowding can result from a combination of increased visitation, relatively stable facility or transportation infrastructure, and changes in visitor use patterns such as bus tours (Lime et al. 1995).

Many studies have attempted to document perceived levels of crowding. Shelby et al. (1989) reviewed 35 studies in the United States and New Zealand that used the same single measure of crowding (rated along a nine-point scale ranging from not at all crowded to extremely crowded). The studies had a wide range in levels of perceived crowding by recreationists from 17 percent of goose hunters experiencing crowding on the Grand River Marsh in Wisconsin to 100 percent of boaters experiencing crowding on the Deschutes River in Oregon. The review also noted that increased crowding appears to vary by time and season of use (e.g., holidays and summer), resource abundance or availability (e.g., opening day of fishing season), resource accessibility or convenience (e.g., near population centers), and management actions (e.g., management restricting density) (Shelby et al. 1989). Understanding perceptions about crowding and recreation satisfaction is important. Studies suggest that when water-based recreation participation at a site exceeds a certain level, the quality of the recreation experience is reduced. An unacceptable level of crowding has the potential to drive recreationists to seek alternative forms of leisure activities.

Research Needs on Conflicts Over Water Use

What role can the PNW Research Station play in assisting to resolve conflicts over water use? Although many of the conflicts that occur over competing demands for scarce water resources occur outside the jurisdiction of managers responsible for water resources on federal forest lands, there are several fruitful areas of research that PNW scientists can address to aid in resolving water-related conflicts. Some of the most promising topical areas include the following (priorities are H = high, M = moderate, L = low):

- Improving understanding of how changes in public values for water affect public use and the effectiveness of water and land management. (H)

- Economics research to evaluate tradeoffs and develop solutions related to the allocation of water among competing and conflicting uses of scarce water resources, and to encourage water conservation. (H)
- The most effective use and development of collaborative efforts (e.g., watershed and basin advisory groups) to resolve basin-scale conflicts on water allocation and use. (M)
- Research to reveal relations between water use and resource management and water-based recreation. (M)
- Contributing to the development and evaluation of programs and policies for allocating water among users. (M)
- Developing improved techniques for measurement and utilization of water-based recreation use trends. (M)
- Promoting water conservation by enhancing public understanding of water resource concerns and tradeoffs through development of educational strategies and opportunities for mutual learning. (L)
- Evaluation of benefits and costs to participants in watershed stewardship, restoration, and education activities. (L)

New and Existing Tools and Solutions for Sustainable Water Use

An array of existing, new, and emerging tools is available for management of water resources. However, additional tools may need to be developed and existing tools fully implemented to respond to the complex problems facing water resource managers. Water allocation and management has become increasingly complex in response to various societal changes; population growth and distribution; the growing pluralism in the values and uses associated with water; and the complex, often contentious political and legal context within which such resources are managed. Despite the fact that strong public sentiment exists in support of many water resource uses, we have a limited capacity to thoughtfully balance competing demands or to fashion appropriate management programs and policies. Thus, in this section, we discuss some of the principal challenges confronting managers, scientists, and citizens as we strive to attain sustainable management of water quantity and quality.

At the core of the challenge facing society is the question of how we can make improved, rigorous, and informed choices about resource management in general, and about management of the water regime in particular, and what new or existing tools are available to guide the process. Political scientist John Dryzek (1987) has identified seven basic institutional forms, each a potential water management tool, through which society structures its choices. These include markets, centralized administration, interest group politics, legal regulation, moral persuasion, small-scale institutions, and collective violence. Lee and Stankey (1992) expanded on Dryzek's discussion, with particular emphasis on the link between these various institutional forms and watershed management.

Markets involve the use of prices as a way of coordinating behavior among individuals. One strength of markets is that they have a decentralized structure with potential for affecting ecological processes at large geographic scales; however, this potential is often not realized because of inadequate attention to creating incentives that would channel independent initiatives in ecologically sustainable ways.

Centralized administration involves formal organizations, such as the Forest Service, with a hierarchical command-and-control structure. Such structures are a common part of the current natural resource management landscape and achieve agreed-on purposes through the exercise of regulation and policy. They are particularly well suited to situations in which there is a relatively high level of agreement on goals.

Interest group politics involve competition and bargaining among independent groups with particular interests. Such groups have always been an essential part of the U.S. political scene, but they have become particularly noteworthy in recent years, as they have sought various ways of advancing their particular agendas. Given the highly pluralistic nature of uses and values associated with water resource management, a diverse spectrum of interests strives to gain attention and influence in the policy and management process.

Law involves formal rules promulgated and enforced by a binding authority. In the U.S. representative form of government, these rules have high levels of legitimacy, buttressed by our constitution, an array of statutes adopted by legislative bodies, and the judicial interpretation of those rules by the courts.

Moral persuasion seeks to control individual behavior by eliciting conformity to certain aspirations and beliefs. Perhaps one of the best examples in the natural resources field has been the exhortation of Smokey the Bear that "only you can prevent forest fires!"

Small-scale institutions involve decentralized and local structures through which people attempt to more directly influence policies and actions that influence them and their communities. In the water management field, there are many examples of such institutions, such as the basin and watershed advisory groups.

Finally, collective violence represents the response when other institutional structures are seen as having failed or when they are seen as unresponsive or inaccessible to other interests. The history of water resource development, especially in the West, reveals many cases where violence became the principal means of effecting change and of asserting one's interests.

Two observations can be made from this brief review of basic institutional structures and processes. First, a relatively diverse set of tools and approaches exists that could be used to manage water resources. Although the techniques of markets (pricing), laws, and administrative regulation receive the most attention, other approaches may hold promise; for example, we have seen increasing interest in the role of small-scale institutions in recent years. Second, as Lee and Stankey (1992) have discussed, each of these approaches has major limitations and shortcomings; for example, many emerging values associated with water lie outside the marketplace, thereby constraining the utility of efforts to use pricing to guide allocation and management decisions. Large-scale administrative systems are ill equipped to resolve the site-specific, particularistic, and idiosyncratic nature of many of the ecological problems that confront us today; this is becoming apparent in efforts to apply the standards and guides of the Northwest Forest Plan in a universal manner.

One response to this situation is to search for ways in which different structures might be combined to offset their respective shortcomings. The efficiency, effectiveness, and equity of individual approaches could probably be enhanced through such measures, but we have limited experience in such joint approaches. Moreover, in examining the various approaches against a set of five evaluative criteria (do they provide for **negative feedback** [learning], do they facilitate **coordination**, are they **robust**, are they **flexible**, and are they **resilient**), Dryzek (1990) concludes that "any 'winner' among the seven types of social choice would then be little more than the best of a poor bunch."

This might be an overly harsh assessment, but it does suggest that we need to continue to search for innovative and creative institutional structures and processes to deal more adequately with the complex issues surrounding resource management. In the following discussion, we examine some traditional approaches and tools as well as some more innovative approaches that are being tested.

Political and Legal Tools

Water law—Numerous federal and state laws currently exist for managing water resources in the Pacific Northwest (see app. 2). The oldest, and perhaps most important, is the doctrine of prior appropriation (see "Executive Summary"), which needs recon-ciliation with changing social values and other state and federal laws for water management. Given the current slate of these laws, states in the Northwest have been unable to balance allocation and adjudication of water to meet the region's needs. New methods or tools for maintaining the integrity of existing water law while integrating the requirements of federal laws, like the ESA, are needed to resolve social demands for balanced water management and maintenance of instream flows for ecological purposes.

Reconciliation of water-related state and federal laws has not yet been achieved. Federal agents responsible for enforcement of the ESA assume that state-certified water rights may be reduced or eliminated by federal law to accommodate Section 9 on "takings," and the Supremacy Clause of the U.S. Constitution indicates that federal regulation may override conflicting state laws. Historically, however, Congress has traditionally deferred to state law on water rights. Even Section 2(c) of the ESA contains language with deference to state water rights. In any case, no federal court has explicitly ruled on enforcement of the ESA Section 9 usurping state-certified water rights (Oregon Water Resources Congress 2000).

Other issues complicate interactions between the ESA and state water law. Oregon and Washington recognize water rights as property, therefore under the Fifth Amendment, they cannot be taken by the federal government without "just compensation." Consequently, enforcement of Section 9 of the ESA to achieve minimum instream flows to protect aquatic species, if supported by the courts, could be costly to the federal government.

Clearly, legal and social tools are needed to address the unresolved issues between state and federal laws. Social precedents have been established to address such conflicts over water allocation and use. Coalitions of user groups working in river basins across the Northwest seek to cooperatively solve water problems. The various watershed and basin advisory groups operate under various memoranda of understanding and cooperative agreements. Some groups make progress on difficult water issues without resolution of discrepancies between state and federal laws. The coalition user groups appear to be a potentially powerful water management tool that is currently under development (see "Social Tools").

Forest Service land use planning rules—Recent changes in the Forest Service land use planning rules provide a tool to improve water resource management on national forests. For the past three decades, national forest planning has been conducted primarily under the umbrella of the NFMA (16 USC 1600-164) of 1964 and the NEPA (P.L. 91-190) of 1969. During the past two decades, forest planning has become more complex and contentious as the agency and an informed public addresses difficult issues such as resource sustainability. Consequently, a new planning rule that proposes additional focus on water resources has been developed (Federal Register 2000) to improve ecological sustainability of national forest resources.

The sections of the rule that address ecological sustainability will require managers to consider how proposed actions might affect essential attributes of water regimes related to function, patterns, processes, and quality.

Clean Water Act and total maximum daily loads—Provision 303(d) of the Clean Water Act (P.L. 95-217) requires that the states develop a list of streams and lakes with impaired water quality and resulting beneficial-use restrictions. The states are subsequently required to develop pollution load allocations for the impaired water bodies, implement the allocations, and eventually restore the impaired water bodies to full beneficial use. Plans for implementation of pollution allocations, known as total maximum daily loads (TMDLs), must be approved by the Environmental Protection Agency. Implementation plans must include planned actions, implementation dates, and monitoring plans to assess progress toward recovery. Oregon, Washington, and Idaho have completed lists of impaired water bodies, and are currently developing TMDLs and implementation plans for each listing. The TMDL process provides a potentially powerful tool for restoring water bodies degraded by water pollution.

Federal Energy Regulatory Commission Relicensing Program—In the mid-20th century, the Federal Energy Regulatory Commission (FERC) licensed many of the dams built in the Pacific Northwest. During the next decade, at least 50 dams built on national forests of the Northwest will require relicensing. Original licenses were based primarily on comparison of the benefits of potential hydropower production, weighed against a narrow range of other (nonpower) values. Although the facilities provided many societal benefits, their operations also have had adverse effects on some national forest resources. The Forest Service will play an important role in relicensing because it has binding statutory authority and responsibility from the Federal Power Act to stipulate conditions FERC must include in new licenses (Sedell et al. 2000).

Relicensing by FERC provides an important opportunity for reevaluating the role of many dams on national forests in the Northwest. It also provides an opportunity to bring their operations into balance with current ecological, social, and economic values in the region. Participation by the Forest Service in the relicensing process could strengthen mitigation and restoration programs on national forests, resulting in benefits to recreation, aquatic habitats, and water quality (Sedell et al. 2000) potentially exceeding $1 billion.

Forest Service land exchanges—The Forest Service maintains an active land exchange program that acquires or exchanges lands to benefit the national forests. Land exchanges are often initiated to consolidate national forest boundaries or to acquire important fish and wildlife habitats. Future land exchanges could be used as a tool for acquisition of water resources for various social and ecological purposes. Water-related land exchanges could benefit recreation, maintain instream flows for aquatic species recovery, and provide other specific benefits for aquatic and riparian ecology.

Inclusions of private land within the boundaries of national forests often consist of large low-gradient stream valleys used for agriculture or rural residential purposes. These streams may be in locations where they are surrounded by good-quality aquatic habitats on national forest land. Such streams, if acquired by the Forest Service, could make key contributions to refuge systems for recovery of endangered salmonids or other equally important purposes.

Economic Tools

Accurate price signals reflecting the true value of natural resources and their use can be essential to their sound management. When markets fail to provide correct price signals, economic incentives can be used to adjust the effective prices of natural resources to attain environmental goals and targets in a cost-effective manner (Baumol and Oates 1988, Tietenberg 2000). The goal of any incentive program is to modify existing market conditions to reflect the true scarcity or value of a good or to reflect the damages caused by excessive use of a good. For water, economic incentives might include price controls, such as taxes and subsidies, and quantity controls that identify clear property rights to water by using marketable permits or transferable quotas that can be traded in water markets. Both approaches can be used as management tools to encourage both conservation and water quality improvements (Crase et al. 2000, Lovell et al. 2000, Weinberg and Kling 1993, Yoskowitz 1999). Well-designed economic incentive programs targeted toward specific individuals or firms often preclude more expensive prescribed command and control actions mandated by water management agencies.

Taxes and subsidies—Taxes and subsidies are used to adjust the price of a good to either encourage or discourage its use to obtain a desired level of use. A well-designed tax essentially raises the price of a good by an amount equal to the external costs associated with use of the good not accounted for in the market place. For example, water managers might impose a tax on water use that reflects the marginal damage associated with negative externalities such as water pollution or loss of fish habitat. Because such a tax would essentially increase the price of water, users would be encouraged to conserve. Subsidies work in the opposite way, by reducing the price of a good to encourage its use. For example, policymakers might subsidize investments in water-saving technologies, such as more efficient appliances, to encourage their use. Subsidies might take the form of direct transfers of money, tax rebates, or low-interest loans. Because subsidies decrease the price of water-saving technologies, potential users would be encouraged in their use.

Tietenberg (1990) and Ekins (1999) provide several examples of the use of taxes and subsidies, most of which are from Europe. For example, emission charges for effluent are being used to control water pollution in France, Italy, Germany, and the Netherlands. The design of such programs can be altered to achieve equity goals as well as use or discharge goals. In Germany, for example, dischargers are required to pay a fee on every emissions unit. However, if dischargers meet or exceed effluent standards, they pay only half the normal discharge fee, effectively rewarding those dischargers who meet or exceed standards. Many countries use the revenue generated from such fees to fund improvements in water quality, subsidize installation of pollution reduction equipment, and compensate victims harmed by pollution.

Water markets, marketable use permits, and transferable quotas—The absence of clearly defined property rights in natural resource use often is one source of externalities (Baumol and Oates 1988). For water, externalities often are associated with overuse of water or declines in water quality. The absence of clearly defined property rights for water via ownership or rental agreement has meant that historical priority and allotments, rather than prices, have determined water use (Dales 1968, Weinberg and Kling 1993). As a result, water typically has not been allocated to those uses of highest value nor has it been used conservatively. One way to encourage more efficient use of water is to establish clearly defined property rights that can be freely traded among water users in open markets. Water markets enable the price of water to be determined in the marketplace and results in an allocation of water to its highest and best use.

Early definitions of beneficial uses of water under the prior appropriation doctrine, in combination with subsidized water projects designed to induce development in Western States, have contributed to wasteful water practices, environmental degradation, overcapitalization of marginal agricultural lands, and have exacerbated water shortages (Graff and Yardas 1998). In recent years, however, many Western States have redefined beneficial uses of water to include instream uses, enabling water rights to be purchased specifically for maintaining instream flows. This change in policy encourages greater conservation of agricultural water for instream uses and allows opportunities for water markets to emerge. These water markets have in turn allowed for the reallocation of scarce water resources via voluntary, compensated transfers in the marketplace rather than by regulatory or judicial intervention (Graff and Yardas 1998).

One of the major purchasers of water rights for instream uses has been the U.S. government. For example, in 1990, Congress authorized $11.7 million for the procurement of agricultural water rights for wetland restoration in the Lahontan Valley of Nevada, which is home to the Stillwater National Wildlife Refuge, Stillwater Wildlife Management Area, Carson Lake, and Fallon Tribal Wetlands. These wetlands are important stopovers on the Pacific Flyway (Lovell et al. 2000). In another example, Congress allocated $0.5 million to transfer senior water rights from the Little Applegate River in Oregon to Applegate Lake to improve fish habitat. The river provides habitat for various fish species including steelhead, chinook, coho, cutthroat and rainbow trout (*O. mykiss*), and Pacific lamprey. States and municipalities also purchase water rights to protect ecologically important wetlands and other aquatic habitats.

Combining economic incentives—Often a combination of economic incentives can be used. For example, the Broadview Water District in the San Joaquin Valley of California used a combination of three economic incentives to motivate improvements in irrigation practices among farmers to reduce agricultural drainage water (Wichelns et al. 1996). The first incentive involved issuing water allotments (or rights) to farmers based on their land within the district. These rights could be traded among users so that farmers not using all of their water allotment are able to sell it to others, thus creating an incentive among farmers to conserve water.

The second incentive involved implementing a crop-specific, tiered water-pricing program. The price of water was based on historical water deliveries that reflected the evapotranspiration, leaching requirements, and cultural treatments associated with different crops. The first tier allowed farmers to purchase water at the usual price. However, if farmers exceeded 90 percent of historical water applications for a particular crop, all water above that level would be charged about 2.5 times the usual price.

The third economic incentive involved implementing a subsidy for investing in improved irrigation technologies. Funds provided by the California State Water Resources Control Board and money collected from the tiered pricing program allowed the water district to offer low-interest loans to farmers willing to invest in water-saving irrigation systems. The subsidy enabled farmers who were not growing high-value crops to overcome the financial constraints associated with converting to more expensive water-saving irrigation systems.

Irrigation and drainage data collected in the Broadview Water District during implementation of the three economic incentive programs suggest that the district was successful in motivating farm-level improvements in water management and in reducing drain water volume (Wichelns et al. 1996).

Social Tools

The conflicts and challenges confronting water resource management are similar to those facing other natural resources. At their core, the problems are deeply grounded in competing values and uses. Multiple parties seek to attain different, often conflicting agendas, and the presence of a high order of pluralism in values and interests means it is difficult to agree on goals, let alone objectives. Scientific and technical understanding, although important, may be of limited value in resolving these problems because political and social factors may constitute overriding concerns.

As a result, interest in innovative alternatives to addressing such problems increases. For example, a variety of techniques and approaches often referred to collectively as alternative dispute resolution (ADR) have emerged; they share a reliance on more formal use of collaborative problem-solving techniques as a means of resolving a specific conflict (Wondolleck and Yaffee 2000). Collaboration is an encompassing notion; Wondolleck and Yaffee (2000), citing the work of Gray, define it as “(1) the pooling of appreciations and/or tangible resources, e.g., information, money, labor, etc., (2) by two or more stakeholders, (3) to solve a set of problems which neither can solve individually.” Such arrangements, which rely on links among players, can take many institutional forms, ranging from formal and complex, to informal and simple.

Various dispute-resolution techniques can be brought to bear on natural resource conflicts including binding arbitration, facilitation, mediation, and nonbinding arbitration. These assisted negotiation techniques differ primarily in the level of responsibility that the facilitator has over the process and in the level of obligation to accept the outcome (Susskind and Cruikshank 1987). Binding arbitration has the highest level of obligation; however, it is of limited use in many natural resource disputes because public officials are often not allowed to relinquish their authority to an arbitrator. The other three types of assisted negotiation differ primarily in the role of the facilitator or mediator. The choice of assisted negotiation technique used often will depend on the level of conflict and complexity of the natural resource issues under dispute.

However, the current limited understanding of the utility of collaborative solutions presents a problem for their use. Identification is needed of the types of issues for which various ADR approaches are best suited and the conditions under which they are most effective. For example, the extent to which potential participants feel they can attain more of their goals through conventional means (e.g., litigation) may limit the use of ADR techniques. Each party must believe that the negotiations will give them the opportunity to exceed their best alternative to a negotiated agreement or they will not become involved in the negotiation process (Fisher and Ury 1981). As a result, consensual approaches are only likely to be effective where all disputing parties believe that they can achieve more at the negotiating table than from other methods.

The concept of collaboration has attracted much attention. For example, the concept is a central element of the proposed new Forest Service planning rule; it identifies collaboration for sustainability as the heart or essence of the new planning process. The proposed rule suggests seven key principles to guide implementation of a collaborative approach: (1) building relations and trust; (2) early, continuing, and appropriate inclusion; (3) up-front agreement of roles, authorities, and processes; (4) shared leadership; (5) development of a common base of science and other information; (6) open communication, conflict management, and explicit recognition of barriers; and (7) learning and organizational capacity building. In summary, this new model of community and collaborative governance, which is focused on watershed-related management issues, places a high level of reliance on positive incentives, partnership arrangements, intergovernmental integration and coordination, and an explicit commitment to ad hoc, consensus-based decisionmaking processes based on field-level experimentation and learning (Kenney 2000).

Collaborative approaches are not without their critics and skeptics. For example, the Southern Utah Wilderness Alliance (1994) has argued that “consensus works only when there is some basis of agreement to begin with; it does not work if participants are coming from diametrically opposing viewpoints,” a situation that is not uncommon in disputes over water resources, as well as many other natural resources. McCloskey (1996), after reviewing work underway by the Applegate Partnership in southern Oregon, commented that “it is also troubling that [collaborative] processes tend to de-legitimize conflict as a way of dealing with issues and of mobilizing support.”

The debate about the relative merits of collaborative and consensus-building approaches requires increased attention. However, interest in such approaches can be traced, in part, to the growing sense of disappointment in the performance of traditional societal choice mechanisms (Dryzek 1987). Clearly, several important issues remain to be resolved. What structural conditions of dispute make collaborative approaches most appropriate and effective? What kinds of criteria might be used to assess their performance? How can a better sense of their relative costs and benefits be acquired? Moreover, there is an opportunity for synthesis-level work designed to assess the performance of community, collaborative, and cooperative management programs undertaken in other parts of the world. For example, there is an extensive body of experience associated with implementation of the Landcare program in Australia. Landcare emerged in the mid-1980s as a community action model involving governments, farmer organizations, and conservation groups. The program had its origins in growing concerns among many parties about the impact of water quality decline, ground-water salinity, and erosion and the need for new institutional structures to more effectively respond (Curtis et al. 1995). That experience in collaborative structures and processes might hold particular relevance for efforts in the Northwest to implement basin and watershed advisory groups.

Particular interest exists in developing new approaches to fostering improved public understanding of complex natural resource management issues. The need to do so is given particular emphasis by what has been described as the technical information quandary. That is, “How can the democratic ideal of public control be made consistent with the realities of a society dominated by technically complex policy questions” (Pierce and Lovrich 1983)? Throughout this report, we stress that a key role of science is to provide an informed understanding of relations, consequences, and options; however, such understanding must be revealed in ways that facilitate informed public discussion and debate. All too often, however, only limited venues exist in which such discussion and debate can occur. As Yankelovich (1991) noted “our society is not well equipped with the institutions or knowledge it needs to expedite **working through**.” By “working through,” he means venues where the kind of thoughtful discussion about such issues as sustainable water management can be undertaken in an informed, deliberative manner. A key feature of such settings is that not only do they facilitate the flow of technical and scientific information to people, but they also provide for open discussion of values and interests, because the goal is integration of technical and scientific knowledge with experiential knowledge held by people who live, work, and recreate in the environmental settings in which we are interested.

In addition to forums for “working through,” processes that use citizen science, and participatory monitoring and evaluation programs, also are ways to engage the public in the learning process (Krueger and Shannon 2000). Examples of this type of learning include the Coastal Observation and Seabird Study Team (COASST 2001), and People for Salmon, a Puget Sound nongovernmental organization (People for Salmon 2000). Each conduct volunteer programs for monitoring seabirds along the Washington and Oregon coast and salmon habitat restoration.

In short, some promising avenues exist for implementing new social tools for more effective water resource management. However, there is a pressing need for more thorough monitoring and evaluation of these efforts to gain a better sense of the conditions under which they are most effective (or not) and how their performance can be evaluated.

Basin advisory groups and watershed advisory groups—Coalitions of user groups have in some cases been more successful than states in working toward resolution of water conflicts at the basin scale. The Deschutes River Basin Conservancy (DRC) provides a successful example from Oregon. The DRC, a 14-member coalition representing all economic sectors in the basin, was formed in 1992 to address water-related conflicts. They developed an assessment of basin resources, incentive-based approaches to addressing resource problems, and pilot projects to improve efficiency of agricultural water use. Half the water saved was dedicated to maintenance of instream flows and the remainder went to farming operations (Western Water Policy Review Advisory Commission 1998). The group also leased water for instream flows.

The DRC is now a formally chartered, private corporation with a board composed of the basin's ranching, agricultural, environmental, recreational, tribal, hydropower, and land development communities; 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. Other precedent-setting coalitions of water users are working to solve water-related problems in the Methow Valley of Washington and the Walla Walla basin in Oregon and Washington.

Interagency collaboration—Some water pollution issues are being addressed more effectively through interagency collaboration than any single agency could accomplish alone. For example, a program to remediate water quality problems associated with abandoned mine lands is being tested as part of a USGS Initiative. The U.S. Department of the Interior, Geological Survey, in coordination with the Forest Service, Bureau of Land Management, and National Park Service, is developing a strategy for gathering and communicating the scientific information needed to formulate effective and cost-efficient remediation of abandoned mine lands. The initiative will use a watershed approach to identify, characterize, and remediate contaminated sites having the most profound effect on water and ecosystem quality within a watershed. The initiative began in 1997 and will conduct pilot tests in two watersheds in Colorado and Montana through 2001. Interagency collaboration on abandoned mine lands is necessary because the magnitude of the problem and costs to remediate degraded water quality are so great. The Environmental Protection Agency (1996b) estimates that decades and billions of dollars will be required to identify and reclaim every site where mining has occurred.

The Watershed and River System Management Program (WARSMP) represents another form of interagency collaboration. It is a long-term collaborative project between the U.S. Department of the Interior, Geological Survey and the U.S. Bureau of Reclamation. Testing of the program began in the Yakima basin in 1997. The goal of the program is to couple watershed and river-reach models that simulate the physical hydrological setting in the basin, routing and reservoir models that account for water availability and use, and reach-specific hydraulic and biogeochemical models conditioned on upstream streamflow (U.S. Department of the Interior, Geological Survey 1999). Their coupled models are then applied to operation of U.S. Bureau of Reclamation projects in the basin. The project provides a database-centered decision-support system (DSS) for use by WARSMP and other projects to manage basin water resources.

The key to coupling the models is linking them through a common hydrologic database. In the DSS, output from one model can be written to the hydrologic database for use as input to another model. The coupling, interaction, and other capabilities in the DSS allows for improved assessments of long-term planning and policy decisions, in addition to the major program thrust of improving short- and mid-term operations, scheduling, and planning decisions for U.S. Bureau of Reclamation projects. A potential opportunity exists for other federal and state agencies to participate in the program and contribute to development of the common database and the models used to drive WARSMP. Such participation could make the program more robust for future basin-scale management of water resources.

Education and learning—In addition to efforts to enhance water supplies, reduce consumption, and enhance efficient utilization through technology, other important opportunities exist to reduce consumption through public education. Such efforts would focus not only on improving understanding of what needs to be done but also on why and how. Developing improved public understanding of such basic notions as the hydrological cycle, for example, could help improve public understanding of the importance of protecting vegetative cover.

At present, little basic descriptive information exists about the level of public understanding of water resources. This knowledge is a necessary precursor to any effort to design an educational program. However, designers of such programs should recognize that the mere presentation of a body of facts does not build understanding. In other words, improving public understanding of water resource management requires more. Rather, we need to focus on creative efforts designed to promote mutual learning, involving citizens, managers, and scientists. This is often best accomplished through on-the-ground and learn-by-doing approaches in various settings.

Although public opinion polls reveal that most people in the United States are concerned about environmental issues (Dunlap et al. 1993), these attitudes are not translating to increased environmental behaviors by the public. This suggests that although changing attitudes might be one important aspect of behavioral change, by itself, it is not an adequate indicator of behavioral change in the target audience. In a review of educational research studies, Zelezny (1999) noted that some educational interventions, both in nontraditional settings (e.g., workshops and nature camps) and particularly in classrooms, were found to improve environmental behavior, especially when participants were actively involved in the program. However, methodological flaws limit these findings. Most studies examined only the self-reported behaviors of subjects as opposed to observed behaviors, and there is some indication that self-reported behaviors do not reflect actual behavioral changes.

To be most effective, information campaigns need to influence the social norms people hold toward certain behaviors (Bright 1994). Other techniques, such as distributing rewards (e.g., incentives) or punishments (e.g., taxes), are often only effective as long as the system is in place. Without an underlying change in norms, people can be expected to return to old behaviors as soon as the incentive or tax structure is removed. One difficulty with many current efforts to influence public behaviors is that people remain unaware of the true consequences of their choices. Ehrenhaldt (1994) argued that for people to make rational choices, they needed to be given alternatives. For water management, the link between energy consumption and salmon habitat should be clear so that people can see that one consequence of poor energy conservation could be declining salmon populations. Not only must people understand the consequences of traditional behaviors, but alternative behaviors (e.g., recycling, water or energy conservation) must be readily accessible if people are to increase their participation in an environmental behavior (Nyamwange 1996).

Technological Tools

The development of technological tools for management and conservation of water resources has advanced rapidly in the United States over the past two decades. Various new and emerging technical tools are currently being used to assist with resolution of water-related problems in Pacific Northwest river basins. Some of these tools are widely accepted and broadly applied, whereas others are still in experimental phases. In either case, the key to successful application of technological tools is that they fit within current socially acceptable and economically feasible paradigms for water management.

DNA fingerprinting of pollution sources—Many watersheds with problems of bacterial pollution contain multiple potential bacteria sources, including storm water, agriculture, septic system drainage, treated wastewater effluent, and natural sources from wildlife. Until recently, if bacterial contamination (usually *Escherichia coli*) was detected in a watershed, the source was difficult to identify because of the complex of possible sources. The development of DNA fingerprinting has proven to be a powerful new tool that water-quality managers can use for identifying sources of bacterial contamination. The DNA analysis of *E. coli* bacteria can now determine if the source is from human fecal waste, livestock, other domestic animals, wildlife, or other sources (University of Idaho Cooperative Extension Service 1998).

Geographical information systems—Geographical information systems (GIS) are computer-based systems capable of assembling, storing, manipulating, and displaying geographically referenced information. The spatial location of data can be defined by using global positioning systems. Geographical information systems are both a data-based system and a set of operations for working with the data (Star and Estes 1990). These operations and systems make it possible to link, or integrate, information that is difficult to associate through any other means (USDI Geological Survey 2000).

Analysis of water resources has potential for many applications that use GIS. For example, GIS technology and water company billing information can be used to simulate the discharge of materials in the septic systems in a neighborhood upstream from a wetland (USDI Geological Survey 2000). The water bills quantify the amount of water used at each address and predict the amount of water that will be discharged into the septic systems. Maps with areas of heavy septic discharge can then be generated to assess source areas that pose particular risk to wetlands.

Another example of the application of GIS technology to water resources is the strong link between GIS and watershed analysis. Watershed analysis (see "Watershed Analysis") is a procedure for assessing the use or conservation of resources at a watershed scale. Displaying, integrating, and analyzing information on water and other resources at that scale is possible by using GIS.

Ecosystem management decision support—Ecosystem management decision support is a new application framework for knowledge-based decision support of environmental assessments. The system integrates state-of-the-art GIS and knowledge-based reasoning techniques to provide an analytical tool to facilitate resource analyses at any geographic scale (Reynolds 1999a, 1999b). The system, which can be applied to water-related issues and assessments, is still under development and is being tested in ecoregion-scale assessments in the United States.

Watershed analysis—Watershed analysis is a relatively new assessment tool that describes the processes and interactions that influence watershed resources and ecosystems. Watershed analysis has been used in Washington since 1993 to evaluate cumulative watershed effects (Washington Forest Practices Board 1993). It is currently mandated on federal lands of the Pacific Northwest for aquatic and terrestrial habitat conservation (FEMAT 1993) within the framework of the Northwest Forest Plan and is currently expanding broadly to land management planning across the United States. The analyses are scaled to watershed sizes that include relevant issues and interactions within the designated watershed.

Watershed analysis, coupled with GIS technology, has become a “cutting-edge” tool for land management planning. It is especially useful for addressing water-resource-based issues. A spatially explicit analysis system like GIS can be used effectively to integrate and analyze the biological, chemical, physical, and social processes that occur in watersheds, specifically the watershed processes that interact in diverse ways to determine transport of sediments, chemicals, and organic debris.

Forest Service roads analysis—Roads provide multipurpose access to forested landscapes of the West but also represent the largest individual source of accelerated sedimentation from forested lands. The Forest Service road network alone totals more than 616 000 km of roads (Coghlan and Sowa 1998), with the majority of road kilometers located in the Western United States. In the last decade, owing to the current reduction in timber harvest on federal lands in the West, the condition of roads and the funds available for road maintenance have declined. To accommodate the reduced need for roads in the existing road network, the Forest Service initiated a new road policy in 1997. One feature of the policy is a new tool, roads analysis, designed to help managers prioritize needed changes in their road systems (U.S. Department of Agriculture, Forest Service 1999). The new roads analysis tool is a six-step integrated ecological, social, and economic approach to transportation planning addressing both present and future roads—including those planned in unroaded areas. The analysis is scalable, flexible, and driven by geographically relevant road-related issues important to the public and to managers. The procedure is intended to integrate existing laws, policies, guidelines, and practices into the analysis and management of roads on the national forests. The essential goal of the analysis is to balance the needs for public access to the national forests with the ecological and environmental risks associated with road access systems. Implementation of the procedure began in 1999.

Outboard motor technology—Newer technologies in outboard engine design, and legislated dates for their implementation, may result in a much smaller discharge of unburned fuel, oil, and other chemicals in U.S. waters after 2004. However, increases in the number of motorboats could neutralize some gains from engineering technology. Recreational motor boating increased 40 percent from 1982-83 to 1994-95, with nearly 23 percent of the U.S. population participating in the activity in 1994 (Cordell et al. 1997). Furthermore, the fact that there were 13.2 million outboard motorboats owned in 1997 (National Marine Manufacturers Association 1997), more than almost any other year, indicates that increased efficiency of engines may not be enough to compensate for the absolute increase in motorboat numbers and the pollution they produce.

Development of common credible databases for water management—Relevant scientific information is a necessary component of any decisionmaking process. Currently, water managers and users in most Northwest basins need a common credible database to guide decisions on water management and allocation. Research information on Northwest water resources is developed by various organizations (see app. 1), but synthesis and integration of the information applicable to individual river basins is rare. Leadership and cooperation are needed to assure the availability of credible and commonly accepted databases for water management.

Forward-looking infrared radar—Forward-looking infrared radar is an emerging tool for assessing variations in the temperature of flowing waters (Faux and McIntosh 2000). The device is sensitive to changes as small as 0.5 °C and can be used to locate sources of thermal pollution on streams, or thermal refuges of value to salmonid survival when water temperatures generally exceed acceptable limits (McIntosh et al. 1994). In the Pacific Northwest, the technique has been used in the Grande Ronde River basin to locate and quantify favorable refuges for salmon during warm summer periods (Torgersen et al. 2001).

Erosion control—New tools are being used to control erosion, reduce sediment and turbidity in surface waters, and save valuable topsoil for agriculture. One emerging tool for erosion control is anionic polyacrylamide (PAM), an acrylamide polymer composed of long chainlike molecules (Sojka and Lentz 1996). The product is synthesized from natural gas and is used primarily to control erosion related to furrow irrigation.

Intensively tested in Idaho, PAM treatment of irrigation water is currently the fastest growing soil conservation technology in irrigated agriculture (Washington Department of Transportation 2000). It provides environmental benefits by halting erosion by about one-half metric ton of soil per 30 g of PAM applied. It also flocculates suspended sediment and aids in its deposition. More than 90 percent of sediment, phosphorous, and pesticides from agricultural return flow is removed by PAM, and it greatly reduces return flow biochemical oxygen demand (Sojka and Lentz 1996). Twenty thousand hectares of furrow-irrigated land received PAM in 1995, the first year of commercialization, halting an estimated 0.9 million Mg of erosion.

The Washington Department of Transportation (DOT) also is using PAM to stabilize soils and remove fine suspended sediment from stormwater runoff at highway construction sites (Washington Department of Transportation 2000). Washington DOT notes that “sediment lost from construction sites can pollute streams and lakes, fill reservoirs, cover and destroy fish-spawning beds, and reduce the overall quality of water for subsequent beneficial use.” Land management agencies also might consider use of PAM to control erosion from roadside ditches.

Research Needs on Tools for Water Management

What role can the PNW Research Station play in development and refinement of new and existing tools and solutions for sustainable water use? Some potentially productive areas include the following (priorities are H = high, M = moderate, L = low):

- Contribute new and synthesize existing scientific information for planners involved in the FERC licensing and relicensing processes. (H)
- Develop protocols for identifying, measuring, and evaluating social tradeoffs between the causes and consequences of altered flow regimes (e.g., conflicts between different types of recreational activities). (H)
- Review the effectiveness of watershed analysis in informing planning for land management. (H)
- Evaluate the effectiveness, cost, and equity implications of implementing social and economic tools and strategies for allocating water and encouraging water conservation. (H)

- Participate in developing scientific information and decision support for watershed and basin advisory groups, and interagency groups coordinating water management at the large watershed or basin scale. (M)
- Test and evaluate mechanisms for improved interagency interactions and coordination on water issues. (M)
- Evaluate alternative processes and models for watershed management and advisory groups designed to better manage conflict, create and disseminate knowledge, and undertake local implementation efforts. (M)
- Provide leadership in the development and coordination of common databases. (M)
- Conduct research on the effectiveness and environmental effects of biological and chemical tools for erosion control on forest roads (including, e.g., PAM). (L)
- Conduct research on various assisted negotiation techniques (e.g., facilitation, mediation, nonbinding and binding arbitration) for resolving natural resource conflicts. (L)

Pacific Northwest Research Station Water Resources Research

The PNW Research Station has been broadly involved with water-related research for decades. Primary areas of focus have been forest and range hydrology in undisturbed landscapes, the effects of human and natural disturbances on the hydrology and slope stability of forests and rangelands, and the interactions among forest and rangeland management, water, and fish habitats. Since the 1970s, the Station has published nearly 1,000 papers on these subject areas. The research results have been extensively used to guide forest and range management in the Pacific Northwest, as well as nationally and globally where the results were applicable.

Some of the results of the Station's water-related research have been integrated with related research results from universities and other agencies in synthesis papers, books, and symposia (see for example, Krygier and Hall 1971, Salo and Cundy 1987, Stouder et al. 1997, Ziemer and Lisle 1998). No comprehensive attempt has been made, however, to integrate, synthesize, and interpret the results of the Station's water-related research within a single document. Such an effort, while beyond the scope of this synthesis, might provide new insights from the existing body of information and help guide future hydrologic and aquatic research by the PNW Research Station.

The Station's current water-related research program is diverse, extensive, and includes more than 60 studies spanning all seven of the Station's research programs. Studies that are currently active address a variety of topical areas and scales ranging from microsites to river basins. A brief topical summary of the studies is listed below.

Aquatic ecosystem assessment and monitoring:

- Develop an efficient, repeatable, and defensible system for stream channel assessment to address aquatic habitat monitoring, restoration needs, and identification of high-risk habitats.
- Develop an efficient, repeatable, and defensible method to monitor sedimentation from roads.
- Establish landscape indicators of watershed condition as measures of aquatic and riparian ecosystem integrity.
- Develop methods for assessing risks to water resources posed by specific roads, or segments of roads, at the national forest and watershed scales.
- Develop aquatic ecosystem classifications for watershed analysis and management.

Aquatic ecosystem structure and function:

- Determine the dominant processes that form aquatic habitats; assess how the processes differ in time and space and how they are affected by land use.
- Define the role of disturbance in creating and maintaining freshwater habitats for anadromous salmonids.
- Assess and interpret the biological and geomorphic consequences of large floods on stream channels.
- Establish the mechanisms responsible for forming and maintaining mountain stream step-pools through field, flume, and modeling studies.
- Examine the effects of windthrow on stream water chemistry in southeast Alaska.
- Continue to analyze the evolution of large woody debris in 3rd- and 4th-order streams in new-growth riparian forests (1949-2000).
- Establish the dynamics of woody debris and sediment in headwater streams.
- Determine the influence of marine nutrients from salmon on stream ecosystems.
- Examine trophic processes regulating aquatic productivity.
- Examine the role of terrestrial invertebrates in aquatic food webs.
- Compare the characteristics of stream systems by using 1:100,000- and 1:24,000-scale contour maps.

Economics:

- Synthesize literature on reporting and evaluating economic tradeoffs among competing water uses, in view of demographic shifts and other demand factors.

Fish and amphibians:

- Determine the structure and function of amphibian and fish communities in headwater streams.
- Synthesize scientific information and assist the Independent Scientific Advisory Board for the Columbia Basin with salmon recovery in the Columbia basin.
- Monitor the recovery of fish and amphibian communities in the Mount St. Helens blast zone.
- Study the ecology of steelhead trout.

- Analyze the response of fish populations in transition zone habitats to upslope perturbations.
- Examine the effects of road culverts on fish passage.

Hydrology:

- Determine the geographic distribution of streamflow in the Willamette basin of Oregon; explain the observed patterns and processes and their management implications.
- Examine the hydraulic redistribution and partitioning of soil water by roots of specific plant species.
- Analyze hydroecological responses to current and changed precipitation patterns in Oregon.
- Improve methods of spatially representing convective precipitation by comparing point observations with satellite-derived precipitation information in eastern Washington and Oregon.
- Develop 48-hour mesoscale precipitation forecasts in real-time with the meteorological models at 4-km spatial resolution for Washington and Oregon, and at 12-km spatial scale for the Pacific Northwest.
- Develop a rain-on-snow algorithm to demonstrate the spatial pattern of potential floods in the Columbia basin.
- Develop a climate history of snow-free days to help define the spatial and temporal variability of fire seasons and water availability for soil and biomass moisture.
- Examine the role of permafrost, snow, rainfall, and atmospheric moisture on the drying and wetting patterns of forest floors in central Alaska.
- Establish a relation between watershed-level characteristics and in-channel conditions.

Land management and aquatic ecosystem interactions:

- Design silvicultural systems to be compatible with water quality, hillslope stability, and aquatic ecosystems.
- Examine the functional convergence in regulation of water use among temperate forest trees.
- Determine if landscape management can enhance major resource values, including fish. Establish links among land management, riparian stand composition, and aquatic habitats, including sediment and woody debris loading in headwater channels.
- Establish links between riparian forests and surface-subsurface water exchange (hyporheic zones) surrounding streams on public lands.
- Establish geomorphic and hydrologic responses to forest harvest activities through retrospective studies and modeling.
- Examine how roads in different hillslope positions produce and capture sediment during large floods.
- Determine the effects of dam removal on downstream channels through integrated geomorphic and ecologic studies.

- Establish geomorphic and ecologic responses of stream channels to altered flow regimes.
- Establish links among up-basin sediment production and transport, forest practices, reservoir operations, and downstream sediment and turbidity levels (as they affect municipal water supplies) in the Santiam, McKenzie, and upper Willamette watersheds of Oregon.
- Investigate the effects of streamside buffer widths and forest stand ages on aquatic and riparian vertebrate communities on the Olympic Peninsula in Washington.
- Analyze the effects of current alternative timber cutting methods on invertebrate and detritus transport from headwaters to downstream food webs and on woody debris.
- Determine the effects of past timber harvesting on stream productivity, and on transport of invertebrates and detritus in headwaters to downstream food webs by using retrospective studies.

Modeling:

- Model the dynamics of woody debris transport and deposition in rivers and streams of the Pacific Northwest.
- Develop a landscape model to explain interactions between mass soil movements, forest management, and stream channel networks.
- Develop models to demonstrate the long-term effects (up to 500 years) of large natural disturbances such as wildfire, floods, forest disease outbreaks, erosional processes, water production, and fish habitat formation in the Pacific Northwest.
- Refine and evaluate a continental-scale biogeography model. The model contains hydrologic modules and will be used to assess ecological responses to global warming.
- Contribute to developing a fully coupled biosphere-atmosphere model that will include a processed-based hydrology model.
- Assess impacts of changing climates on hydrology and vegetation in small watersheds in Oregon, Washington, and Montana, through modeling.
- Improve the links between generalized vegetation and watershed hydrology models to achieve improved simulation of ecosystem structure.
- Develop a spatial database of atmospheric temperature inversions at 5-km scale for the United States to help identify variable stream temperatures.
- Develop a spatial database of surface wind at 5-km scale for the United States to help determine evaporation rates of surface moisture.
- Improve an orographic precipitation model and apply it with varying wind regimes to develop a climate history for the Olympic Peninsula.

Recreation:

- An integrated framework for assessing and evaluating recreational uses of water.

Current water-related research in the PNW Research Station is a multimillion dollar multiprogram effort addressing an array of research topics. Because large portions of the Station's resources are devoted to water-related research, an annual Station-level interprogram review of studies would provide improved coordination of current work, a sharper focus for future work, and economic efficiencies in research funding. Current staffing and funding within the Station preclude simultaneously addressing all potentially productive high-priority research topics. Coordination meetings could facilitate selection of the highest priority research topics and the most appropriate staff and funding levels to address those topics.

Although additional research in several individual subject areas is needed, one of the particular strengths of the PNW Research Station is its comparative advantage over other research organizations in coordinating large teams of scientists conducting research that integrates across a broad range of scientific disciplines. Studies such as the interior Columbia basin assessment (Quigley and Arbelbide 1997) and the Coastal Landscape Analysis and Modeling Study (Spies et al., in press) are two examples of such work.

The PNW Research Station is currently positioned to contribute significantly to future resolution of water issues on forested watersheds and to participate in resolution of issues in downstream waters. All of the Station's research programs are actively involved in water-related research and are poised to initiate additional research on social, economic, hydrologic, and ecologic aspects of the Northwest's emerging water issues.

Conclusion

Human attempts to manage water resources for societal benefits date back to the earliest historical records. Archaeological evidence indicates that the fortunes of early civilizations often were linked to the skills with which they managed water for agricultural and domestic use. Some of the water management problems encountered by early civilizations such as salinization, water-logging of irrigated lands, and climatic changes owing primarily to natural events, persist today.

Although evidence of development and use of water resources date back to the earliest civilizations, problems with water management have become more widespread in modern times. Much of the developing world faces shortages of water for domestic use, sanitation, and agriculture into the 21st century. Major problems with water availability and use currently occur on every continent and are often exacerbated by geographic disparities between the source of water and the location of its use. Problems with the uneven distribution of water resources in relation to human populations are also prevalent in the Western United States and the Pacific Northwest.

Drought conditions in the Pacific Northwest at the onset of 2001 and 2002 and throughout the Nation created possible effects of reduced water supplies for fish, energy production, recreation, and the economy in general, and reveal the precarious nature of the region's water supply. Despite the general perception that the Northwest has abundant water resources, in literally only a few months, available water supplies became inadequate to meet the many demands, thereby creating problems.

National forests are the single largest producer of water in the Northwest and also produce the highest quality water in the region. Waters flowing from the national forests, which usually are located in the upper portions of river basins, often are stored, diverted, and manipulated downstream for various human benefits. Human uses of water alter the quantity and quality of natural flow regimes, with various ecological, social, and economic consequences.

More than 50 agencies and organizations are responsible for research and management of water resources in the region. A large body of scientific literature on water resources and water management is available to water managers in the Northwest, but a holistic synthesis and integration of the information by subbasin has not been accomplished.

Water resources on forested landscapes of the Northwest are in better condition than those in agricultural and urban landscapes downstream. The generally mountainous, federally owned forested landscape produces a disproportionately high share of the region's runoff, and water quality assessments indicate that forested lands also produce the highest quality water. On the other hand, agricultural and urban areas present different impacts on water. The marginal costs and benefits of policies and programs designed to enhance water quantity or quality likely differ across land use categories. For example, it is conceivable that under certain circumstances, greater marginal gains in water quality could probably be achieved with policies and programs that address surface runoff from urban areas and agricultural lands rather than from forest lands. Developing an overall strategy for efficient management of water resources may necessitate consideration of the full array of water quantity and quality enhancement opportunities available over the full range of land uses and human activities.

The Pacific Northwest has abundant water resources, but the spatial and temporal distribution of precipitation and runoff in the region is more variable than in any other comparably sized area of the United States. Supplies are abundant west of the Cascade crest and generally scarce in the arid and semiarid intermountain region where demands for water, especially for agriculture, are greatest. The uneven distribution of water at the regional scale is generally related to maritime influences of the Pacific Ocean west of the Cascade crest, continental influences east of the Cascade crest, arctic influences that enter the area from British Columbia, and orographic effects from the Coast, Cascade, and Rocky Mountains. Seasonal and spatial variability in precipitation and runoff complicate management of the region's water resources and create persistent problems and conflicts in some geographic areas between offstream and instream uses of water, and between certain user groups. Unanticipated changes in water supply (e.g., the drought of 2001 in the West) can quickly change public perceptions and policies about water use for fish, energy, recreation, or for maintenance of the general health of the regional economy.

Major water developments, particularly in the Columbia River basin, have alleviated some problems with the spatial arrangement of water and significantly increased water supplies in arid and semiarid areas. Few additional options for improving the distribution of water across the region are available, especially on national forest lands.

Human activities have altered natural flow regimes in two ways over large areas of the Pacific Northwest with documented consequences for both natural ecosystems and human populations. First, human activities can change the natural spatial and temporal distribution of the quantity of surface waters. Use of water either instream or offstream can significantly alter normal physical flow patterns in ways that benefit the interests of some user groups and detract from the interests of others. Second, activities that change the quality of natural waters by altering thermal, chemical, pathogen, or nutrient characteristics have widespread and significant impacts on aquatic ecosystems and human uses of water. Changes in instream storage, off-stream consumptive uses of water, and landscape-scale land use activities are leading causes of altered physical flows, while sedimentation, human sewage, industrial and agricultural wastes, and thermal loading from land use activities are major modifiers of water quality.

Natural flow regimes in the Pacific Northwest have been intentionally altered to enhance human benefits from available water resources and to reduce the risks of floods associated with natural flow regimes. Development of Pacific Northwest water resources has enhanced human population growth, drinking water supplies, hydro-power production, agriculture, industrial production, flood control, and slack-water navigation. It has increased some forms of water-oriented recreation, reduced others, and fundamentally changed the ecology of many Northwest waterways and aquatic community composition.

Conflicts between user groups over scarce water resources occur in nearly every river basin in the Northwest and are complicated by Western water law that has remained largely unchanged for more than 140 years. The conflicts revolve around rapidly increasing human populations; changing social values that no longer fully support current water use and impacts from agriculture, ranching, and forest management; and declining salmon runs. They also express emerging interests in the region's recreation, tourism, residential, and industrial sectors and perceptions that the region's environmental quality is deteriorating. Mixed federal, state, tribal, and private land ownership also create conflicts. Sustainable development of water resources in the Northwest will require a new balance between off-channel consumptive uses of water and nonconsumptive instream uses to solve current and emerging conflicts over allocation of water resources.

There is an extensive array of existing, new, and emerging legal, political, economic, social, and technological tools and techniques for managing water resources in the Pacific Northwest. Full implementation of new and existing tools and development of additional tools and schemes are needed to address the current complexity of water management in the region. Water allocation and management have become increasingly complex as the population of the Western United States has grown, and social and economic values related to water use have changed. The public now desires balanced water management for generation of electric power, and water for domestic, industrial, agricultural, recreational, and ecological uses.

English Equivalents

When you know:	Multiply by:	To find:
Millimeters (mm)	3.94	Inches
Centimeters (cm)	0.39	Inches
Meters (m)	3.28	Feet
Cubic meters (m^3)	.000811	Acre-feet
Kilometers (km)	.6215	Miles
Square Kilometers (km^2)	.386	Square miles
Hectares (ha)	2.47	Acres
Liters (L)	.0353	Cubic feet
Liters per kilogram (L/kg)	.016	Cubic feet per pound
Milligrams (mg)	0.001	Gram
Megagrams (Mg)	1.102	Tons
Celsius (°C)	1.8 and add 32	Fahrenheit
Megawatts (MW)	3.4×10^6	Btu/hr

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Appendix 1

Principal Agencies, Universities, and Nongovernmental Organizations (NGOs) That Participate in Water Resources Management and Research in the Pacific Northwest

Idaho:

- Center for Ecological Research (Idaho State University)
- Department of Water Resources (state)
- Forestry Sciences Laboratory, USDA Forest Service (federal)
- Idaho Cooperative Fish and Wildlife Research Unit (federal)
- Water Resources Research Institute (University of Idaho)

Oregon:

- Agricultural Experiment Station (Oregon State University [OSU])
- Building Codes Agency (state)
- Center for Analysis of Environmental Change (OSU)
- Center for Groundwater Research (Oregon Groundwater Institute)
- Center for Water and Environmental Sustainability (OSU)
- Department of Agriculture (state)
- Department of Energy (state)
- Department of Environmental Quality (state)
- Department of Fisheries and Wildlife (state)
- Department of Forestry (state)
- Department of Geology and Mineral Industries (state)
- Department of Land Conservation and Development (state)
- Department of Transportation (state)
- Department of Water Resources (state)
- Division of State Lands (state)
- Economic Development Department (state)
- Environmental Health Sciences Center (OSU)
- Executive Department (state)
- Forest Research Laboratory (OSU)
- Governor’s Watershed Enhancement Board (state)
- Marine Board (state)
- Oregon Cooperative Fishery Unit (federal)
- Oregon Cooperative Wildlife Unit (federal)
- Public Utilities Commission (state)

Washington:

- Center for Streamside Studies (University of Washington [UW])
- Center for Urban Water Resources Management (UW)
- Department of Ecology (state)
- Department of Water Resources (state)
- Department of Fish and Wildlife (state)
- Department of Natural Resources (state)
- Institute of Forest Resources (UW)
- Northwest Indian Fisheries Commission (tribal)
- Olympic Natural Resources Center (UW)
- Washington Agricultural Experiment Stations
- Washington Cooperative Fish and Wildlife Research Unit (federal)
- Water Research Center (UW and Washington State University [WSU])
- Willapa Alliance (non governmental organization [NGO])

Pacific Northwest:

- American Rivers (NGO)
- Agricultural Research Service (federal)
- Bonneville Power Administration (federal)
- Bureau of Land Management (federal)
- Bureau of Reclamation (federal)
- Columbia Gorge Commission (NGO)
- Columbia River Intertribal Fish Commission (tribal)
- Conservation Technology Information Center (NGO)
- Department of Energy (federal)
- Federal Emergency Management Administration (federal)
- Federal Energy Regulatory Commission (federal)
- Klamath Compact Commission (NGO)
- National Council for Air and Stream Improvement (private industry)
- National Marine Fisheries Service (federal)
- National Oceanic and Atmospheric Administration (federal)
- National Park Service (federal)
- Natural Resources Conservation Service (federal)
- National Research Council (federal)

- Northwest Power Planning Council Office of Ocean and Coastal Resource Management (NGO)
- Pacific Marine Fisheries Council Stream Systems Technology Center, USDA FS (federal)
- Pacific Rivers Council (NGO)
- U.S. Army Corps of Engineers (federal)
- U.S. Environmental Protection Agency (federal)
  - Region 10
  - Western Ecology Division
- U.S. Fish and Wildlife Service (federal)
- U.S. Forest Service (federal)
  - Region 1
  - Region 2
  - Region 6
- Pacific Northwest Research Station (federal)
- Rocky Mountain Research station (federal)
- U.S. Department of the Interior, Geological Survey (federal)
- Waterwiser (federal)
- Western States Water Council (NGO)

British Columbia:

- Ministry of Environment, Lands, and Parks (provincial)
- Environment Canada (federal)
- Fisheries and Oceans Canada (federal)
- Ministry of Agriculture, Food, and Fisheries (provincial), BC Hydro
- Department of Hydrogeology (University of British Columbia)

Appendix 2

Table 4—Major laws currently governing water and watershed management on federal lands of the Pacific Northwest

Source	Law	Effective date
Congress	Rivers and Harbors Act [33USC 401]	1899
	Migratory Bird Conservation Act	1929
	Taylor Grazing Act, as amended, 49 U.S.C. 315; 48 Stat. 1269 (1970)	1934
	Oregon and California Act (P.L. 75-405)	1937
	Water Pollution Control Act [P.L. 80-845]	1948
	Water Pollution Control Act—Amendments	1956
	Fish and Wildlife Coordination Act	1958
	Multiple Use Sustained Yield Act [16 USC 528]	1960
	National Forest Management Act [16 USC 1600-164]	1964
	Land and Water Conservation Fund Act (16 U.S.C. 460)	1964
	Water Quality Act [P.L. 89-234]	1965
	National Environmental Policy Act [P.L. 91-190]	1969
	Water Pollution Control Act [P.L. 92-500]	1972
	Endangered Species Act [16 USC1531-1544]	1973
	Sikes Act	1974
	Federal Land Policy & Management Act, P.L. 94-579	1976
	The Clean Water Act [P.L. 95-217]	1977
	Public Rangelands Improvement Act (49 U.S.C. 1901)	1978
	Emergency Wetlands Resource Act (16 U.S.C. 3901)	1986
	Water Quality Act (amendments to P.L. 95-217)	1987
	North American Wetlands Conservation Act	1989
	Safe Drinking Water Act [33 USC 1251-1387]	2000
Executive Order	11990, Protection of Wetlands	1977
	19880, Floodplain Management	1977

Table 5—Research needs

General priorities	Water distribution	Altered flow and water quality	Conflicts over water use	Tools and solutions
High	• Establishing information on natural spatial and temporal historical and current variability in water yield and water quality from the region’s major basins and subwatersheds. • Biological research to improve understanding between outcomes of land management and influence on aquatic and riparian habitats. • Developing improved understanding of the hydrologic and ecologic role of headwater catchments and small stream channels in the context of river basins.	• Evaluating economic tradeoffs between the causes and consequences of altered flow regimes. • Learning how to manage forested landscapes with fewer roads. • Establishing the comparative productivity of the best remaining salmonid habitats today with the historical productivity of salmonid habitats at the large watershed scale.	• Improving understanding of how changes in public values for water affect public use and the effectiveness of water and land management. • Economics research to evaluate tradeoffs and develop solutions pertaining to allocation of water among competing and conflicting uses of scarce water resources, and to encourage water conservation.	• Contribution of new, and synthesis of existing scientific information, for planners involved in the FERC licensing and relicensing processes. • Develop protocols for identifying, measuring, and evaluating social tradeoffs between the causes and consequences of altered flow regimes (e.g., conflicts between different types of recreational activities). • Review the effectiveness of watershed analysis in informing planning for land management. • Evaluate the effectiveness, cost, and equity implications of implementing social and economic tools and strategies for allocating water and encouraging water conservation.

Table 5—Research needs (continued)

General priorities	Water distribution	Altered flow and water quality	Conflicts over water use	Tools and solutions
Medium	• Developing improved understanding of water management impacts on recreational opportunities, including the displacement of recreationists from one location to another. • Defining the historical distribution and abundance of salmonids in large watersheds. • Hydrologic and biological research to improve understanding of the relation between land management and water yield and water quality.	• Defining the effects of forest management on flow regimes at large scales through watershed studies. • Improving understanding of how subsurface and surface flows may be affected by roads, and their significance to downstream flow regimes.	• The most effective use and development of collaborative efforts (e.g., watershed and basin advisory groups) to resolve basin-scale conflicts on water allocation and use. • Research to reveal relationships between water use and resource management and water-based recreation. • Contributing to the development and evaluation of programs and policies for allocating water among users. • Developing improved techniques for measurement and utilization of water-based recreation use trends.	• Participation in development of scientific information and decision support for basin advisory groups, watershed advisory groups, and interagency groups coordinating water management at the large watershed or basin scale. • Testing and evaluating mechanisms for improved interagency interactions and coordination on water issues. • Evaluate alternative processes and models for watershed management and advisory groups designed to better manage conflict, create and disseminate knowledge, and undertake local implementation efforts. • Provide leadership in the development and coordination of common databases.

Table 5—Research needs (continued)

General priorities	Water distribution	Altered flow and water quality	Conflicts over water use	Tools and solutions
Low	• Studying the effects of Douglas-fir and true fir removal on water yield from ponderosa pine sites in the intermountain region of the Pacific Northwest. • Providing a better understanding of the options for and consequences of additional water storage on federal lands.	• Improving understanding of the consequences and implications of altered flow regimes on social uses and values of water, including outdoor recreation, subsistence use, and sense of place, and developing methods for mitigating adverse impacts. • Water quality research to assess the effects of recreation on drinking water, especially in relation to pathogens.	• Promoting water conservation by enhancing public understanding of water resource concerns and tradeoffs through development of educational strategies and opportunities for mutual learning. • Evaluation of benefits and costs to participants in watershed stewardship, restoration, and education activities.	• Conduct research on the effectiveness and environmental effects of biological and chemical tools for erosion control on forest roads (including, e.g., PAM). • Research on the array of assisted negotiation techniques (e.g., facilitation, mediation, nonbinding and binding arbitration) for resolving natural resource conflicts.

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