Robert J. Naiman
Editor

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Balancing Sustainability and Environmental Change

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Fundamental Elements of Ecologically Healthy Watersheds in the Pacific Northwest Coastal Ecoregion

ROBERT J. NAIMAN, TIMOTHY J. BEECHIE, LEE E. BENDA, DEAN R. BERG, PETER A. BISSON, LEE H. MACDONALD, MATTHEW D. O'CONNOR, PATRICIA L. OLSON, AND E. ASHLEY STEEL

Abstract

Characteristics of streams and rivers reflect variations in local geomorphology, climatic gradients, spatial and temporal scales of natural disturbances, and the dynamic features of the riparian forest. This results in a variety of stream types which, when coupled with the many human uses of the Pacific Northwest coastal ecoregion, presents a difficult challenge in identifying and evaluating fundamental, system-level components of ecologically healthy watersheds. Over 20 types of streams are found in western Oregon, Washington, and British Columbia and in southeastern Alaska, a region where extractive forest, agricultural, fishing, and mining industries and a rapidly increasing urban population are severely altering the landscape. Yet stream characteristics remain the best indicators of watershed vitality, provided the fundamental characteristics of healthy streams are accurately known. The premise of this article is that the delivery and routing of water, sediment, and woody debris to streams are the key processes regulating the vitality of watersheds and their drainage networks in the Pacific Northwest coastal ecoregion. Five fundamental components of stream corridors are examined: basin geomorphology, hydrologic patterns, water quality, riparian forest characteristics, and habitat characteristics. Ecologically healthy watersheds require the preservation of lateral, longitudinal, and vertical connections between system components as well as the natural spatial and temporal variability of those components. The timing and mode of interdependencies between fundamental components are as important as the magnitude of individual components themselves.

Key words. Stream, river, watershed, Pacific Northwest, riparian, sediment, woody debris.

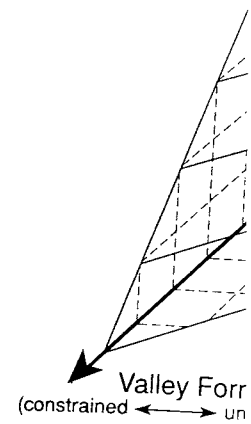
Introduction

Watersheds in the Pacific Northwest coastal ecoregion play a vital role in shaping and supporting diverse cultures and professions. Specific characteristics of streams and rivers reflect an integration of countless physical and biological processes, providing a long-term memory of environmental conditions. Streams and adjacent riparian forests provide clean water, habitat for fish and wildlife, recreational opportunities, raw materials, and spiritual values for many American and Canadian cultures (Salo and Cundy 1987, Raedeke 1988, Naiman and Décamps 1990, Gregory et al. 1991). In combination, these features have enormous value but represent substantial managerial difficulties, especially when competing interests vie for limited resources. Difficult issues are magnified when natural ecological processes and their variability in space and time are poorly understood (Décamps and Naiman 1989).

For over a century, human alteration of the Pacific Northwest has proceeded without a basic understanding of watershed dynamics, especially for the stream corridors, or of the long-term consequences of land use alterations. Comprehensive studies of stream corridors and watersheds are rare, and most have been done since 1975 (Likens 1989, Strayer et al. 1986). Investigations of running waters as ecological systems are rudimentary, with major conceptual advancements only in the last decade (Vannote et al. 1980, Newbold et al. 1982, Hynes 1985, Naiman et al. 1988). Longitudinal, lateral, and vertical connections in controlling the ecological vitality of streams and rivers are recent concepts requiring additional investigation. Yet, in combination, these and subsequent studies point to running waters as ecological systems demonstrating considerable variability in space and time and requiring a high degree of connectivity between system components for the maintenance of long-term environmental health (see Stanford and Ward, this volume).

Connectivity is manifested in such features as access to required habitat during the life history of fish and wildlife (Salo and Cundy 1987, Raedeke 1988), stream temperature regimes that synchronize the migration and emergence of aquatic organisms (Sweeney and Vannote 1978, Quinn and Tallman 1987), riparian forests that regulate nutrient and material exchanges between forests and streams (Swanson et al. 1982, Peterjohn and Correll 1984), and hydraulic regimes that are within an accepted range for evolutionary adaptation of specific organisms (Statzner et al. 1988).

Variability is reflected in the wide variety of stream types in the coastal ecoregion (Naiman et al. 1991), resulting from differences in geology, climate, and stream size (Figure 6.1). Important geologic processes include



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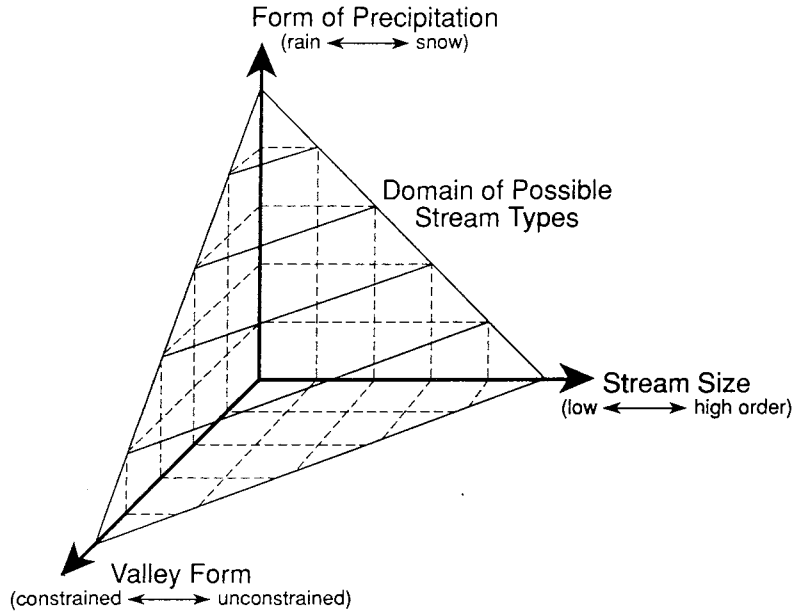

FIGURE 6.1. Principal factors influencing stream characteristics in the Pacific Northwest coastal ecoregion.

volcanism, continental and alpine glaciation, and erosional processes, including mass wasting. Climatic processes include the dominant form of precipitation (e.g., rain, snow, or transition), the seasonal timing, and the runoff patterns. Stream size is a function of the spatial position of the channel in the drainage network and upstream geomorphic and climatic processes. Thus a broad array of stream types may be found within a relatively small area, with each having different biological characteristics and presenting different managerial challenges.

The phrase *ecologically healthy* refers to functions affecting biodiversity, productivity, biogeochemical cycles, and evolutionary processes that are adapted to the climatic and geologic conditions in the region (Karr et al. 1986, Karr 1991). Collectively, these functions can be a measure of system vitality. Some tangible measurements of ecological healthy watersheds include water yield and quality, community composition, forest structure, smolt production, wildlife use, and genetic diversity. Our working hypothesis is that delivery and routing of water, sediment, and woody debris to the stream channel are the key processes determining the ecological health of watersheds in the Pacific Northwest coastal ecoregion. This article will present a broad overview of several fundamental components of ecologically healthy watersheds in this ecoregion, and present a conceptual model of principal interdependencies between those components.

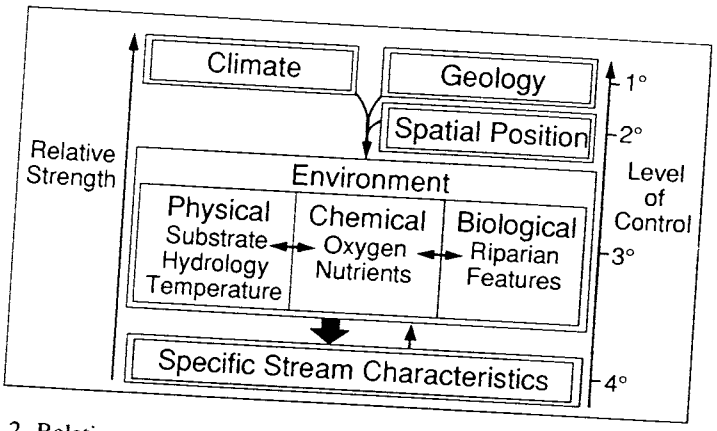

FIGURE 6.2. Relative strength of factors influencing stream characteristics, and principal feedback loops between components (see text for explanation).

Fundamental Components

An efficient approach to understanding the bewildering array of stream types is through a hierarchy of controlling factors (Frissell et al. 1986), with each assigned a ranking based on perceived ability to influence other components (Figure 6.2). However, components with a lower hierarchical ranking may influence higher ranked components through feedback loops (e.g., feeding strategies or disturbance; Starfield and Bleloch 1986, DeAngelis et al. 1986, Naiman 1988).

Based on this analysis, we chose five components that reflect different hierarchical levels of control on stream characteristics, that are integrative of species-specific processes (e.g., population dynamics), and that are essential for maintaining the long-term environmental vitality of drainage networks (Table 6.1). All processes influence either water, sediment, and woody debris delivery to the channel or the routing of those materials through the drainage network, or are responsive to material delivery and routing processes. These five fundamental components are basin geomorphology, hydrologic patterns, water quality, riparian forest characteristics, and habitat characteristics.

The geographic reference for our observations is limited largely to high precipitation basins west of the Cascade Mountains in northern California, Oregon, and Washington but may have application to the coastal regions of British Columbia and southeastern Alaska (Figure 6.3). The majority of rivers draining into the Pacific Ocean along the northwestern coast of North America originate in steep, mountainous terrains of the Northwestern Cordillera (McKee 1972). Along the coast of Washington and Oregon, the Northwestern Cordillera is represented by the Coast Range and the Cascade Mountains to the east. These watersheds have diverse geomorphic processes

Table 6.1. Six fundamental components of ecologically healthy watersheds in the Pacific Northwest Pacific Northwest coastal ecoregion.

Component	Approximate Hierarchical Level	Factors Considered	Sphere of Influence
1. Basin geomorphology	1°-2°	A. Physiographic and geologic setting B. Significant geomorphic processes C. Natural disturbance regimes	Effects all factors except climate
2. Hydrologic patterns	1°-2°	A. Discharge pattern flood characteristics and water storage B. Bedload and sediment routing C. Subsurface dynamics	Channel geomorphology and other physical characteristics, some aspects of chemical regime, riparian forest, and in-channel community dynamics
3. Water quality	3°-4°	A. Biogeochemical processes B. Fundamental parameters	Feedbacks to terrestrial vegetation and direct effects on chemical and biotic characteristics
4. Riparian forest characteristics	2°-3°	A. Light and temperature B. Allochthonous inputs C. Woody debris source	Most aspects of the physical, chemical, and biotic characteristics
5. Habitat characteristics	3°	A. Fish habitat preferences B. Fish community dynamics C. Spatial and temporal dynamics D. Woody debris accumulations E. Wildlife communities F. Trophic pathways	Influence in other biotic communities in stream and strong feedbacks to physical, chemical, and terrestrial dynamics

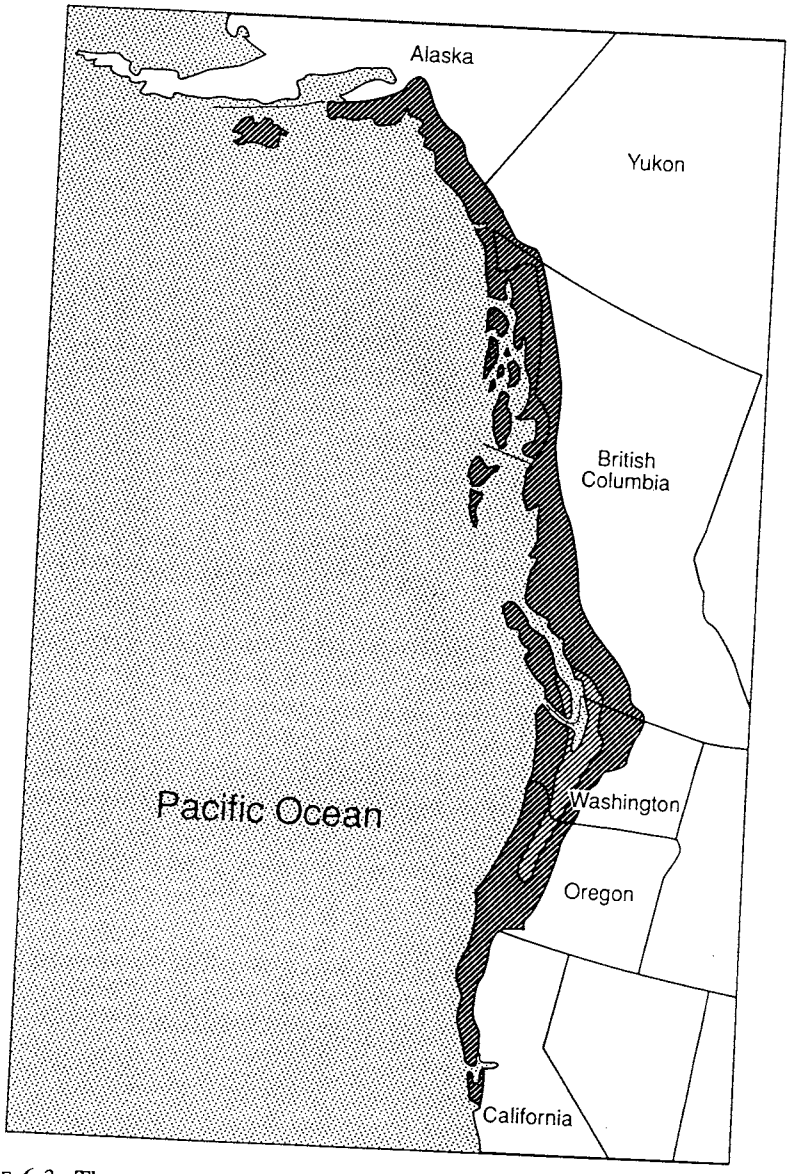

FIGURE 6.3. The coastal ecoregion of the Pacific Northwest as referred to in this article.

that vary along a longitudinal gradient extending from mountain ridges to the sea. Subduction of oceanic crust beneath continental lithosphere along the Pacific Coast results in steep, high elevation mountains. Heavy precipitation due to orographic lifting of moist air from the Pacific Ocean, together with the steep terrain, results in erosion dominated by mass wasting. The

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geology of the Pacific Northwest mountains contains a diversity of lithologies, including marine sedimentary sequences, metasedimentary rocks, various old and more recent volcanics, and granitic plutons (McKee 1972). Suspect terrain, or rafted continental crust, also contributes to the geologic complexity.

The most recent continental glaciation ended approximately 14,000 years B.P. and significantly altered the landscape of northwestern Washington (north of Centralia), British Columbia, and parts of southeastern Alaska (Crandell 1965). The retreating ice sheets deposited thick layers of till, lake clay, and outwash sand in valley bottoms and the Puget Lowland. Typically, major rivers and many smaller tributaries within these regions continue to incise through glacial sediments.

Basin Geomorphology

Natural Disturbances and Stream Size

Basin geomorphology in ecologically healthy watersheds is affected by the type, frequency, and intensity of natural disturbances. Characteristics of these disturbances reflect the spatial position of channel segments in the drainage network. Processes of material delivery and routing are highly interactive with hydrologic patterns and riparian vegetation.

Geomorphic Processes and Forms in Low-Order Channels.

In the Pacific Northwest, low-order (e.g., first- and second-order) stream segments represent >70% of the cumulative channel length in typical mountain watersheds (Benda et al. 1992). Hence low-order channels are the primary conduits for water, sediment, and vegetative material routed from hillslopes to higher-order rivers. First- and second-order basins are naturally prone to catastrophic erosion because steep slopes adjacent to steep channels favor landslides and debris flows.

In the few studies conducted in the coastal ecoregion, first- and second-order channels in steep bedrock of mountain basins do not transport significant quantities of sediment by water flow; hence these channels have limited amounts of stored alluvium (Figure 6.4, top). Swanson et al. (1982) estimated that fluvial transport accounted for approximately 20% of the total sediment yield from a first-order basin in the central Oregon Cascades. In the Oregon Coast Range, Benda and Dunne (1987), using a sediment budget approach that included specifying sediment routing by debris flow, estimated that fluvial processes accounted for 10 to 20% of the total sediment yield.

Low-order channels are filled primarily with colluvium, characterized by coarse, unsorted sediments, including silts and clays derived from landslides and debris flows (Benda and Dunne 1987). Low-order channels also contain substantial amounts of boulders (>27 cm diameter) and woody debris (>10 cm diameter) because streamflow is not competent to transport the largest

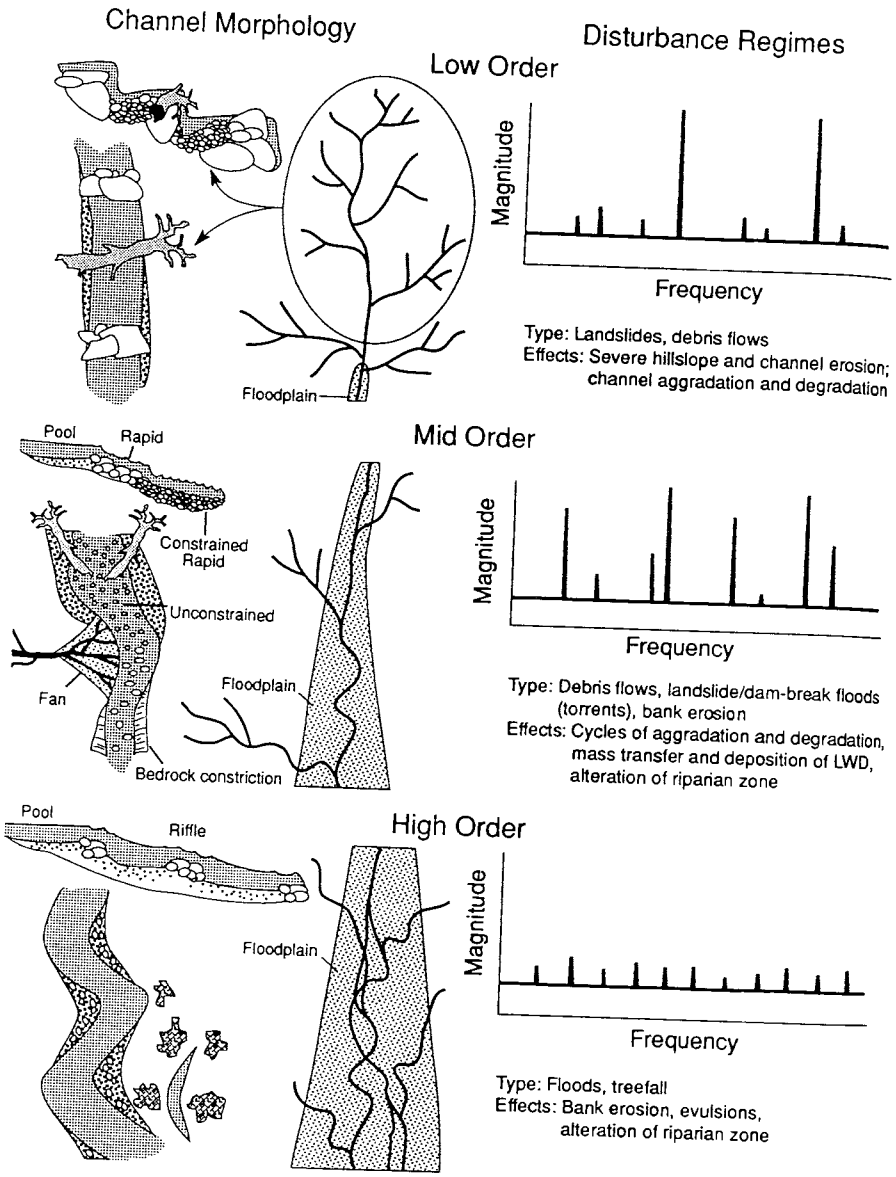

FIGURE 6.4. Generalized channel morphology and disturbance regimes associated with low-, mid-, and high-order streams in the Pacific Northwest coastal ecoregion.

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materials. First- and second-order channels have steep gradients (typically >8 degrees), but have lower gradients over shorter (<10 m) lengths due to accumulations of woody debris organized into debris jams which create a stepped longitudinal profile (Swanson and Lienkaemper 1978). Woody debris jams store sediment and contribute to discontinuous sediment transport during storms (Heede 1972, Mosley 1981). Bedforms in steep first- and second-order channels are generally limited to plunge pools in coarse-textured substrate, migrating gravel sheets originating from streamside landslides, and local accumulations of finer sediment upstream from woody debris and boulder obstructions. Woody debris jams can account for the majority of energy loss of flowing water in steep, low-order channels (Beschta and Platts 1986), implying that less energy is available for sediment transport.

Landslides occur on steep slopes during large rainstorms or rain-on-snow events (Swanston and Swanson 1976). Furthermore, wildfires kill vegetation, and loss of root strength may result in landslide and debris flow activity during large rainstorms (see below). Certain landslides at the heads of low-order valleys are transformed into debris flows, eroding accumulated sediment and organic debris from first- and second-order channels (Benda and Dunne 1987). Debris flows are one of the most common forms of mass wasting in mountain watersheds of the coastal ecoregion, and are the principal process transporting sediment and woody debris in first- and second-order channels (Swanson et al. 1985). Recurrence intervals of debris flows have been estimated to be once in 500 years for first-order channels in the central Oregon Cascades (Swanson et al. 1982), and once in 750–1,500 years for first- and second-order channels in the Oregon Coast Range (Benda and Dunne 1987).

Geomorphic Processes and Forms in Mid-Order Channels.

Third- through fifth-order channels, referred to as mid-order channels, are characterized by moderate to steep gradients (1 to 6 degrees), substrates ranging from boulders to gravels (or sands in some streams), and abundant large organic debris in jams and single pieces (Figure 6.4, middle). True alluvial channel systems in the coastal ecoregion begin at third-order channels (e.g., where the majority of sediment and organic debris is transported by water).

Mass wasting often dominates the amount and type of deposition along narrow valley floors of mid-order channels. Debris flow deposits in confined valleys create fans at mouths of first- and second-order basins, and levees and terraces along valley floors (Benda 1990). Streams are often forced toward the opposite valley wall by alluvial or debris flow fans. For example, 65% of stream meanders in a fifth-order basin in the Oregon Coast Range with a sinuosity of >1.1 were maintained by debris flow fans (Benda 1990). Landslides and debris flows also deposit large volumes of sediment and vegetative material (1,000 – 10,000 m^3) directly into mid-order channels. Local channel aggradation and logjams persist at the site of deposition for years

to decades (Benda 1988, Perkins 1989). In the central Oregon Coast Range, debris flows control the distribution of boulders in alluvial channels (Benda 1990).

Earthflows often impinge on third- through fifth-order valley floors, causing local constrictions and streamside landslides (Swanson et al. 1985). Deposition of entire trees and large volumes of sediment cause local channel aggradation at the site of earthflows and immediately downstream. Streams within narrow valley floors may impinge directly on hillslopes, causing erosion in the form of rockfall in nonglaciated basins, or landslides or slumps in glacial deposits, which further affects channel morphology.

An important catastrophic process in mid-order channels is the landslide/dam-break flood. Deposits of landslides and debris flows often temporarily dam streams along narrow valley floors (Figure 6.4). A rapid failure of the dam and subsequent release of the ponded water may cause an extreme flood, destroying riparian vegetation and removing in-channel organic debris. Accelerated sediment transport by streamflow follows in the wake of the dam-break flood.

Channel form is influenced by mass wasting deposits (see above) but also reflects normal alluvial processes. Bedforms include alternate pool and riffle morphology at meanders, and migrating gravel sheets originating from local inputs of sediment. In addition, a kind of bedform called scour lobe occurs as flow convergence erodes channel beds, forming pools, and flow divergence downstream deposits bars or gravel lobes (Lisle 1987). Scour around bedrock bends may also produce scour lobes. Channels dominated by large substrate may develop a boulder-cascade or step-pool morphology. This bedform is characterized by organized aggregations of boulders which create a sequence of cascades and boulder pools (Whittaker and Jaeggi 1982, Grant et al. 1990). Pools tend to be deep in relation to channel widths; width-depth ratios are 1:10.

Third- through fifth-order channels transport the majority of sediment delivered to them rather than storing it for long periods, because of relatively steep gradients, well-armored channel banks, and narrow valley floors. Channels with these characteristics tend to contain flood flows. Hence terraces, overflow channels, and oxbow lakes tend to be limited in these areas. Channels are typically single thread, with the exception of diversion of streams around woody debris jams and mass wasting deposits.

Mass wasting influences the temporal distribution of sediments in alluvial channels, either because it deposits sediment directly into alluvial channels or because the deposits provide a source for accelerated sediment transport further downstream (Benda and Dunne 1987). The stochastic nature of sediment supply to alluvial channels by debris flows and landslides may promote significant temporal variation of bedforms. For example, in the Oregon Coast Range, episodic debris flows are responsible for channel aggradation which results in a gravel-bed morphology, while the absence of debris flows results in a mixed bedrock- and boulder-bed morphology at the scale of

stream reaches to entire tributaries (Benda 1990). In addition, spatial variability in channel form in mid-order streams can be significant due to frequent deposits of sediment and organic debris from landslides, debris flows, and earthflows.

Geomorphic Processes and Forms in High-Order Channels.

Large rivers of sixth order and higher integrate the diversity of erosional processes in time and space (Figure 6.4, bottom). Hence sediment supply is more steady in time, and as a result the channel form (that which is dependent on the sediment supply rate, such as pools) is more uniform in space. In addition, extensive alluvial terraces and floodplains isolate the river from direct contact with hillslopes and low-order tributary basins, and therefore limit the direct influences of mass wasting.

Large rivers sort sediment by size or selectively transport it along the longitudinal gradient from third- through sixth- and higher-order channels. As gradient decreases and channels widen, transport of large sediment decreases. The coarsest sediment is found in upper watersheds, often adjacent to mass wasting deposits; the finest sediment, such as sand and small gravel, is in the lower reaches (Brierley and Hickin 1985). Particle comminution or abrasion further limits sediment size downstream. General exceptions to this decline in substrate size downvalley include local accumulations of larger particles at tributary confluences, aggradation of finer sediment behind debris jams, and landslide and debris flow deposits.

Large discharge and easily erodible banks in large rivers favor the development of meandering floodplain channels, creating alternating pool and riffle morphology (Dunne and Leopold 1978). Other common bedforms in large rivers include mid-channel bars formed by organic or inorganic obstructions, and transverse bars formed by flow separation due to changing channel geometry (Figure 6.4, bottom). The scale and dimension of the pool-riffle morphology depend on bank height and composition, size and type of riparian vegetation, size of bedload, discharge regime, and so forth. Rivers tend to be slightly deeper and significantly wider than steep stream channels upvalley; width to depth ratios range from ~10 to >20.

Lateral migration of rivers occurs continuously and does not depend on extreme events, though migration may occur more rapidly during large floods. Evulsions are common and multiple thread channels are formed, often during flood events, because of weak bank deposits. This leads to the development of floodplains kilometers wide containing numerous active and semi-active channels (Sedell and Froggatt 1984). Meander cutoffs create oxbow lakes, the size and number depending on meander history of the river, width of the floodplain, and groundwater characteristics of the alluvial plain. Wetlands become numerous within and along cutoff meanders and oxbow lakes. If the hydrologic regime is characterized by a high flood frequency, lateral migration may also occur more frequently. Hence vegetation patterns along

these types of rivers will contain young successional stages and perhaps a greater heterogeneity of stand ages.

Small tributaries, originating from steep areas or as springs, cross alluvial terraces and floodplains with larger rivers. These small channels are similar, though smaller in scale, to larger alluvial channels, and they have been referred to as wall-base channels (Peterson 1982*a*, *b*). Wall-base channels meander through easily erodible alluvial sediments and their bedforms are dominated by alternate pools and riffles, scour lobes, and plunge pools.

Erosion and Sedimentation in Ecologically Healthy Watersheds

While erosion and sedimentation are often viewed negatively from a biological point of view, they are essential to the ecological functioning of aquatic and terrestrial communities because they provide the sources and the surfaces necessary for habitat. In mountain regions in particular, erosion and sedimentation are often violent (e.g., landslides, debris flows, landslide/dam-break floods, and snow avalanches) and produce mortality among terrestrial and aquatic organisms. Geomorphic surfaces in streams or on land in the wake of these powerful processes often evolve into productive and biologically attractive sites because of the revitalization of geochemical cycles, introduction of buried and unburied organic debris, and opening of forest canopies, thus increasing sunlight. In ecologically healthy watersheds of the Pacific Northwest, these violent geomorphic processes vary considerably in extent and frequency. Disturbance regime is the term generally used in discussing the results of these processes.

A disturbance is any significant fluctuation in the supply or routing of water, sediment, or woody debris which causes a measurable change in channel morphology and leads to a change in a biological community (Pickett and White 1985). The disturbance regime, therefore, is the type, frequency, magnitude and spatial distribution of changes in biological communities. Changes in the supply or the routing of sediment and organic debris are usually the result of local mass wasting or large floods. Some specific effects of mass wasting deposits on valley floors and channels have been covered in the previous sections on low- and mid-order channels. Floods not associated with mass wasting have less of an influence on low- to mid-order rivers (Grant 1986).

Although fluvial transport of sediment is often limited by supply of sediment, large floods can generate considerable bank erosion. Moreover, during floods, sediment transport resulting from bank erosion in low-order channels reaches its maximum. Hence the potential for bedload waves propagating from low- to mid-order streams exists during floods. As these waves pass downstream, they may locally cause accelerated bank erosion, thereby creating a positive feedback mechanism or a complex fluvial response. Given the potential for significant sediment transport by floods, watershed influences on the magnitude and timing of annual (and less frequent) floods are

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Erosion in mountain terrains of the coastal ecoregion is dominated by mass wasting. Therefore, triggering mechanisms such as rainstorms and wildfires were responsible for episodic transfers of sediment and organic debris from hillslopes and low-order channels to third- and higher-order streams and rivers (Swanson et al. 1982, Benda 1990). Past tense is used because wildfires are typically suppressed, while timber harvest activities have created a new pattern of disturbance across landscapes. Little is known about frequencies, magnitudes, and spatial distributions of historic wildfires and rainstorms, and therefore characteristics of natural erosional patterns (or disturbance regimes) in large watersheds are not well understood.

Wildfires, of varying intensities and in various locations, are controlled, to some extent, by climate and local topography (Teensma 1987). In Mount Rainier National Park, Washington, Hemstrom and Franklin (1982) estimated average recurrence intervals for stand-resetting wildfires to be ~450 years. In coastal forests of the Olympic Peninsula and Oregon Coast Range, a recurrence interval of a large stand was about two centuries (Agee 1990). In contrast, recurrence intervals of rainstorms that initiate landslides and debris flows are a few decades or less (Pierson 1977). A wildfire followed by large storms has the potential of inducing a spate of erosion that may result in sedimentation, and therefore a large channel disturbance over stream reaches to entire drainage networks (Benda 1990).

Erosion- and sedimentation-related disturbances in channels exhibit spatial variability because storms and fires act on different areas at different times. The scale of heterogeneity may range from individual small basins (and channels) to a major portion of a large watershed (numerous channels).

Several aspects of disturbance regimes are important to the functioning of biological communities in mountain watersheds. Unfortunately, knowledge of natural disturbance regimes is limited because of the length of time required for the processes to operate (100 to 1,000 years) and therefore to be observed by humans, and because recent use has altered the disturbance regimes in ways not fully understood. Nevertheless, we are able to conceptualize some attributes of natural disturbance regimes.

Disturbances related to erosion and sedimentation in low- to mid-order basins are thought to be characterized by high magnitude and low frequency because of the large number of mass wasting events and the potential for wildfires to range over these basins (Swanson et al. 1982, Benda 1990) (Figure 6.4). Within larger watersheds (mid-order, Figure 6.4) asynchronous combinations of fires and rainstorms act to limit the magnitude of the sediment and organic debris movement downstream. Though events may not be coupled in time within a larger watershed, they occur (collectively) more frequently because of the greater area and therefore greater probability of occurrence. This creates a disturbance regime, as far as sediment flux is

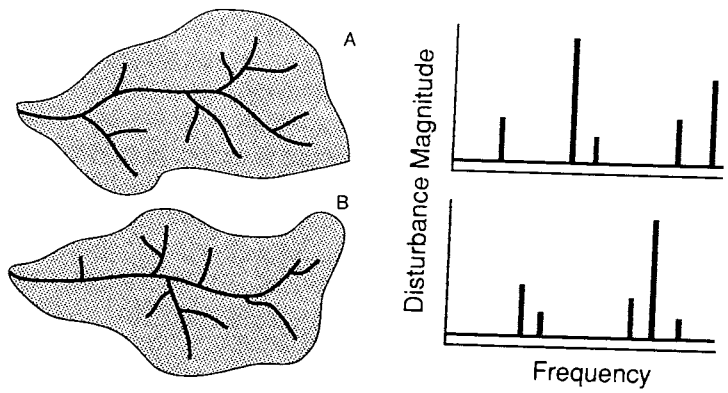

FIGURE 6.5. In ecologically healthy watersheds there is a natural spatial and temporal heterogeneity of disturbances between subbasins.

concerned, characterized by lower magnitude and increasing frequency (Figure 6.4, middle). In high-order rivers, the integration of many occurrences of erosion and the isolation of larger systems from direct influences of mass wasting conspire to further reduce the magnitude of sediment-related disturbances while increasing their frequency (Figure 6.4, bottom).

Spatial heterogeneity of erosion and sedimentation due to asynchronous fires and rainstorms may lead to adjacent basins having decoupled patterns of disturbance (Figure 6.5). In this example, the degree of disturbance can be thought of as time since the last event and the magnitude of that event. This potential habitat variability can be viewed as a habitat diversity. At the scale of a larger watershed, stochastic occurrences of mass wasting lead to basins having a unique variety of disturbance regimes. This results in a spatial and temporal distribution of subbasins in states of alternating low, intermediate, and high disturbance.

Therefore, the type, intensity, and frequency of erosional events and their spatial distribution across landscapes are important considerations to understanding the relationships between geomorphic process, form, and ecological functioning of watersheds. The temporal and spatial scales at which these processes occur, however, complicate their study. Our minimal knowledge of natural disturbance regimes limits our understanding of the functioning of ecologically healthy watersheds over long periods and large spatial scales, thus precluding accurate environmental assessments of the long-term effects of land use in watersheds in the coastal ecoregion.

Hydrologic Patterns

Hydrologic patterns of ecologically healthy watersheds in the coastal ecoregion are strongly related to the timing and quantity of flow, characteristics of seasonal water storage and source area, and the dynamics of surface-subsurface (e.g., hyporheic) exchanges.

FIGURE 6.6. Flood regions

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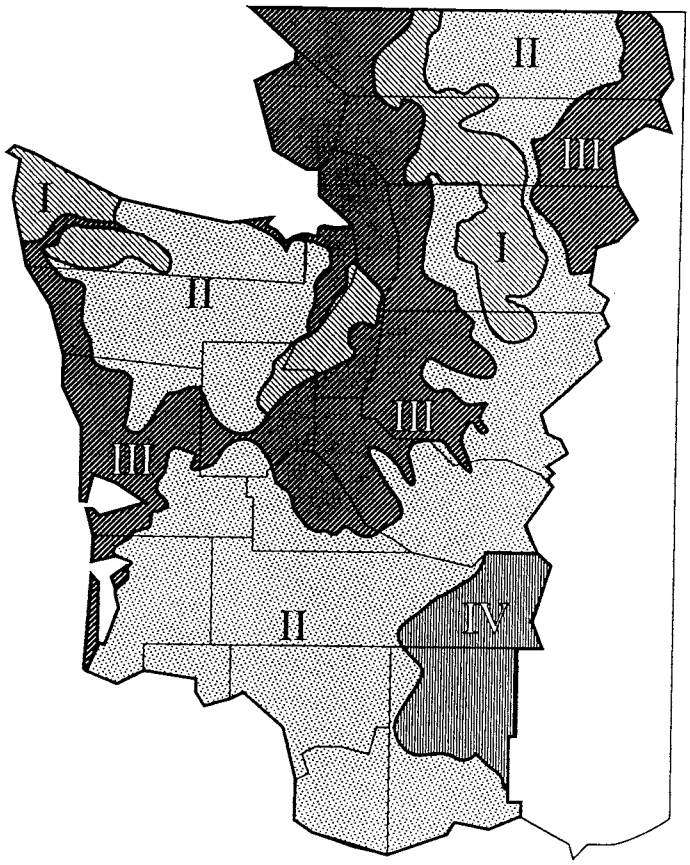

FIGURE 6.6. Flood regions of western Washington, USA.

Timing and Quantity of Flow

Distinct flood regimes in the coastal ecoregion of Washington have been identified in two analyses of regional stream gauging data (Bodhaine and Thomas 1964, Cummans et al. 1975). A map of these flood regions provides perspective on the spatial variability of runoff intensity (Figure 6.6).

Comparison of the Stillaguamish River (Region I), Nooksack River and Cedar River (Region II), and Pilchuck Creek (Region III) provides an example of basic differences in amount and form of precipitation, seasonal timing, and water storage within a region (Figure 6.7). Region I comprises the western Cascades and the northwestern portion of the Olympic Peninsula. The Cascade Mountain portion of Region I is located in the atmospheric convergence zone east of the Strait of Juan de Fuca where air masses moving north through the Puget Lowland collide with air moving east through the Strait, causing heavy precipitation. Region II covers most of the rest of

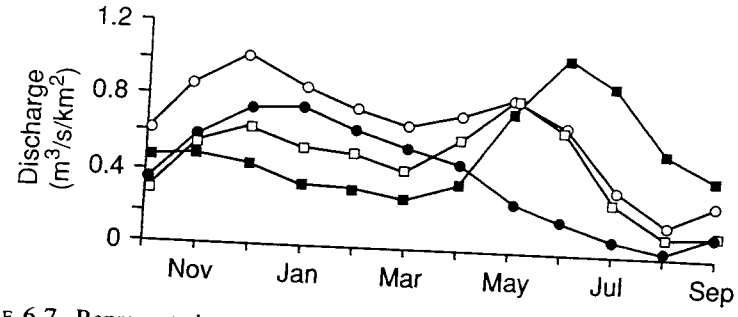

FIGURE 6.7. Representative annual flow regimes for the three major flood regions of western Washington. Region I: Stillaguamish River (-O-); Region II: Nooksack River (■) and Cedar River (□); Region III: Pilchuck Creek (●).

the western Cascades, including intermediate mountain elevations where rain-on-snow events are most common (Berris and Harr 1987). Rain-on-snow events are also common in the Cascade Mountain portion of Region I. Rain-on-snow events are periods of accelerated runoff resulting from melting of a warm snowpack caused by warm winds and rainfall. In western Washington and Oregon, these occur in early winter and spring, when snow levels are likely to fluctuate over hundreds of meters in elevation. Region III covers the Puget Lowland (in a rain-shadow) and the higher elevations west of the Cascade crest (snow dominated); in this area rain-on-snow events are least common because elevations are either too low to produce frequent snow or too high to produce frequent rain.

The predicted peak discharges of a 25-year recurrence interval flood in the three dominant Cascade flood regions are markedly different (Figure 6.8). Discharges calculated from the regression formulae of Cummans et al. (1975) (standardized to units of discharge per unit watershed area with standard errors of 32, 39, and 50% in Regions I, II, and III, respectively) show that Region I produces the highest discharge, Region III the lowest, and Region II an intermediate amount. In addition, smaller drainage areas produce more runoff per unit area than larger ones, regardless of region. This reflects the decreasing likelihood of a storm covering the entire watershed as watershed area increases, and the increase in floodplain storage (e.g., lakes and wetlands) as watershed size and stream order increase.

The predicted peak discharges of 2-year, 25-year, and 100-year recurrence interval floods in Region I show a similar pattern of discharge per unit watershed area (Figure 6.9). As before, the discharge was standardized and calculated (after Cummans et al. 1975) for hypothetical watersheds of three different sizes. Standard errors of the estimates are 25, 32, and 40% for the 2-year, 25-year, and 100-year recurrence interval floods, respectively. Predicted flood discharge decreased with increasing drainage area. The 25-year flood was about twice the magnitude of the 2-year flood; the 100-year flood was about triple the magnitude of the 2-year flood (Figure 6.9).

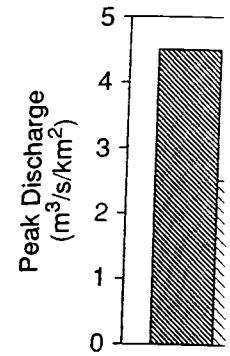

FIGURE 6.8. Estimated
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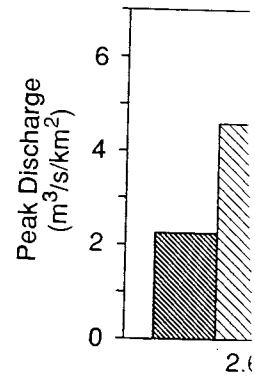

FIGURE 6.9. Predicted pe
interval floods in Region

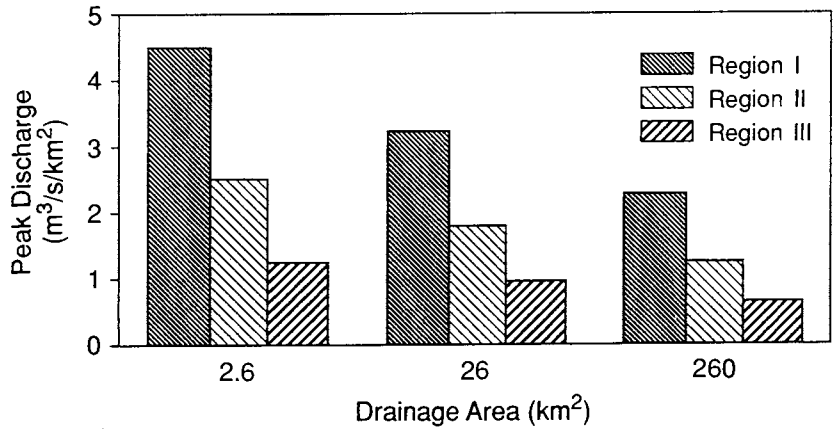

FIGURE 6.8. Estimated 25-year recurrence interval peak discharges for the three dominant flood regions in western Washington, by drainage area.

The significance of floods to high-order channels and associated riparian forests is as a disturbance creating heterogeneous habitat and as a recharge source for alluvial aquifers. Identifying a characteristic flood threshold at which significant disturbance occurs for a given stream, location, or region may be desirable to assess ecological effects. Once identified, such thresholds could define the spatial and temporal limits of disturbance in floodplain and riparian environments. This concept is best explored in the context of the following case study.

The potential for defining an ecologically significant flood recurrence interval is suggested by a study of the Skagit River, Washington. Stewart and

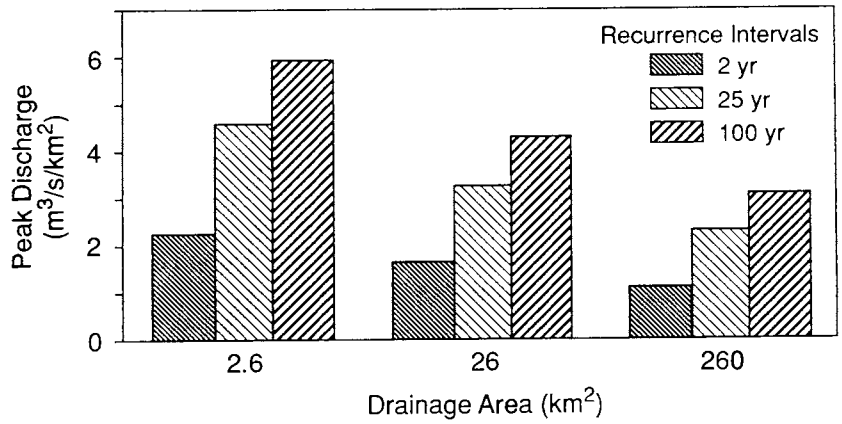

FIGURE 6.9. Predicted peak discharge of 2-year, 25-year, and 100-year recurrence interval floods in Region I (western Washington, USA) by drainage area.

Bodhaine (1961) reconstructed Skagit River floods (1815–1958) based on accounts of Native Americans and white settlers and on field measurements. The floods occurred in 1815, 1856, 1880, 1882, 1894, 1896, 1897, 1906, 1909, 1917, 1921, 1932, 1949, and 1951. These 14 floods, occurring in a period of 143 years, suggest that significant floods recur, on average, every 10 years. Alternatively, the probability of a flood of this magnitude (4,000 m^3/s) occurring in any year is 0.10. Six of the 14 floods occurred within 5 years of each other, suggesting that large floods occur in cycles, resulting in clusters of large floods concentrated in relatively short intervals. Although effects of such floods on riparian and floodplain environments were not well documented, these 14 floods resulted in extensive floodplain inundation. Additional analysis of the Skagit River flood history by Stewart and Bodhaine (1961) produced a flood frequency curve scaled to the mean annual flood. The 10-year recurrence interval flood had a discharge almost double the mean annual flood—suggesting, perhaps, a threshold. Further hydrological and ecological analyses would be necessary to determine whether the 10-year flood recurrence interval can be matched with patterns of riparian vegetation succession, thus providing evidence of an ecologically significant flood threshold.

Runoff Processes

Runoff processes influence quantity, quality, and timing of surface and subsurface flow. Water routing influences riparian vegetation, nutrient inputs, and stream productivity. Processes acting on runoff before the flow reaches the channel are numerous (Dunne 1978). In the heavily forested Pacific coastal ecoregion, overland flow is usually not an important process because infiltration capacities greatly exceed precipitation intensity (Harr 1976). Lateral subsurface flow is the dominant runoff process (Dunne 1978, Burt and Arkell 1986, Beschta et al. 1987, Troendle 1987). Subsurface flow may occur as matrix flow, or through macropores such as root channels, animal burrows, and even larger soil pipes (Higgins 1984, Roberge and Plamondon 1987, Beaudry et al. 1990). Shallow soils (over bedrock) and numerous macropores and soil pipes enable a quick stream response to storm events. The discontinuous network of soil macropores and pipes promotes rapid subsurface flow. Deeply incised depressions in steep, mountainous terrain of the Pacific Northwest have a greater response than broader depressions (Sidle 1986). The wetter the soil and the steeper the hydraulic gradient, the quicker the contribution of storm water or snowmelt to streamflow. Thus in winter and spring, when swales and stream valley bottoms are saturated, storm precipitation reaches the stream rapidly (Dunne 1978, O'Loughlin 1986).

The wetted area of the drainage network expands and contracts seasonally in response to precipitation, local topography, and soil characteristics (Hewlett and Nutter 1970, Dunne 1978, Burt and Arkell 1986). Investigations in humid mountainous regions throughout the world substantiate the applica-

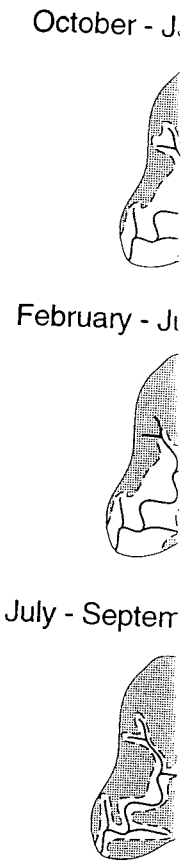

FIGURE 6.10. Variable source
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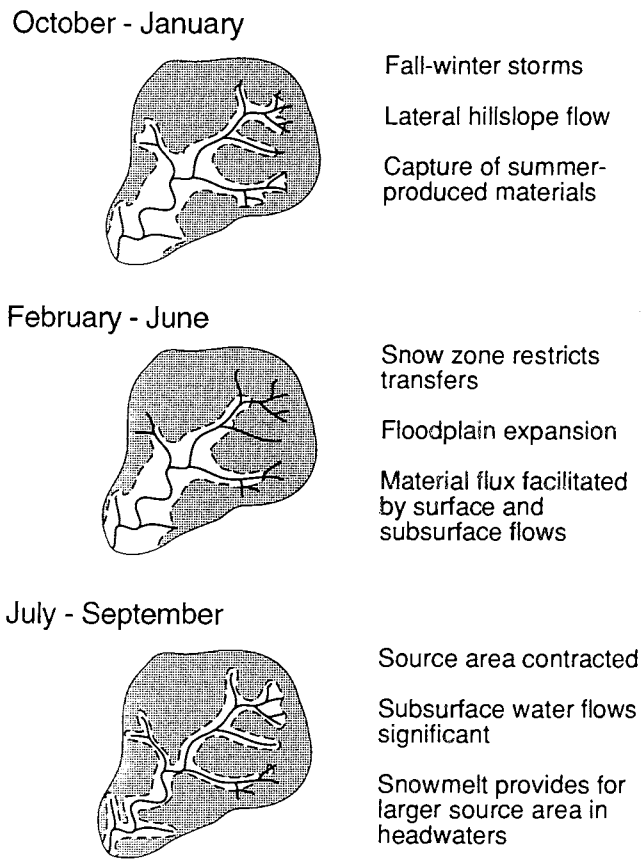

FIGURE 6.10. Variable source area concept for water availability and storage for three hydrologic seasons : October – January, February – June, and July – September.

bility of this variable source area concept (Swistock et al. 1989, Wolock et al. 1989, Sunada and Hong 1988, Fritsch et al. 1987, Rhodes et al. 1986, O'Loughlin 1986, Satterlund 1985, Troendle 1985, Bruijnzeel 1983) (Figure 6.10). These studies conducted outside the Pacific Northwest show enough similarities to extend the concept to the Pacific Northwest coastal ecoregion.

Generally, variable source area has been applied only to runoff in small watersheds. However, the concept should be extended to larger watersheds or to explain other processes, such as nutrient cycling and characteristics of riparian forests that are important to the stream ecosystem (Rhodes et al. 1986, Oliver and Hinckley 1987, Burt 1989). The dynamics of the variable source area are important where runoff timing and duration influence ecological processes. For example, during summer drought, source areas contract as drainage from hillslopes decreases (O'Loughlin 1986). As soil tem-

perature rises, biological activity increases in the shallow soil mantle until it is eventually reduced by low moisture availability (Maser and Trappe 1984, Waring and Schlesinger 1985). In autumn, precipitation increases and the variable source area expands. Water levels rise and the groundwater recharge phase begins. Increased water contact within the soil enhances the capture of carbon and nutrients (Rhodes et al. 1986, Wolock et al. 1989).

Runoff Processes in Low-Order Watersheds.

Variability in channel pattern and flow regimes creates a habitat mosaic along the longitudinal and lateral axes of streams (Minshall 1988, Pringle et al. 1988). At high elevations, low-order watersheds predominate. Topography, soil attributes, and initial source of flow (e.g., glacial, snow, seeps, hillslope runoff) influence the flow regime and variable source area for the low-order channels. Low-order watersheds are major source areas for downstream surface water and for recharge of alluvial aquifers (Compana and Boone 1986). However, water storage is limited by steep hillslopes and shallow soils adjacent to the channel. Exceptions occur in zones of small floodplains and wet meadows where local subsurface water may contribute to streamflow, in alpine areas during snowmelt, and in permanent snowfields or glacier-fed streams.

Subsurface areas may act as a storage compartment in winter and as a source for organic and inorganic nutrients (Triska et al. 1989*a*). Deep percolation and groundwater recharge occur beneath the snowpack (Compana and Boone 1986, Munter 1986, Rhodes et al. 1986). Groundwater levels and soil moisture remain high through midwinter. Subsurface flow is sufficient to sustain baseflow and contributes nutrients to streams during winter.

At high elevations, the variable source area for lower-order streams expands substantially during snowmelt as soil layers become saturated (Figures 6.4 and 6.10). When soil is fully saturated, overland flow is generated by continued snowmelt. Overland flow is important for providing additional nutrients to the stream. For example, nitrate-nitrogen concentrations are higher in overland flow than in groundwater flow, with the highest concentrations occurring during peak discharge (Rhodes et al. 1986). This nitrogen pulse is important for providing nutrients to the nitrogen-limited streams of the coastal ecoregion.

In midsummer, water levels recede and the variable source area contracts as soil water is withdrawn and transpired by vegetation (Harr 1976, Walters et al. 1980). The subsurface hydrologic gradient toward the stream increases as stream water levels subside. The subsurface storage compartment drains relatively quickly toward the stream (zone of convergence) transporting nutrients and carbon from the riparian forest (Peterjohn and Correll 1984, Triska et al. 1989*a*, *b*). During drier periods, the variable source area may shrink to the channel, with the channel then acting as the primary storage compartment.

Runoff Processes in Mid-Order Watersheds

Alluvial stream processes dominate in third- through fifth-order watersheds and channels. Variable source area and storage expand as the stream valley widens. However, surface storage in oxbow lakes and overflow channels remains limited (Benda 1990). Water movement from the hillslopes and the level of soil saturation at the hill bottom are still important runoff components (O'Loughlin 1986). One result is formation of wetlands at the base of hillsides. Wetlands are important storage areas for flow, expanding the variable source area through the season (Holland et al. 1990, Carter 1986, Wald and Schaefer 1986). In the upper reaches, riparian wetlands are restricted due to narrowness of the valley. However, wetlands form landward of fluvial floodplain features such as scroll bars, and on alluvial fans deposited by tributaries at the base of hillslopes (L. Mertes, University of California, Santa Barbara, pers. comm.). Beaver (*Castor canadenis*) also contribute to the formation of storage features (Naiman et al. 1988). During dry seasons, some wetlands become part of the variable source area; however, others are perched and do not act as a water or nutrient source to the stream, but as a sink (Beaudry et al. 1990).

Local groundwater aquifers are recharged by ample winter precipitation and snowmelt and are an important component of streamflow and the variable source area throughout the year (Walker 1960, Hewlett and Nutter 1970, Freeze and Cherry 1979, Burt and Arkell 1986). Overbank flooding provides additional recharge to groundwater and wetlands. Flooding duration is shorter than in higher-order channels. For example, the two-year flood duration in a mid-order stream (at 500–1,000 m elevation) is approximately 1–2 days. The two-year flood duration for higher-order streams is approximately 3–4 days (estimated from the USGS – Water Resource Data Reports, 1950–86). Aggradation due to mass wasting or episodic debris flows can increase the flood stage and duration for mid-order streams.

Runoff Processes in High-Order Watersheds

Higher-order (>sixth-order) watersheds and channels occur at lower elevations where the dominant form of precipitation is rain. As the stream valley broadens, the variable source area expands and remains more spatially and temporally stable (Figures 6.4 and 6.10). Tributaries still exhibit seasonal expansion and contraction, but not to the degree seen in lower-order streams at higher elevations. Flow hydrographs (Figure 6.7) indicate that winter storm and snowmelt are the dominate flow generators. Tributaries confined to lower elevations show no influence from rain-on-snow events; higher-order streams are still influenced by rain-on-snow events.

At low and moderate flow conditions, the main river channel meanders across the floodplain (Leopold et al. 1964). Over time, cutoff channels, oxbow lakes, meander scrolls, and other backwater and high water channels develop on the broad valley floor. Along some reaches, logjams redirect

flow into secondary channels, or the river forms new channels (Walker 1960, Lienkaemper and Swanson 1987). Increases in depression storage serve to lengthen the time of ponding, and to dampen flood peaks, while prolonging the duration of inundation. Nonperched systems supply water to subsurface systems following flood recession (Mitsch and Gosselink 1986, Wald and Schaefer 1986). When floodplains become inundated by overbank and breach flow (Hughes 1980), the riparian vegetation decreases water velocities due to increased resistance, causing an increase in flood stage (Dunne and Leopold 1978, Ponce and Lindquist 1990).

Precipitation, side valley runoff, and groundwater seeps contribute to water inputs and erosion of the floodplain (Dunne 1978, Higgins 1984). Major floods occur during periods of maximum soil moisture and highest subsurface and wetland water levels, thus there is little room for temporary storage. Some floodwaters are placed in long-term storage in groundwater and deeper wetlands. Flooding is not restricted just to snowmelt or storm events. Lesser magnitude floods are due to accumulated sediment, beaver dams, fallen trees, and debris dams (Sedell et al. 1988). Thus, in ecologically healthy watersheds in the Pacific Northwest coastal ecoregion, the valley bottoms are wet or flooded most of the year.

Tributaries, originating from seeps, springs, and wetlands at the base of hillslopes, flow across river terraces. Most are low gradient with stable flow regimes from strong groundwater influences. Other tributaries, classified as valley-wall tributaries (Cupp 1989*a*, *b*; Swanson and Lienkaemper 1982), start near the top of the valley slopes. These have steep gradients and variable flows. Unlike the headwater tributaries originating in the alpine/glacier area, the basins of these streams are heavily forested and contribute less suspended sediment. The flow regime of these tributaries is dominated by late winter and early spring precipitation, whereas the flow regime of the higher-order main channel is regulated by winter storms, snowmelt, and groundwater.

Lowland rivers become a network of islands, wood debris dams, sloughs, oxbow lakes, and beaver ponds (Sedell et al. 1988). The channel pattern becomes anastomosed (multiple channels) due to significant reduction in gradient, sediment inputs from upstream causing channel aggradation and backwater effects (Smith 1973). The backwater effect creates additional overbank flooding, deposition of fines, and buildup of river levees, backswamps, and other floodplain features. The alluvial deposits along the higher-order channels of the western Cascades result in some of the highest specific yields of groundwater in the United States (Martin 1982, Lum 1984, Davis 1988).

Hyporheic Processes and Subsurface Habitat

Streams in the Pacific Northwest coastal ecoregion have three interactive aquatic habitats: surface or in-channel habitat, floodplain habitat, and subsurface or hyporheic habitat. The subsurface habitat, or hyporheic zone, is

the interstitial habitat beneath the streambed that is the interface between surface water and the adjoining groundwater. Traditionally, the hyporheic zone has been considered a relatively thin area extending only tens of centimeters vertically and laterally beneath and alongside the stream (Pennak and Ward 1986). However, recent investigations on gravel-bed rivers show that these habitats can extend throughout the alluvial gravels of floodplains. Stanford and Ward (1988) found the average hyporheic habitat to be 3 km wide and 10 m deep in an alluvial floodplain on the Flathead River, Montana. Thus, in areas of extensive alluvial gravel floodplains, the hyporheic zone contributes substantially to total habitat area.

Vertical and lateral dimensions of subsurface water movements are controlled by geologic structure and layering of aquifers in the continental glacial till deposits of Washington, British Columbia, and Alaska. Toth (1963) suggests that there are three distinct systems; local systems, intermediate systems, and regional systems. Under this framework, local systems develop only where there is pronounced typographic relief. Increasing typographic relief is hypothesized to increase the depths and the intensities of the local flow systems.

Occurrence of fractured bedrock, as found throughout the Cascades, provides an avenue for upwelling of regional groundwater systems (Freeze and Cherry 1979). In lower-gradient alluvial valleys, the local water system may stagnate, allowing regional or intermediate systems to dominate or mix with local systems. Boundaries between systems are located at the highest and lowest elevations of local hills and depressions (Toth 1963). Thus the stream channel may serve as a zone of convergence between different groundwater systems. Chemical characteristics of the groundwater systems are different and are reflected in the variability of chemical parameters found within the stream or along the banks.

Hyporheic areas are important regulators of nutrient inputs to streams. The hyporheic zone, as a retention or storage compartment, provides a medium for biotic processing (Hynes 1983, Bencala 1984, Grimm and Fisher 1984, Dahm et al. 1987, Stanford and Ward 1988, Triska et al. 1989*a*, *b*). Nutrient and organic fluxes within the hyporheic zone are hypothesized to be a function of the direction and type of groundwater or surface water influence. Close to the channel, groundwater and stream water mix (Triska et al. 1989*b*, Vervier and Naiman 1992). Triska et al. (1989*b*) found that within 3.5 meters of the channel, at least 80% of the subsurface water was stream water.

The rate of exchange between the subsurface and stream ecosystems varies with the dominant hydraulic process (discharge or recharge). Dominance of groundwater or surface water depends on the season or magnitude and duration of storms (Compana and Boone 1986, Gilbert et al. 1990, Vervier and Naiman 1992). As surface water rises in the channel, groundwater recharge dominates (Freeze and Cherry 1979, Beaudry et al. 1990).

Hyporheic Processes in Low-Order Channels

Spatial connectivity of hyporheic zones in the steeper bedrock-controlled channels may be discontinuous due to constrained topography (Figure 6.4). Hyporheic zones are limited to small floodplains, meadows, and stretches of stream where coarse sediment is deposited over bedrock. System continuity is further interrupted by mass wasting and debris dam breaks which gouge channels.

Local hyporheic systems are fed by subsurface flow from hillsides. Subsurface flow through porous soils can be significant from forested slopes (Sloan and Moore 1984) where root channels, decayed root holes, worm holes, piping, and animal burrows are common (Sklash and Farvolden 1979, Higgins 1984, Roberge and Plamondon 1987, Beaudry et al. 1990).

In zones of bedrock fracture, mixing between local and regional groundwater systems may occur (S. Burgess, Civil Engineering, University of Washington, pers. comm.). However, in the subsurface ecosystem, local groundwater dominates. Dominance affects several parameters, such as quality of organic matter, water chemistry, and faunal distribution (Triska et al. 1989*a*, *b*; Gilbert et al. 1990). Relatively high subsurface velocities on hillsides mean less soil contact time and mineralization than in downstream areas (Wolock et al. 1989).

Hyporheic Processes in Mid-Order Channels

As valleys broaden to a wider alluvial floodplain with less topograhic constraints, the spatial connectivity of the hyporheic zone becomes more continuous (Figure 6.4). Local groundwater systems still dominate the subsurface ecosystem. Depth and intensity of the local system should be greatest in this zone (Toth 1963). As the floodplain widens and topographic relief decreases, stagnation of the local system promotes mixing of intermediate and regional systems, especially during drier periods when hydraulic gradients toward the stream are strongest (Freeze and Cherry 1979).

As surface discharge declines, as during the summer drought period, the system is dominated by groundwater discharge. Exceptions occur during storms (Vervier and Naiman 1992). During surface low-water periods the hyporheic zone acts as a source of water, nutrients, and energy to the stream (Wallis et al. 1981, Bencala 1984, Naiman et al. 1987, Ford and Naiman 1989, Triska et al. 1989*a*, *b*).

Hyporehic Processes in High-Order Channels

In higher-order streams, with wide floodplains and unconstrained valleys, the spatial extent of hyporheic habitat is greater than upstream (Figure 6.4). However, discontinuities in spatial connectivity increase as the influence of local groundwater system decreases. For example, small topographic variations created by fluvial structures such as scroll bars, cutoff channels, oxbow lakes, and wetlands create discontinuities. As a result of local system

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Water Quality

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dynamics and varying topography on the floodplain, alternating recharge and discharge areas are found across the valley (Toth 1963, Winter 1987).

Soil and substrate permeability in the floodplain and channel is variable due to erosional and depositional fluvial processes and deposition of till during the continental glacial period. However, duration of overbank flows and ponding is longer in higher-order watersheds, enhancing opportunities to transmit organic matter and nutrients from surface water to the hyporheic zone. Subsurface storage and retention of nutrients increases as the spatial extent of channel features (e.g., side bars and channel bars) increases (Bencala 1984).

Functions of Hyporheic Zones

Hyporheic zones act as sensitive indicators of ecological health, since processes there substantially influence energy and nutrient resources in riparian forests and aquatic surface systems (Wallis et al. 1981, Hynes 1983, Peterjohn and Correll 1984, Lowrance et al. 1984, Grimm and Fisher 1984, Stanford and Ward 1988, Ford and Naiman 1989, Triska et al. 1989*a*, *b*; Gibert et al. 1990). Hyporheic zones can act as a sink, storage, or source depending on spatial location and season.

Retention of nitrogen, phosphorus, and organic carbon within the subsurface zone occurs during the recharge phase. Low hydraulic gradients and slower velocities enhance biotic activity (Winter 1987, Triska et al. 1989*a*, *b*). However, anaerobic processes such as denitrification may dominate during this phase due to saturated soil conditions (Hixson et al. 1990). As the recharge phase shifts to a discharge phase, aerobic processes such as nitrification become dominant. The type and intensity of biochemical processes will influence biodiversity and the spatial distribution of animals using hyporheic habitat.

Numerous and often contradictory hypotheses exist concerning the flux of carbon, nitrogen, and phosphorus from subsurface to surface waters. For example, Fisher and Likens (1973) reported that groundwater diluted organic carbon in stream systems in New Hampshire. Hynes (1983) also hypothesized that hyporheic zones serve as a sink for organic matter in Ontario. Yet groundwater has been found to be a significant source of carbon and nutrients to streams (Hynes 1983, Grimm and Fisher 1984, Dahm et al. 1987, Naiman et al. 1987, Ford and Naiman 1989). Rutherford and Hynes (1987) suggest that the hyporheic zone is too heterogeneous to make a source or sink conclusion. The results, equivocal to date, point to the need for better information about an inherently complicated system that is of fundamental importance for watershed functions (Pinay et al. 1990).

Water Quality

Selection of Fundamental Water Quality Elements

Water quality is a fundamental component of watershed health because it effectively integrates the full range of geomorphic, hydrologic, and biologic processes (Hem 1985). Alterations to any one of these processes will affect

one or more water quality parameters (Frere et al. 1982, Peterjohn and Correll 1984). Hence changes in water quality indicate a change in some aspect of the terrestrial, riparian, or in-channel ecosystem. Conversely, water quality affects the aquatic, riparian, and hyporheic ecosystems (Hynes 1966, 1970; Stanford and Ward 1988, MacDonald et al. 1991). These interactions are extremely complex, and recognition of their importance does not simplify the problem of associating an observed change in water quality with a particular cause. In ecologically healthy streams there is considerable spatial and temporal variability in water quality parameters due to the large number of controlling factors and the uneven distribution of these factors in space and time (Feller and Kimmins 1979, Bencala et al. 1984, Keller et al. 1986).

We focus on just five of many water quality elements related to ecologically healthy systems: (1) nitrogen (particularly nitrate-nitrogen), (2) phosphorus (principally phosphates), (3) turbidity, (4) temperature, and (5) intragravel dissolved oxygen. Other important elements related to the ecological health of watersheds, such as buffering capacity (pH and alkalinity), organic nutrients (forms of dissolved organic carbon), and potential toxicants (wastes, insecticides, herbicides), are not considered here. The five elements chosen were selected after discussions with water quality experts and a review of the results of a recent project sponsored by the Environmental Protection Agency to develop guidelines for monitoring the effects of forestry activities on streams in the Pacific Northwest and Alaska (MacDonald et al. 1991). Consideration was limited to the physical and chemical constituents of water even though channel, riparian, and other biological characteristics are equally important for maintaining an ecologically healthy system (MacDonald et al. 1991). The intent is that, taken together, these five elements provide an indication of the basic health of lotic systems in the Pacific Northwest coastal ecoregion.

Role and Expected Values

Nitrogen and phosphorus are typically limiting nutrients in coastal ecoregion streams (Hem 1985). The mass flux of N and P is a function of critical processes such as the efficiency of terrestrial nutrient cycles, flow and transformations of organic material, and erosion of particulate matter (Sollins et al. 1980, Harr and Fredriksen 1988, Martin and Harr 1989). Use of both nitrogen and phosphorus is complementary because phosphorus tends to be sorbed and transported in particulate form, while nitrogen usually is dissolved and transported by subsurface and groundwater flow (Mohaupt 1986). In the absence of other limiting factors such as light, increased concentrations of plant-available nitrogen and phosphorus stimulate primary production (Gregory et al. 1987).

The range of conditions found from southeastern Alaska to northern California, and from the coast to the permanent snow zone, make it difficult

to specify expected values. For example, mean annual nitrate-nitrogen concentrations in undisturbed headwater streams range from less than 0.01 mg/L (Harr and Fredriksen 1988, Martin and Harr 1989) to 1.2 mg/L (Brown et al. 1973). Because atmospheric inputs usually are larger than the loss of nitrogen by leaching, there is a small net input of 0.1–2.6 kg N ha^{-1} yr^{-1} in undisturbed forested watersheds west of the Cascades (Feller and Kimmins 1979, Martin and Harr 1989).

Mean annual phosphorus concentrations in small forest streams typically are less than 0.06 mg/L (Brown et al. 1973, Feller and Kimmins 1979, Harr and Fredriksen 1988, Martin and Harr 1989). Annual phosphorus budgets for four forested coastal watersheds range from a net gain of 0.1 kg ha^{-1} yr^{-1} to a net loss of 0.3 kg ha^{-1} yr^{-1} (Feller and Kimmins 1979).

Turbidity is a measure of light scattering by a water sample. In most cases, suspended silt and clay particles are the primary cause of high turbidities, although colored organic compounds, finely divided organic matter, and microorganisms such as plankton also contribute (APHA 1989). Turbidity is useful as an easily measured indicator of suspended sediment concentrations (Kunkle and Comer 1971, Aumen et al. 1989), and hence a first approximation of erosion rates. Suspended sediment has wide-ranging effects on salmonids, invertebrates, and other aquatic organisms (Everest et al. 1987, Chapman and McLeod 1987).

Expected values for turbidity are difficult to specify because turbidity is discharge dependent and extremely variable throughout the region. Hence turbidity standards usually are expressed in terms of an allowable increase over background (Harvey 1989). The absolute values necessary to protect designated uses, such as sight feeding by salmonids, are <25 NTU (EPA 1986); greater values generally are encountered only during major floods (Aumen et al. 1989).

Water temperature greatly affects rates of chemical and biological processes. Although absolute stream temperatures are largely a function of the subsoil environment and climatic conditions (Beschta et al. 1987), stream temperature is a relatively sensitive indicator of riparian conditions (Brown and Krygier 1970, Harr and Fredriksen 1988). As noted previously, stream channel morphology also affects the temperature regime. Temperature is largely a function of discharge and incoming solar radiation, and is relatively predictable for specific locations.

Intragravel concentration of dissolved oxygen (DO) is critical for salmonid reproduction, invertebrates, and other aquatic life. Furthermore, the concentration of intragravel DO integrates numerous other factors, including temperature, bed material particle size, and the deposition of fine sediment and particulate organic matter (MacDonald et al. 1991). In undisturbed alluvial streams the concentration of intragravel dissolved oxygen should approach saturated values; values substantially less than saturation suggest blockage of interstitial water flow (Chapman and McLeod 1987) or high

Table 6.2. Relative importance of factors controlling the observed values of selected water quality elements in coastal ecoregion streams.

	Water Quality Element				
Controlling Factor	Nitrogen	Phosphorus	Turbidity	Temperature	Intragravel Dissolved Oxygen
Climatic and atmospheric inputs	High	Low	Moderate	High	Low
Geology and soils	Moderate	High	High	Moderate	High
Stream order	Moderate	Moderate	Moderate	High	Moderate
Constrained or unconstrained channels	High	High	High	Moderate	Moderate
Vegetation	High	Moderate	Moderate	High	Low

oxygen demand from the breakdown of organic materials (Ringler and Hall 1975, Plamondon et al. 1982).

Little data are available for intragravel DO values for ecologically healthy watersheds. Suggested one- and seven-day minimum values for intragravel DO are 5.0 and 6.5 mg O_2/L, respectively (EPA 1986). Idaho is considering an intragravel DO standard of 85% of the saturated value (Harvey 1989), but adoption of this standard has been slowed by uncertainty over intragravel DO values in undisturbed streams, and by the high spatial variability of intragravel DO in a stream segment or even within a salmonid redd (Chapman and McLeod 1987).

Taken together, these five fundamental elements are one indication of the suitability of streams for cold-water fishes and provide an integrated view of watershed health. Other parameters could be supplemented, but these five represent a best *initial* indication of watershed health over the range of environmental conditions found in the Pacific Northwest coastal ecoregion.

Controlling Factors

Expected values of these five fundamental elements are a function of multiple controlling factors, and each element has a unique response to the set of controlling factors. Table 6.2 qualitatively summarizes the relative importance of five factors—climatic and atmospheric inputs, geology and soils, stream order, valley type (constrained versus unconstrained channels), and vegetation—on the selected water quality elements.

The first controlling factor—climatic and atmospheric inputs—strongly affects nearly all water quality elements. In the Bull Run watershed near Portland, Oregon, for example, precipitation accounts for approximately 60% of the dissolved ionic load in surface runoff (Aumen et al. 1989). Atmospheric nitrogen inputs generally exceed nitrogen losses (Feller and Kimmins 1979). Solar radiation is a dominant variable in predicting stream temper-

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Riparian Forest

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atures (Beschta et al. 1987). Turbidity is highly responsive to the size and spacing of storm events (Brown 1983). Climatic and atmospheric inputs also help define basic processes such as the volume and timing of runoff, weathering rates, and the likelihood of mass failures. Thus virtually all water quality parameters are affected by climatic and atmospheric inputs (Risser, this volume), but nitrogen and water temperature generally are more responsive than phosphorus or intragravel DO.

Geology and soils are important factors in determining the amount and type of erosion, hence the levels of turbidity, phosphorus, and indirectly intragravel DO (Everest et al. 1987, Chapman and McLeod 1987). Nitrogen also is relatively sensitive to geology and soils because losses occur primarily in dissolved form, and this is a function of soil and groundwater processes (Feller and Kimmins 1979, Sollins et al. 1980).

Relatively few studies have related values of these fundamental elements to stream order in undisturbed watersheds. In general, increasing stream order reduces temporal variability, but absolute effects are uncertain. In interior Alaska stream order has no effect on phosphorus or turbidity, while nitrogen shows a slight decrease downstream (Hilgert and Slaughter 1988). Changes in stream temperature are more predictable, with the observed temperature generally increasing downstream. Intragravel DO should decline with increasing stream order because the larger volume of water reduces the reaeration rate, mean water temperatures are higher, and the finer bed material associated with higher-order streams reduces subsurface permeability.

Differences in water quality between geomorphically constrained and unconstrained channels will result from differences in subsurface flow paths, sideslope gradients and resultant erosion and transport rates, and width of riparian and hyporheic zones. Turbidity is most likely to be sensitive to valley form, with lesser or indirect effects on other water quality elements.

Vegetation is the final controlling factor. Healthy watersheds in the Pacific coastal ecoregion generally have a dense forest cover, and this helps keep water temperatures and sediment loads in the range suitable for salmonids. In addition, both density and vegetation type affect nitrogen fixation and uptake (Sollins et al. 1980).

Since all five fundamental elements respond directly or indirectly to the same basic driving forces of runoff, erosion, and weathering, there are significant interactions among these elements. The use of several water quality elements is necessary to assess the specific condition (health) of the drainage network, and to fully evaluate the effects of natural and anthropogenic changes.

Riparian Forest Characteristics

The natural characteristics and ecological health of streams and rivers are intimately linked to the surrounding landscape by the biotic and physiochemical properties of the riparian zone. The riparian zone extends from the edge of the average high water mark of the wetted channel toward the uplands

(Figure 6.11). This zone includes terrestrial areas where vegetation and microclimate are influenced by perennial or intermittent water associated with high water tables, and by the ability of soils to hold water. Beyond this is the riparian "zone of influence," a transition area between the riparian zone and the upland forest where vegetation still influences the stream under some conditions (Gregory et al. 1991).

In ecologically healthy watersheds, riparian forest characteristics are strongly controlled by climate (e.g., hydrologic regime), channel geomorphology, and the spatial position of the channel in the drainage network. Historically, riparian forests formed a continuous ribbon of vegetation along stream channels. Upon closer examination, this vegetative ribbon was a mosaic of different stand ages and species from the headwaters to the sea (Maser et al. 1988). Riparian forests once covered large areas, especially in the alluvial lowlands (Sedell et al. 1988).

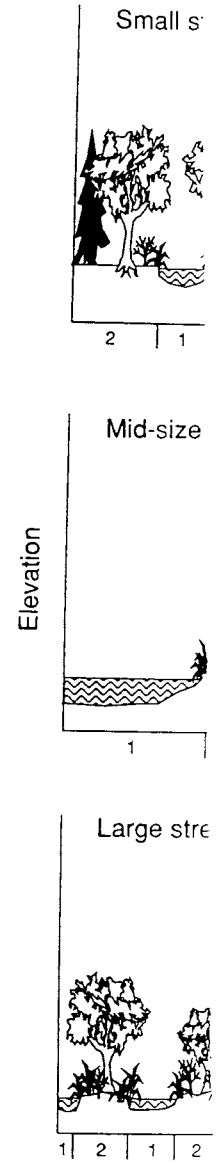
The width of the riparian zone, and the extent of the forest's influence on the stream, are strongly related to stream size and valley morphology. Small streams possess relatively little riparian vegetation; they are more influenced by vegetation in the upland forest (zone of influence) (Figure 6.11). Mid-order streams and rivers (third to fifth order) typically have a distinct band of riparian vegetation, whose width is defined by long-term (>50 yr) channel dynamics and the annual discharge regime. Large rivers are characterized by well-developed, complex floodplains with long periods of seasonal flooding, oxbow lakes in old river channels, a diverse forest community, and moist soils. Ecologically healthy watersheds require the influence of riparian forests on streams, especially in relation to controlling the light and temperature regimes, providing nourishment for the stream biota, and being a source of large woody debris (Table 6.3).

Light and Temperature

The amount and quality of light reaching streams are determined by forest vegetation height, forest canopy density, stream channel width, and channel orientation in relation to the sun's path in the sky. Light is important for streams because of its influence on water temperature, on primary production by aquatic plants, and on the behavior of organisms.

Seasonal and daily water temperatures are strongly influenced by the amount of solar radiation reaching the stream surface through the forest canopy (Beschta et al. 1987). The temperature of water entering a small stream typically reflects that of the forest's subsoil environment, but changes as water flows downstream. Water temperature is an important factor for environmental vitality because of its controlling influence on the metabolism, development, and activity of stream organisms.

Small forested streams typically receive 1 to 3% of total available solar radiation (Naiman and Sedell 1980, Naiman 1983, 1990). Small streams have relatively cool but stable daily temperatures, low rates of primary pro-



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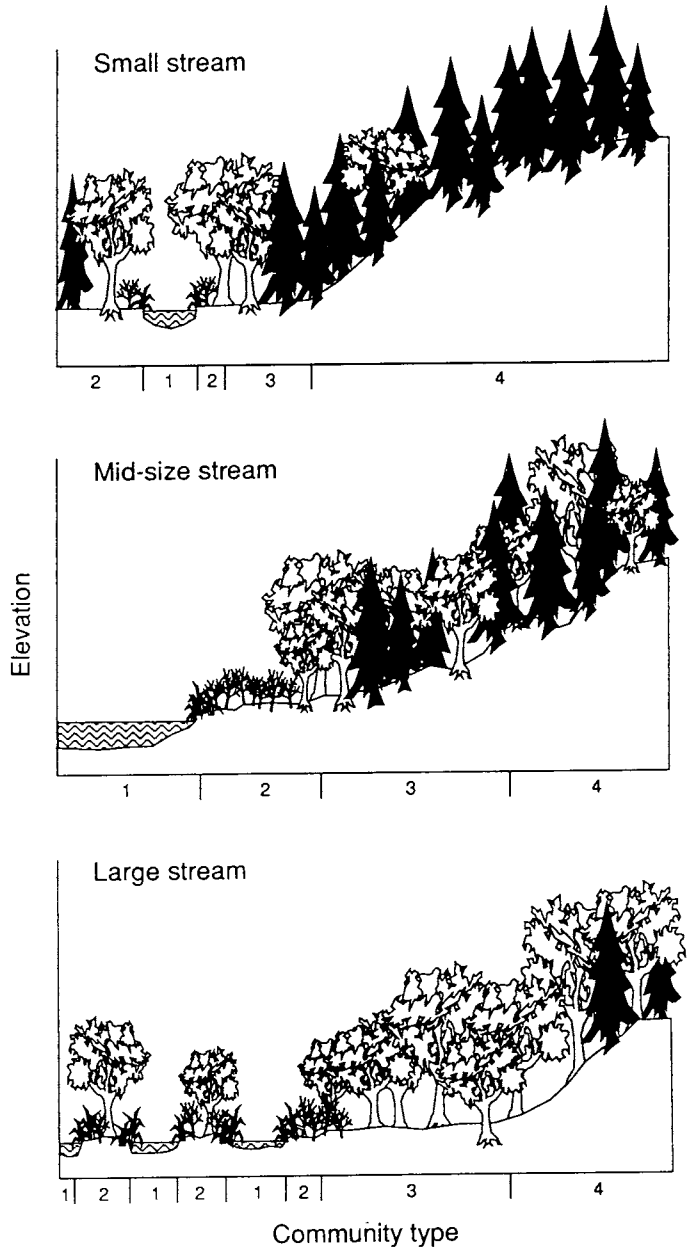

FIGURE 6.11. The natural characteristics of the riparian zone change with stream size. In low- and mid-order streams the links between the riparian forest and the stream are strong. In large rivers the links are not as strong in the main channel but they do remain strong in the secondary channels. Key: (1) active channel, (2) riparian zone, (3) zone of influence, (4) uplands. Note that (2) and (3) make up the complete riparian zone of influence.

Table 6.3. Functions of riparian vegetation with respect to aquatic ecosystems.

Sites	Components	Functions
Aboveground/above channel	Canopy and stems	Shade controls temperature and in-stream primary production Source of large and fine plant detritus Wildlife habitat
In channel	Large debris derived from riparian vegetation	Controls routing of water and sediment Shapes habitat: pools, riffles, cover Substrate for biological activity
Streambanks	Roots	Increases bank stability Creates overhanging banks, cover Nutrient uptake from ground and stream water
Floodplain	Stems and low-lying canopy	Retards movement of sediment, water, and floated organic debris during floods

Source: Swanson et al. (1982), p. 269.

duction, and organisms that are behaviorally adapted to reduced light and cool temperatures (Naiman and Sedell 1980). In mid-order streams and rivers, gaps appear in the riparian forest canopy. These gaps allow 10 to 25% of the total available solar radiation to reach the stream surface. Daily variations of ~2–6°C and seasonal variations of 5–20°C in water temperature may occur, primary production by attached algae and diatoms increases, distinct day-night differences exist in species-specific behavior to light levels, and the biota are metabolically adapted to slightly warmer temperatures. In larger rivers, most available solar radiation reaches the water surface of the main channel through wide gaps in the forest canopy. However, in contrast to reaches upstream, the main channel of large rivers tends to be deeper or more turbid, restricting light penetration through the water. Daily variations in temperature are not as large as in mid-order streams, and depending on water depth, primary production may be less. In addition, primary production is augmented by phytoplankton suspended in the water column and vascular plants rooted near the shore. Finally, most organisms are adapted for life in waters that are dark, or with reduced visibilities.

As water flows downstream, temperature changes in response to factors involved in the heat balance of water, all of which are strongly influenced by the riparian forest. The net rate of gain or loss of temperature is the algebraic sum of net solar radiation, evaporation, convection, conduction, and advection. Net radiation is generally dominated by the amount of direct-beam solar radiation reaching a stream's surface. Heat gain or loss from evaporation and convection depends on the vapor pressure and the temperature gradient at the water surface and the air immediately above the surface,

respectively. Wind speed at the air-water interface is also an important controlling variable. Conduction of heat between water in the stream and the channel substrate depends on the type of material making up the substrate. Bedrock channels are more efficient than gravel-bed channels at conducting heat. Heat exchange by advection occurs when tributaries or groundwater of different temperatures mix with the main streamflow, thereby either increasing or decreasing the main stream temperature.

The influence of shading by the riparian forest on the heat balance of a small stream can be enormous because net solar radiation, evaporation, convection, conduction, and advection remain relatively small over a 24-hour period, even in midsummer, relative to groundwater temperature. Should the forest canopy be opened by a disturbance, the net heat exchange can be significantly altered. For example, during winter, streams without riparian canopies may experience lower temperatures because the lack of cover enhances energy losses by evaporation, convection, or long-wave radiation. Long-wave radiation losses are greatest when clear skies prevail, particularly at night, resulting in the formation of surface and anchor ice. During summer, the lack of a forest canopy cover results in large (3–10°C) diel variations in temperature as the amount of direct solar radiation increases (Beschta et al. 1987).

Instantaneous temperatures and cumulative temperatures (e.g., degree-days per unit of time) have a significant influence on biotic characteristics. Instantaneous temperature significantly affects water viscosity, and therefore the amount of energy required to swim. It influences an organism's metabolism, dictating the amount of food required for daily activities and reproductive products. Further, species preferences for temperature influence the ability of an organism to successfully compete for resources, and thereby influencing community composition and abundance. Fish and invertebrates have specific requirements for the number of degree-days needed for egg development and for the timing of reproduction and emergence, thereby reducing competition for food and reproduction sites by subtle differences in phenology or life history strategies (Sweeney and Vannote 1978).

Sources of Nourishment

Annually, riparian forests add large amounts of leaves, cones, wood, and dissolved nutrients to low- and mid-order streams (Gregory et al. 1991). These organic inputs originate as particles falling directly from the forest into the stream channel (or moving downslope along the forest floor by wind and water driven erosion) and as dissolved materials in subsurface water flowing from the hyporheic zone.

The riparian forest is an important regulator of stream productivity through the amounts and qualities of material directly contributed to the stream. Small streams directly receive 300–600 g C/m^2 annually from the forest, with the

rate per unit area decreasing as channel width (and the gap in the forest canopy) increases (Conners and Naiman 1984). In deciduous riparian forests >80% of these inputs may be leaves that are delivered over a six-to-eight week autumn period. In coniferous riparian forests ~40–50% of the material may be cones or wood. The chemical quality of the material (i.e., nitrogen and lignin content) strongly influences the rate of decay and subsequent trophic pathways (Melillo et al. 1983, 1984). The complete decay process takes about one year for most high quality materials such as leaves and herbaceous plants and may take several years or decades for low quality materials such as cones and wood (Gregory et al. 1991).

Subsurface water moving from the uplands to the stream also carries large quantities of dissolved organic matter and nutrients essential for stream function. The riparian forests chemically alter these materials as the subsurface water flows pass their root systems. Riparian forests take up nutrients for growth, promote denitrification by subtle changes in the position of oxic-anoxic zones, and modify the chemical composition and availability of carbon and phosphorus (Pinay et al. 1990). Exact mechanisms regulating these processes are not well understood (Triska et al. 1989*a*, *b*). Yet the presence of riparian forests significantly regulates the amount of nitrogen and phosphorus reaching streams from upland areas (Karr and Schlosser 1978, Schlosser and Karr 1981*a*, *b*; Peterjohn and Correll 1984).

Large Woody Debris

Large woody debris (LWD) is the principal factor determining the characteristics of aquatic habitats in low- and mid-order forested streams. The amount of LWD in streams can be substantial, ranging from >40 kg/m^2 in small streams to 1–5 kg/m^2 in large rivers (Harmon et al. 1986). The importance of LWD relates to its ability to control the routing of sediment and water, to shape the formation and distribution of pools, riffles, and cover, and to act as a substrate for biological activity (Swanson et al. 1982; Table 6.3).

Wood boles (>10 cm diameter) enter streams of all sizes from the riparian forest. However, the spatial distribution of LWD varies systematically from small streams to large rivers, reflecting, in part, the balance between stream size and wood size (Bilby 1981). Wood in small streams is large relative to channel dimensions and to peak stream flow. Thus LWD cannot be easily floated and redistributed, and consequently is randomly distributed and often located where it initially fell. But these small channels are often in the steepest part of the drainage network, and are most prone to catastrophic flushing by extreme landslide/dam-break floods (Benda 1990). Mid-order streams are large enough to redistribute LWD but narrow enough that LWD accumulations across the entire channel are common. LWD tends to be concentrated in distinct accumulations spaced several channel widths apart along the stream. In large rivers, LWD is commonly collected in scattered, distinct accumulations at high water and particularly on the upstream ends of islands

and at bends in the river (Lienkaemper and Swanson 1987, Potts and Anderson 1990). Natural anchors such as root wads, large limbs, or lodging of LWD between other obstructions improve debris retention and are important considerations for environmental health of the system.

LWD in streams influences channel morphology as well as sediment and water routing. In small streams LWD creates a stair-stepped gradient where the streambed becomes a series of long, low gradient sections separated by relatively short, steep falls or cascades (Grant et al. 1990). Therefore, much of the streambed may have a gradient less than the overall gradient of the valley bottom, because much of the decrease in altitude, and in potential energy, takes place in the short, steep reaches. This pattern of energy dissipation in short stream reaches results in less erosion to bed and banks, more sediment storage in the channel, slower downstream movement of organic detritus, and greater habitat diversity than in straight, even-gradient channels (Bisson et al. 1987).

Comparison of volumes of stored sediment and annual sediment export suggests that small forested streams with natural amounts of LWD annually export often <10% of sediment stored in the channel system (Swanson et al. 1982). LWD makes up ~40% of the obstructions that trap sediment in forested streams (Bilby and Ward 1989). Unfilled storage capacity serves to buffer potential sedimentation impacts on downstream areas when pulses of sediment from the uplands enter stream channels. Scattered LWD in channels reduces the rate of sediment movement downstream, routing sediment through the stream ecosystem slowly, except in cases of catastrophic flushing events or when the storage capacity is filled.

By redirecting water flow, LWD has both positive and negative effects on bank stability, on the lateral geomorphic mobility of channels, and on the stability of aquatic habitats (Keller and Swanson 1979). LWD-related bank stability problems in steep-sided, bedrock-controlled streams result from undercutting of the soil mantle on hillslopes by debris torrents. Undercut slopes are subject to progressive failure by surface erosion and small-scale (<1,000 m^3) mass erosion over a period of years. Both bank instability and lateral channel migration may be facilitated by LWD accumulations in channels with abundant alluvium and minimal bedrock influence. Changes in channel conditions and position often occur as a stream bypasses a LWD accumulation and cuts a new channel. Where channels pass through massive debris accumulations, streamflow may become subsurface much of the year. In areas of active earthflows from the forest, lateral stream cutting may undermine banks, encouraging further hillslope failure and accelerated sediment supply to the channel. On balance, however, LWD generally stabilizes small streams by dissipating energy and by protecting streambanks.

As a result of these mechanisms, LWD helps regulate the distribution and temporal stability of fast-water erosional areas and slow-water depositional sites. LWD and riparian vegetation provide cover and nourishment for all stream organisms, serving as habitat or substrate for substantial biological

activity by microorganisms, invertebrates, and other aquatic organisms (Gregory et al. 1991, Naiman 1990). Filter feeding invertebrates, algae, and diatoms attach in large numbers to LWD, significantly influencing nutrient cycling and, consequently, downstream water quality. LWD accumulations on the streambanks provide habitat for small mammals and birds that feed on stream biota (Doyle 1985). An alteration to the supply rate or the size of LWD from the riparian forest has consequences that may take tens to hundreds of years for natural processes to correct.

Habitat Characteristics

In ecologically healthy watersheds, interactions between channel geomorphology, hydrologic pattern, spatial position of the channel, and riparian forest characteristics produce habitat for terrestrial and aquatic organisms. Fundamental habitat features influencing animal population dynamics, productivity, biodiversity, and evolutionary processes are related to riparian forest dynamics, spatial and temporal variability of the habitat, and maintenance of migratory connectivity. In our discussion we offer six examples: salmonid habitat preferences, fish community habitat requirements, watershed-scale patterns in habitat, influence of LWD on habitat development, the potential role of woody debris piles to act as nodes of ecological organization in fluvial corridors, and habitat alterations by wildlife communities. We then discuss an example of food web dynamics shifting in response to changing habitat. In combination, these examples have broad implications for ecosystem health.

Salmonid Habitat Preferences

Each salmonid species indigenous to the coastal ecoregion employs a different life history strategy (Everest 1987), and consequently utilizes a different suite of habitats (Bisson et al. 1982). These differing life history strategies allow salmonids to fully utilize available habitats in a single watershed by segregating habitats spatially and temporally. It is well known that healthy salmonid populations respond to characteristics and location of spawning areas, postemergent rearing areas, summer (low water) rearing areas, winter rearing areas, and estuarine conditions at smolting. For example, rearing habitats in small streams are used differently by juvenile steelhead (*Oncorhynchus mykiss*) and coho salmon (*O. kisutch*). During the summer rearing period, coho tend to occupy pools, whereas steelhead prefer riffles and glides (Bisson et al. 1988), but during winter coho move to wall-base channels (Peterson and Reid 1984) and steelhead occupy terrace tributaries (Scarlett and Cederholm 1984). Furthermore, spawning areas and timing of spawning may nearly overlap among species such as pink salmon (*O. gorbuscha*), chum salmon (*O. keta*), and coho salmon. However, because pink salmon and chum salmon migrate to sea soon after emergence, there is no competition among juveniles of these species while in streams.

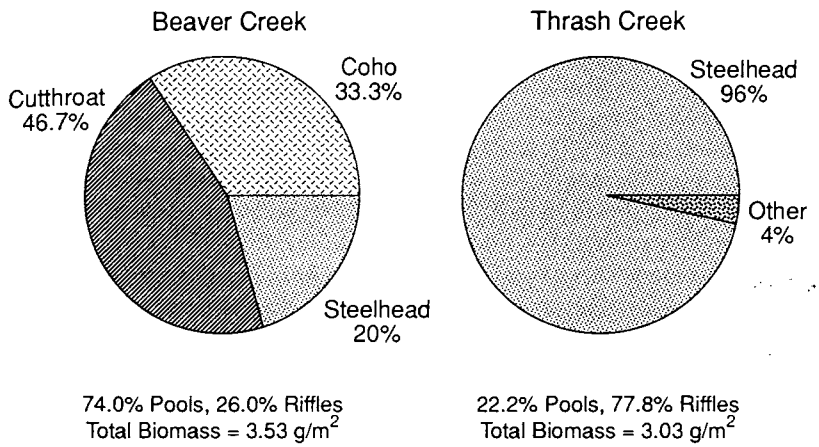

FIGURE 6.12. Juvenile fish habitat preferences in two western Washington streams with different proportions of pool and riffle areas (P. A. Bisson, unpublished data).

In stream reaches (defined as a section of channel >10 m in length), habitat preferences influence which portions of streams are dominated by juveniles of different species during summer (Figure 6.12). However, these influences are also affected by the availability of suitable spawning gravels for each species, and by other habitat factors, such as cover. Though the habitat requirements of juvenile coho salmon, steelhead trout, and cutthroat trout (*O. clarki*) have been extensively studied, species occupying the larger rivers, floodplains, and estuaries during the juvenile life history stages (e.g., chinook [*O. tshawytscha*], chum, and pink salmon) are not well known. However, it is clear that healthy salmonid populations utilize habitats throughout the drainage network during different stages of their life cycles, suggesting that connectivity between habitats is of fundamental importance.

Fish Community Habitat Requirements

Compared with forested ecosystems in eastern North America, fish species diversity in the coastal ecoregion is low. This results from zoogeographic barriers (McPhail 1967, Reimers and Bond 1967), the geologically short time interval since the last glacial period, and an unpredictable and often severe maritime climate (Moyle and Herbold 1987). What the coastal ecoregion streams lack in species richness, however, is partly offset by a remarkable differentiation among locally adapted stocks. For example, Nehlsen et al. (1991) have identified a large number of distinctive stocks of salmonids within California, Oregon, Idaho, and Washington, 214 of which are considered to be currently at risk of extinction. Fish assemblages in coastal streams are therefore characterized by relatively few, but highly adapted and often genetically unique, native species.

Stream fishes in the coastal ecoregion face unpredictable streamflows and substrate conditions, and relatively low levels of aquatic productivity because of large seasonal environmental changes. Moyle and Herbold (1987) have summarized the general adaptations of western species to life in streams; these include large body size, long life and reproductive spans, high fecundity, extensive migrations, and feeding specialization. Such adaptations confer the ability to migrate to areas where food resources are abundant or conditions for successful reproduction exist (Northcote 1978), and also the abilities to spread the risk of reproduction over several years (important in climatic and geologic unstable areas) and to make maximum use of scarce food resources through morphological and behavioral specialization.

Ecologically healthy watersheds provide a wide array of stream conditions (Naiman et al. 1991), nearly all of which are used directly in various life history stages of one or more species (Everest 1987). Fishes in coastal ecoregion streams tend to have dynamic life cycles closely linked to climate, valley form, and the input and transport of sediment and woody debris within the drainage network. Reproduction is associated with specific hydrologic and climatic conditions. Spawning migrations usually occur when streams possess intermediate flows, typically in autumn or spring. Eggs are laid in well-sorted, clean gravels that have a relatively low probability of scouring. Often these substrates are located in unconstrained channels that exhibit some braiding. Fish species that spawn on aquatic vegetation or on mud substrates (Umbridae, Gasterosteidae, some Cyprinidae) locate suitable areas in beaver ponds and in backwaters and sloughs on the floodplain; *connections* between the river mainstem and floodplain channels must be maintained for successful reproduction of these species to occur. Most fishes in the coastal ecoregion avoid spawning in steep, constrained river valleys unless their lack of mobility prevents migration to reaches with a shallower gradient. In such cases, tributary mouths or other geomorphic features characterized by coarse sediment deposits and low gradient may provide easily accessible but localized spawning sites.

Egg and alevin survival within stream gravel depends on the redd remaining relatively free of fine sediment and maintaining good permeability to ensure that developing embryos have an adequate oxygen supply (Chapman 1988). Deposition of fine sediment during incubation reduces survival to emergence through anoxia or physical entrapment. In general, emergence is timed to avoid large freshets that carry fry downstream away from rearing areas. Increases in the magnitude and frequency of storm flows, particularly in spring, can have a significant impact on survival of juvenile salmonids (Hartman et al. 1987). Other taxa such as Cottidae, Cyprinidae, and Catostomidae, which usually spawn in spring and early summer, may be similarly affected by changes in discharge patterns.

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ing boulders and LWD (Bisson et al. 1987, Moore and Gregory 1988*a*). The complexity of channel margins can be an important factor influencing early rearing (Moore and Gregory 1988*b*); therefore, ecologically healthy streams possess complex margins that include backwaters, secondary channels, fallen trees, boulders, and other features that create areas of slowly moving water. Undercut streambanks with the root systems of riparian trees also provide excellent habitat for fry, as well as protection from terrestrial predators. Interactions between stream channels and riparian vegetation become critical to the maintenance of habitat for fry.

As fish grow larger they become better able to maintain feeding stations in swifter currents and more adept at avoiding predators. Preferred habitat often shifts from stream and river margins to deeper water, where the availability of drifting aquatic invertebrates may be greater (Chapman and Bjornn 1969). Some larger salmonids and cyprinids move from tributaries into the river mainstem with the onset of summer. In most cases such movements are timed to take advantage of seasonally abundant food. However, in certain instances summer movements are dictated by the thermal regime, with cold-adapted species seeking out groundwater seeps and congregating around the mouths of cooler tributaries or at the bottom of thermally stratified pools (Berman 1990). Beschta et al. (1987) point out that many fish stocks are adapted to local temperature regimes and that significant alteration of these regimes can lead to disruption of important life cycle events, such as the timing of migrations.

Segments of streams and rivers that provide productive rearing environments in summer may not be optimal winter rearing sites. Periods of high discharge and low food availability force some fishes to seek overwintering locations away from headwater streams and adjacent to, but not in, river mainstems (Peterson 1982*a*, Tschaplinski and Hartman 1983). Quite often these areas are located in seasonally flooded wetlands, beaver ponds, and spring-fed tributaries at the base of steep valley walls (Skeesick 1970, Cederholm and Reid 1987, Brown and Hartman 1988). Almost invariably they are characterized by pondlike conditions having relatively stable discharge and low current velocities. Although such sites serve as important refugia from high flows and heavy sediment loads, certain types of invertebrates can be abundant in them and winter growth rates of fish in off-channel ponds and swamps can be considerably greater than those overwintering in the mainstem (Peterson 1982*b*, Brown and Hartman 1988). Some species that do not emigrate from headwater streams or main channel habitats to seasonally flooded wetlands and spring-fed tributaries along the valley floor instead make use of the protection afforded by woody debris accumulations along the channel margin (Bustard and Narver 1975). Perhaps at no other time of the year are riparian vegetation and floodplain interactions more important to the maintenance of productive rearing habitat in watersheds than during winter.

Watershed-Scale Patterns in Habitat

Spatial patterns of physical habitat expressed at the scale of large watersheds (>100 km^2) in the coastal ecoregion are largely controlled by regional geology and geomorphology. The bedrock geology is the result of millions of years of lithologic and tectonic processes, whereas the geomorphology of individual watersheds has been heavily influenced by glaciation for at least 20,000 years. These factors combine to create unique spatial patterns of salmonid habitats for individual watersheds. For example, in the recently deglaciated South Fork of the Stillaguamish River, Washington, low gradient (<2%), pool-dominated habitats tend to be located on a 1,700 year old terrace adjacent to the main river, whereas riffle-dominated streams tend to occupy slightly higher-gradient streams (2–4%) incised into the older terraces (Benda et al. 1992, Beechie and Sibley 1990). Both types of stream channels are downcutting into glacial-age clay and outwash sand deposits, whereas bedrock channels in this valley are steeper and provide little habitat for anadromous salmonids.

Along a longitudinal gradient from the headwaters to the mouths of major river systems, fish communities are correlated with stream order and stream gradient (Platts 1974). Valley-wall or headwater streams, usually first- and second-order tributaries, are not accessible to anadromous salmonids and may be dominated by resident cutthroat trout and rainbow trout. When fish are absent, these tributaries remain an important part of the stream system, since they transport allochthonous nutrients such as leaf litter, sediments from the hillslope, and LWD to higher-order tributaries.

In moderate-gradient (2–5%) third- to fifth-order streams, anadromous salmonids tend to dominate when there are no barriers to upstream migration. Steelhead and cutthroat trout occupy the steepest streams in this range, whereas coho salmon tend to utilize all accessible, low-gradient tributaries. Small tributaries with gradients less than 2% are usually utilized by coho salmon during the spawning and summer rearing stages. Steelhead and cutthroat trout of several age classes may coexist with juvenile coho salmon when the habitat is diverse.

Chinook salmon tend to utilize larger tributaries and main rivers that are used little by steelhead and coho salmon. Chinook spawning preferences are for larger gravels than most other salmonid species, allowing them to avoid competition for spawning space. Chinook juveniles rear in deeper and faster water than either coho or steelhead, alleviating some of the competition for rearing space and food resources.

Influence of Woody Debris on Habitat Development

Large woody debris is an important part of salmonid habitats in streams, both as a structural element (Grette 1985, Bilby 1985, Sedell et al. 1988) and as cover or refugia from high flows (Bisson et al. 1982, Murphy et al. 1985). Furthermore, LWD tends to reinforce meanders (Mason and Koon

Table 6.4. Longitudinal patterns in channel roughness, effectiveness of LWD in controlling channel morphology, and habitat complexity in an ecologically healthy watershed.

Stream Order	Channel Roughness	Effect of LWD	Habitat Complexity
1	Very high	Very high	Moderate
3	High	Very high	High
5	Moderate	High	Very high
7	Low	Low to moderate	Moderate
9	Low	Low to moderate	Moderate

1985) and trap sediment (Bilby 1979) and smaller organic debris (Naiman and Sedell 1979*a*, Harmon et al. 1986) in stream channels. Historically, woody debris piles covered enormous areas of small streams and large rivers. For example, a driftwood jam on the Skagit River, Washington, was reported to have been 1.2 km long and 0.4 km wide (Sedell et al. 1988). Current estimates of woody debris biomass and volume in aquatic ecosystems are extremely variable. Biomass reports range from 18 Mg/ha to 550 Mg/ha and volumes from 45 m^3/ha to 1,400 m^3/ha (Harmon et al. 1986).

A habitat classification scheme to describe woody debris accumulations separates the debris piles by their typical geomorphic settings; in the main channel, in a side channel, along a cut bank, on an overflow bank, at the island head, or on a gravel bar (Mason and Koon 1985). The habitat functions of LWD vary along the longitudinal gradient from headwaters to mouth (Table 6.4). In low-order, high-gradient streams LWD has a reduced function as a structural element in pool formation because the roughness of a large log is small relative to the inherent roughness of a boulder and bedrock channel. As stream order increases and gradient decreases, LWD becomes increasingly important in creating salmonid habitats. In streams where LWD spans the width of the channel, LWD becomes a dominant roughness element relative to gravel and pebble substrates. Thus, in third- to fifth-order streams, LWD is a dominant channel-forming feature.

As roughness elements, LWD pieces deflect the flow of water and increase hydraulic diversity. Flow deflections create a number of pool types that serve as different habitats for juvenile salmonids in summer (Bisson et al. 1982). When LWD pieces are too small or located such that they do not create pools, they create local hydraulic diversity (i.e. localized low-velocity areas) that serve as refugia for juveniles at higher discharges (Murphy et al. 1985). LWD in third- to fifth-order streams also traps sediments and nutrients which often enhance the suitability of gravels for spawning and slows the transport of vital nutrients in the stream system. This also allows invertebrate communities to more fully utilize the allochthonous inputs to the stream.

Though LWD is less frequently a dominant channel-forming feature in larger rivers, it remains an important feature along the channel banks. LWD in rivers can influence meander cutoffs (Swanson and Lienkaemper 1982) and provide cover and increase invertebrate production for juvenile salmonids (Ward et al. 1982).

Additionally, in ecologically healthy watersheds, large estuaries and slough complexes historically provided significant rearing areas for salmonids. These largely have been eliminated to convert land to agricultural or residential uses (Maser et al. 1988). Much of the lower floodplain area in the Puget Lowland is now diked to contain floods, and large areas of wetlands and marshes no longer serve as habitat. These areas are critical for maintaining healthy anadromous fish populations, because the fish make physiological and metabolic adjustments to either marine or fresh waters in this transition zone.

Woody Debris Accumulations as Nodes of Ecological Organization

The functional role of large piles of debris deposited on riverbanks has received little investigation. Substantial amounts of LWD are associated with streams of old-growth Douglas-fir (*Pseudotsuga menziesii*), western hemlock (*Tsuga heterophylla*), and Sitka spruce (*Picea sitchensis*) forests. Lienkaemper and Swanson (1987) measured 92 Mg/ha to 300 Mg/ha in the wetted channel. In mid- and high-order streams substantial debris is deposited outside the channel but the mass has not been measured. These large accumulations of debris appear to provide critical nodes of biotic organization within the river-riparian corridor. By this we mean that woody debris accumulations act as key loci of habitat for small mammals and invertebrates, which in turn act as prey for larger predators. Without the woody debris accumulations, much of the biodiversity and productivity of the riparian zone would disappear.

In coastal Oregon at least 80 species of snag- or log-dependent wildlife frequent riparian forests (Cline and Phillips 1983). The importance of downed logs and standing snags for habitat complexity in forest ecosystems is well known (Raedeke 1988, Spies and Cline 1988; Franklin, this volume). Woody debris accumulations in close proximity to the channel add complexity to the habitat for terrestrial life and may be a critical resource for connecting upland and aquatic communities.

Twenty North American species of small mammals are known to use coarse woody debris for denning, feeding, and reproduction (Harmon et al. 1986). Doyle (1990) indicates that woody debris accumulations in riparian environments of montane areas provide superior habitat for several species of small mammals. In her study, several less commonly captured species of small mammals were collected only in riparian habitat. Deer mice (*Peromyscus maniculatus*) and chipmunk (*Tamias townsendii*) are often located in microhabitats that contain relatively large amounts of woody debris (Doyle

1990). Shrew (*Sorex trowbridgii*) and mole (*Neurotrichus gibbsii*) have also been found in association with decayed wood (Maguire 1983, Whitaker et al. 1979). These same woody debris accumulations may also provide unique habitat for invertebrates and decomposers (Anderson 1982, Shearer and von Bodman 1983). This is an aspect of watershed health requiring substantial investigation in the near future.

Habitat Alterations by Wildlife Communities

Wildlife communities are also sensitive indicators of ecological health at the watershed scale, provided a broad spatial and temporal perspective is taken. Wildlife affect ecological systems through feeding strategies and day-to-day activities (e.g., ponding water, burrowing). These are important control processes on the riparian forest and the stream channel which have reverberations throughout the entire ecological system. The fundamental features of the role of wildlife in ecologically healthy watersheds are related to the use of wildlife to detect broad-scale environmental change, the nature of long-term population cycles and their relation to environmental conditions, and the seasonal phenology of habitat use and migration to maximize individual fitness (e.g., connectivity).

The riparian zone provides an exceptional array of vegetative conditions that support diverse and productive wildlife communities (Thomas et al. 1979, Oakley et al. 1985). Whereas fish are usually incapable of modifying the physical environment of streams, some wildlife populations are quite capable of modifying the structure and dynamics of riparian zones (Kauffman 1988, Naiman 1988, Pastor et al. 1988). Large herbivores such as elk (*Cervus elaphus*) and deer (*Odocoileus hemionus* and *O. virginianus*) may alter the abundance of understory vegetation through browsing of herbaceous plants and by rubbing or trampling. These activities contribute to a patchy mosaic of plant communities in various successional stages, which in turn increase habitat and soil complexity (Figure 6.13).

Interactions of wildlife with riparian plants not only affect vegetative patchiness but may also alter habitat characteristics of stream channels themselves (Figure 6.13). Water quality parameters including temperature, light, nutrients, and sediment are all influenced by wildlife activities (Green and Kauffman 1989). Beaver have perhaps the most profound effects on streams and riparian habitat (Naiman et al. 1986, 1988). Beaver ponds provide suitable environments for lentic species as well as stream-dwelling forms preferring low current velocity. Beaver ponds are known to be important overwintering areas for some coastal fishes (Bisson et al. 1987). Beaver ponds also serve as important storage and processing sites for terrestrial plant materials entering the stream (Naiman and Melillo 1984), and thus play a major role in regulating nutrient availability downstream (Dahm et al. 1987). Beaver herbivory decreases tree density and basal area by as much as 43% within forage zones around beaver ponds (Johnston and Naiman 1990). Selective

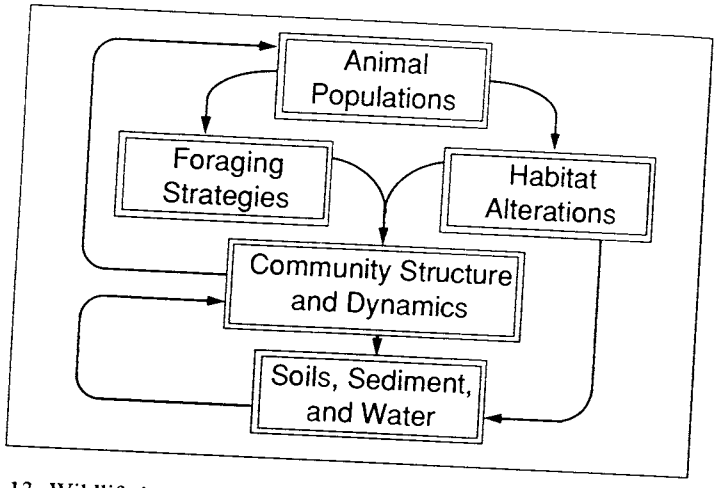

FIGURE 6.13. Wildlife influence ecosystem dynamics by their foraging strategies and by physical habitat alterations. These impacts are transmitted to the riparian forest community, resulting in long-term changes to biogeochemical cycles in soils, sediment, and water. (*Note*. After Naiman 1988. Copyright by American Institute of Biological Science. Used by permission.

foraging also alters tree species composition, which may affect habitat availability for other wildlife species. Because only a small fraction of the wood biomass felled by beaver is actually ingested, beaver contribute large amounts of woody debris to both riparian zones and stream channels. Flooding of alluvial terraces and valley floors by beaver dams causes long-term changes in forest stand succession, which in turn affects the location and dynamics of vegetation patches on a broad scale (Johnston and Naiman 1987).

Food Web Dynamics

Trophic processes in stream ecosystems are strongly influenced by channel morphology and the nature of riparian and upland vegetation (Vannote et al. 1980). In steep, cool headwater streams (first and second order), much of the organic matter processed by the aquatic community originates from riparian trees and is stored in stream channels by LWD (Naiman and Sedell 1979*a*, Cummins et al. 1982). Invertebrate communities are often dominated by detritivorous species that break down wood fragments, needles, leaves, and other debris particles into successively smaller pieces. Because small headwater streams in the coastal ecoregion are often heavily shaded and nutrient poor, aquatic plant production is limited to epilithic diatoms and a few green and blue-green algae. Large aquatic consumers are relatively rare and omnivory tends to be the rule (Anderson and Sedell 1979). Typical assemblages of large consumers in headwater Cascade Mountain streams include crayfish (*Pacifastacus leniusculus*), Pacific giant salamander (*Di-*

camptodon ensatus), sculpins (*Cottus* spp.), and coastal cutthroat trout (*Oncorhynchus clarki clarki*). Small streams draining the Coast Range usually have lower gradients, and anadromous fishes can penetrate far into watershed drainage networks. Assemblages of large consumers include, in addition to the taxa listed above, steelhead, coho salmon, sea-run cutthroat trout, lamprey (*Lampetra* spp.), and occasionally dace (*Rhinichthys* spp.). Other anadromous salmonids (chinook, chum) may be transitory residents of small coastal streams from several days to several months before migrating to the ocean.

Mid-order streams have a more even balance of allochthonous (terrestrial) and autochthonous (aquatic) sources of organic matter than headwater streams (Naiman and Sedell 1979*b*). A substantial fraction of the allochthonous material processed in third- to fifth-order streams is transported from headwater tributaries rather than entering laterally from riparian vegetation, although the latter source of organic matter remains important (Conners and Naiman 1984). Because much of it has already been consumed and excreted by aquatic invertebrates, fluvially transported organic matter has been reduced to fine particles, and invertebrate communities contain species that are adapted to processing this fine organic material. Mid-order stream channels are less heavily shaded than headwater streams, and periphyton production plays a greater role in community metabolism (Naiman and Sedell 1980, Gregory et al. 1987). Invertebrates specialized to consume algae are prominent members of the benthic community. In unconstrained valleys, composition of riparian vegetation along these streams also changes to a more even mixture of conifer and hardwood species. Deciduous trees contribute considerable amounts of easily decomposed and relatively nutrient-rich materials (leaves, catkins) to the streams on a seasonal basis.

In many respects, mid-order streams possess the greatest diversity of both trophic pathways and physical habitat conditions within the watershed. Pool-riffle sequences remain intact and are coupled with lateral habitat development in the form of backwaters and secondary channels on alluvial surfaces. These streams tend to support the greatest diversity of cold-water fishes, such as Salmonidae and Cottidae, and usually contain all of the large consumers found in headwater tributaries as well as species adapted to larger rivers, provided suitable temperatures exist. Salmonids typically found in third- to fifth-order streams include bull trout (*Salvelinus confluentus*; rarely in coastal streams), Dolly Varden (*S. malma*), and mountain whitefish (*Prosopium williamsoni*). Juvenile chinook salmon make greater use of these streams for rearing, and both chum and pink salmon use them to spawn. Because summer temperatures are warmer than in first- to second-order streams, mid-order streams also possess a more diverse community of minnows (*Rhinichthys* spp., *Richardsonius balteatus, Ptychocheilus oregonensis, Acrocheilus alutaceus*), and suckers (*Catostomus* spp.) than are represented in headwaters (Li et al. 1987). Included in this assemblage are species that consume algae and detritus.

Seasonal input of nutrients from the carcasses of spawned-out salmon can be an important source of nitrogen and phosphorus in these and downstream systems (Brickell and Goering 1970, Sugai and Burrell 1984), although carcasses can provide nutrients to small streams if they are retained in the channel by large woody debris (Cederholm and Peterson 1985).

In addition, riparian wildlife may benefit from nutrients transported to watersheds in the form of returning adult fish. Cederholm et al. (1989) documented the consumption of experimentally released coho salmon carcasses by 22 species of mammals and birds (51% of the total number of species observed in riparian zones) in small streams on the Olympic Peninsula, Washington. Cederholm and Peterson (1985) found that the presence of large woody debris served to hinder downstream transport of dead fish and increase carcass availability to terrestrial scavengers. Accumulations of salmon carcasses attract aggregations of scavenging birds to larger rivers (Stalmaster and Gessaman 1984). Long-term declines in the numbers of spawning salmon may result in a significant loss of seasonally abundant nutrients to some wildlife species (Cederholm et al. 1989, Spenser et al. 1991).

The trophic support of large streams (>sixth order) is dominated by autotrophic production of phytoplankton, periphyton, and rooted vascular plants, and by fine particulate organic matter transported into these larger systems from upstream sources and laterally from the floodplain (Vannote et al. 1980, Cummins et al. 1982). Although the direct input of wood and leaf litter from riparian forests is relatively unimportant compared with aquatic plant production and fluvially transported organic material, the food web of higher-order streams is still heavily dependent on resources, including nutrients, that originate from upstream areas (Naiman et al. 1987) as well as from periodic inundation of the floodplain (Pinay et al. 1990). Zooplankton and benthic detritivores are important invertebrate consumers in large streams, and fish communities reflect this shift in available food organisms. Both plankton feeders and benthic insectivores are well represented in the fishes of large rivers. Included among these are many of the thermally tolerant forms inhabiting mid-order streams as well as additional species of minnows (*Mylocheilus caurinus, Hybopsis crameri, Couesius plumbeus*) and other species that often inhabit marshes and sloughs (*Novumbra hubbsi, Percopsis transmontana*). Also represented among the fishes of larger streams are euryhaline species (*Acipenser* spp., *Thaleichthys pacificus, Gasterosteus aculeatus* [occasionally in smaller streams], several Cottidae, *Platichthys stellatus*) that inhabit brackish water ponds, the estuary, or ocean and move into rivers to feed or spawn. Introduced species (*Cyprinus carpio, Carassius auratus, Esox americanus, Gambusia affinis*, several Ictaluridae, many Centrarchidae, several Percidae) have become established in the lower reaches of many Pacific Northwest river basins. In general, nonnative fishes were imported from eastern North America and are associated with aquatic vegetation along the channel margin and floodplain. Some exotic species are piscivorous and in certain areas have displaced native forms from preferred

habitat, either through predation or competition (Li et al. 1987). Overall, however, introduced fishes have tended to increase species richness in large streams.

An Ecologically Healthy Watershed

In reference to the original working hypothesis—that delivery and routing of water, sediment, and woody debris are the key processes regulating the characteristics of drainage networks in the Pacific Northwest coastal ecoregion—we offer several observations. The available evidence suggests that ecologically healthy watersheds are maintained by an active natural disturbance regime operating over a range of spatial and temporal scales. Ecologically healthy watersheds are dependent on the nature of the disturbance (e.g., fire, landslides, debris torrents, channel migration) and the ability of the system to adjust to constantly changing conditions. This natural disturbance regime imparts considerable spatial heterogeneity and temporal variability to the physical components of the system. In turn, this is reflected in the life history strategies, productivity, and biodiversity of the biotic community.

This natural disturbance regime produces a dynamic equilibrium for riparian forests, habitat, water storage, water quality, animal migration, and biodiversity resulting in resilient and productive ecological systems. The net result is an ecological system, at the watershed scale, which possesses a biotic integrity strongly valued for its long-term social, economic, and ecological characteristics.

The heart of an ecologically healthy watershed is the riparian forest (Décamps and Naiman 1989, Naiman and Décamps 1990). The riparian forest is shaped by channel geomorphology, hydrologic pattern, spatial position of the channel in the drainage network, and the inherent disturbance regimes. Yet the riparian forest affects, and is affected by, habitat dynamics, water quality, and the animal community. This strongly suggests that maintenance of riparian forests in their historic abundance and in healthy ecological condition is of fundamental importance for long-term ecological and socioeconomic vitality of watersheds in the Pacific Northwest coastal ecoregion.

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PETER A. BISSON,
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