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Streamside Management: Forestry and Fishery Interactions

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CHAPTER THREE

Stream Channels: The Link Between Forests and Fishes

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ABSTRACT The hydraulic characteristics of flow through channels are an important component of fish habitat. Salmonids have evolved in stream systems in which water velocity and flow depth vary spatially within the watershed and temporally on a daily, seasonal, and annual basis. Flow requirements vary during different phases of the freshwater life cycle of salmonids: free passage is necessary during migration of adults; clean and stable gravel beds ensure successful incubation of eggs; and adequate velocity and depth of flow provide space for summer rearing and overwintering. The life cycles of salmonid species have adapted to the temporal variations in flow conditions by timing the phases of the life cycle to take advantage of the seasonal discharge characteristics. Spatial variability enhances species diversity by creating a variety of habitats within stream reaches; these are partitioned among individual species and age groups having different tolerances for velocity, depth, and cover conditions.

Channel morphology is determined largely by sediment and water input to the channels, and is formed during storm events when flow is great enough to transport the coarse sediments lining the channel bed. The resulting channel shape consists of a sequence of recognizable units known as riffles, pools, and boulder cascades. Water flowing down the stream is forced continually to adjust its velocity and depth in response to the changing channel shape: flow is shallow and fast in riffles, and slow and deep in pools. Large obstructions such as woody debris, boulders, and bedrock outcrops alter channel width, increasing the variation in velocity and depth in the vicinity of the obstruction and anchoring the position of pools. Discharge also varies through time, creating additional variations of hydraulic conditions.

Forest management can affect channel morphology by changing the amount of sediment or water contributed to the streams, thus disrupting the balance of sediment input and removal. Excessive input of coarse sediments from landslides can smooth the channel gradient by filling pools. Removing large woody debris from channels reduces sediment storage and eliminates the local hydraulic variability associated with the obstruction. Loss of habitat diversity by either mechanism may reduce or change the fish species found in a stream reach. If the changes result in decreased space, populations may also decrease. Strategies to minimize the effects of land management on channel morphology and fish habitat should include practices that minimize increases in coarse

sediment input, and that preserve the morphologic complexity of the channel.

THE STREAM CHANNEL

The stream channel links hillslopes to streams and couples terrestial and aquatic ecosystems. Along with its flow pass the products of erosion from the surrounding hillslopes and the nutrients, organic matter, and detritus from the adjacent forest. The form of the stream channel is determined by its association with the hillslope and forest and by the character of the inorganic and organic matter supplied to it. Floods scour and deposit sediments and mold channel perimeters into a variety of shapes, creating flow conditions throughout streams. From lowland rivers to headwaters, streams are characterized by extreme temporal and spatial variability in flow and bed composition. This variability is overlaid on a stream system that has rather definite patterns of channel morphology.

Fish habitat is a function of channel and flow conditions, and thus the type, quality, and availability of habitat are highly variable within watersheds. The life cycles of salmonids have evolved to exploit the spatial and temporal variation in channel conditions. Correspondence of patterns between physical and biological systems is a result of organisms becoming adapted and acclimatized to the most probable physical state of their environment (Cummins et al. 1984). At a given life history stage, each species has a range of tolerance for specific conditions that permits it to respond and adapt to environmental fluctuations. Many species can tolerate brief exposure to extreme conditions, but long-term exposures usually result in death or movement to more hospitable habitats. The juxtaposition and sequencing of different habitats can thus influence fish production when change in either life history requirements or local conditions necessitates movement.

An increasing awareness of linkages between the forest and the stream channel raises concerns that land use activities within a watershed may result in changes that exceed the ability of the biota to adjust to them. Since the stream channel integrates processes occurring on a watershed scale, it may respond to human activities in unforeseen, complex, or synergistic ways. One manifestation of this response may be transformations of the morphology of the channel itself, hence a shift in the quantity or quality of habitat.

This paper begins with a description of habitat requirements of salmonids during their freshwater phase. We then describe characteristics of stream channels in the Pacific Northwest and examine sediment transport and hydrologic processes that ultimately determine the type, distribution, and quality of aquatic habitat. We also consider the role of large woody debris in determining channel shape. We conclude with a discussion of the effects of land use practices on stream channels and suggest options for management.

HABITATS FOR SALMONIDS

Habitat Requirements

Identification of habitat requirements is complicated by the many ways in which fish use streams. Most fish in small streams are specialists and utilize habitats having specific characteristics in order to satisfy the unique demands imposed by spawning and incubation, summer rearing, and overwintering (Mundie 1974, Bustard and Narver 1975, Reiser and Bjornn 1979). Only a few species go through all the phases of the life cycle shown in Figure 1. Cutthroat trout and Dolly Varden may pass through their entire life cycle in fresh water, whereas pink and chum salmon typically migrate to the ocean soon after emergence and return to the stream only to spawn. Most coho salmon, chinook salmon, and steelhead trout spend one or more winters in fresh water before migrating to the ocean. The life history of salmonids of the Pacific Northwest is described in greater detail by Everest (this volume).

Habitat use and requirements also vary among age groups within species. But these and other important distinctions notwithstanding, most salmonids are similar enough to permit the following general discussion of the role of hydraulic processes in determining habitat suitability at each stage of their freshwater life cycle.

All salmonids construct a nest or redd in gravel substrates. Redds are typically located at the tails of pools where water movement through gravel will be continuous (Hazzard 1932, Burner 1951). The female selects and excavates the nest site and prepares a pit in which she and her mate deposit their gametes. The fertilized eggs are buried by subsequent upstream excavations. After spawning, the redd site gradually is covered by sediments transported from upstream and often becomes nearly indistinguishable from the rest of the streambed. Hydraulic conditions can affect the activities of spawning fish in a variety of ways. Low flows may prevent access to upstream spawning sites (Reiser and Bjornn 1979). At high flows, excessive water velocity may prevent the female from constructing her redd, though such conditions are usually temporary.

Incubation in the gravel may take up to nine months depending on species and the temperature of the intragravel water. After hatching, the young fish, known as sac fry, reside in the gravel. The ability of sac fry to escape the hazards associated with low flows, such as reduced concentrations of dissolved oxygen and the accumulation of metabolic wastes, is limited to movement of short distances in downward or lateral directions. At very low flows, redds may become dewatered and the eggs or embryos desiccated or frozen (McNeil 1966). High flows are also a potential hazard. Bedload movement accompanying high flows may bury eggs deep under the streambed and prevent escape, or embryos may become part of the bedload and crushed as they are scoured out of their redds (Reiser and Bjornn 1979).

When the young fish emerge from the gravel, their relative passivity toward the environment changes abruptly. They must

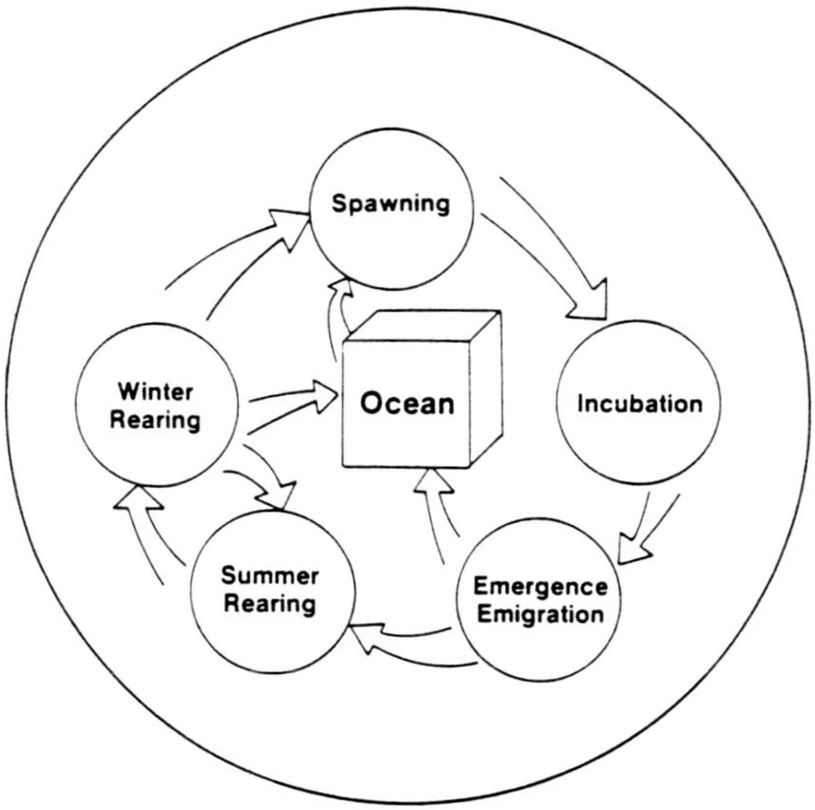


Figure 1. Generalized life cycle of salmonids.

continually swim against the current to avoid being swept downstream. Areas of low velocity, such as shallow stream margins, typically contain the highest densities of newly emerged fish in the spring and early summer (Hartman 1965, Everest and Chapman 1972). Many fish move long distances from spawning sites before finding adequate rearing areas (Chapman 1962, Allen 1969). Because predators may be attracted to dense concentrations of young fish, the presence of protective cover is very important.

New behavior patterns develop with the approach of summer. Two major factors appear to control behavior at this time: food and living space (Chapman 1966). Several species exhibit territorial behavior and occupy specific foraging stations in the stream, which they defend against intruders (Kalleberg 1958, Allen 1969). The size and location of these stations depend on many variables, including current velocity, water depth, cover, substrate, proximity to food sources, and the presence of other fish. Foraging stations are selected to minimize energy costs of defense and maintaining position in a current while maximizing net energy gain (growth) through feeding (Fausch 1984). Maintaining this balance is important, and fish may rapidly shift position if the balance changes toward greater energy costs.

Juvenile salmonids typically spend their time at feeding stations or "focal points," facing into the current, waiting for food items to drift within sight (Wickham 1967). Most fish prefer feeding positions below the principal surface drift patterns (Chapman 1966, Fausch 1984). Although they can maintain position in moderately fast currents, they lack the stamina for sustained swimming at higher speeds (Brett 1964). The best feeding sites are adjacent to but out of higher velocity flows.

Food items are derived from both the stream and adjacent riparian areas. Water currents carry drift items downstream where they become available to waiting fish. Invertebrates, mostly insects, are mainly produced in the substrate within riffles. At times of low instream production such as late summer, or at times of high availability of invertebrates from the riparian zone, food from terrestrial sources may be a significant part of the fish's diet (Mundie 1969). Streams having stable banks can support vegetation that harbors terrestrial insects, many of which may fall into the stream and become part of the drift (Reiser and Bjornn 1979). Food in aquatic habitats is described by Gregory et al. (this volume).

The presence of cover is also important. Cover is any material or condition that provides protection from predators, competitors, or variations in streamflow (Boussu 1954, Lewis 1969). Logs, woody debris, overhanging vegetation near the water surface, rubble, boulders, undercut banks, or water depth may all serve as cover (Platts et al. 1983). The importance of cover varies between species and age groups and seasonally.

During the fall, many fish begin to move in search of habitats that provide greater security. The availability of cover and refuges from high velocity flows plays an increasingly important role in habitat selection; populations increase in pools having dense accumulations of woody debris, meandering channels with deeply undercut banks, and off-channel ponds and sloughs (Bustard and Narver 1975, Peterson 1982, Tschaplinski and Hartman 1983). Floodplains and other intermittently wetted areas provide seasonal access to off-channel habitats. Habitat stability is especially important in maintaining populations during the winter, as major changes in channel morphology can accompany seasonally high streamflows. Because habitat stability varies along with changes in channel shape, fish populations in unstable stream channels tend to fluctuate.

Microhabitat use also changes with the onset of shorter days and cold temperatures in the fall. At moderately low temperatures, many fish spend less time feeding and become more closely associated with cover. At very low temperatures, some species such as steelhead trout seek refuge in the substrate (Chapman and Bjornn 1969).

Habitat and Streams

Thus far we have discussed the kind of habitat variables important to fish. We have focused on the physical variables related to the flow and substrate characteristics of streams so that we can evaluate the role that channel morphology plays in determining fish habitat. In so doing, a number of questions must be evaluated. Where is habitat located and how does the channel morphology determine its availability?

What are the channel processes that determine shape and hydraulic characteristics, and how does forest management change those processes and ultimately affect habitat quality?

The answers to these questions are as yet incomplete. Nonetheless, we can characterize processes in the stream channel that determine the array of hydraulic and morphologic conditions used by fish. Salmonid rearing space is determined by the hydraulic characteristics of streamflow; therefore, the shape, gradient, and roughness of channels and the volume of flow all play a part in determining habitat availability. In many cases, we can identify the types, magnitudes, and frequencies of processes that lead to changes in channel morphology. Because these processes reflect geologic and hydrologic constraints, their relative importance varies spatially within a stream reach, from reach to reach, and between streams.

In the following section we describe those factors that influence channel shape, with emphasis on patterns and processes common to Pacific Northwest streams. We then relate channel form to fish-rearing habitat and illustrate how fish communities have adapted to the predominant channel features found in headwater streams. (The role of channel morphology in providing suitable habitat for spawning and egg incubation is discussed more fully by Everest et al., this volume.) Finally, we discuss the ways in which watershed disturbance may affect those processes, disrupt channel morphology, and alter fish habitat.

FACTORS THAT DETERMINE CHANNEL SHAPE

Stream channels have similar forms and processes throughout the world. Water and sediment mold channels as they flow through drainage networks. Obstructions and bends formed from resistant material can locally control channel form by influencing flow and sediment deposition. In forest streams where structural elements such as woody debris, bedrock, and boulders are commonly abundant, these effects are particularly important.

Sediment load, water discharge, and structural elements--the controlling independent variables of channel morphology--determine the shape of the channel along the stream network. The form of any channel cross section reflects a balance between the channel's capacity to carry sediment away from that point and the influx of sediment to that point. A stable channel is one whose morphology, roughness, and gradient have adjusted to allow passage of the sediment load contributed from upstream (Leopold and Bull 1979). Characteristics of the banks also influence the cross-sectional shape of the channel and help to regulate channel width at any point in the stream. Figure 2 provides a cross-sectional view of a channel typical of small streams in the Pacific Northwest.

Origin of the Sediment Load

Type, amount, and timing of sediment input influence channel morphology. The characteristics of the sediment load imposed on the

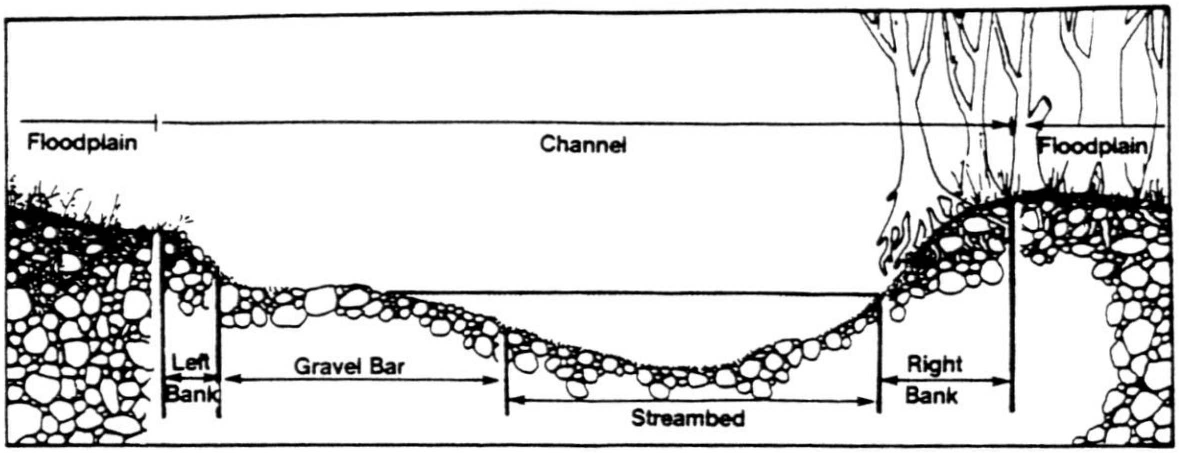


Figure 2. Cross-sectional view (from downstream) of a well-defined stream channel typical of streams of the Pacific Northwest.

stream are determined by the nature of the sediment transport processes active on the hillslopes and by the soil and bedrock types present. The variety of sediment delivery mechanisms and the characteristics of the sediment produced by each are discussed in detail by Swanson et al. (this volume).

Each sediment delivery process produces characteristic amounts and grain sizes of sediment. Landslides, tree throw, and soil creep (where transfer of material to streams is accomplished through bank erosion) contribute the entire spectrum of sediment sizes found in channels, while sources such as road erosion, animal burrowing, and rain splash contribute mostly fine-grained sediments. Erosion of sediment from each of these sources occurs in response to different mechanisms and thus occurs with different timing. For example, landslides generally occur during major rainstorms, tree throw is associated with drier windstorms, and bank erosion occurs during moderate-size flood events.

Transport and Storage of Sediment

The fate of the sediment introduced into a stream depends on the volume introduced, its grain-size distribution, and the timing of its input. Suspended sediment is made up of fine particles supported by turbulence in the water column. The greater the turbulence and flow velocity, the large the particle carried in suspension. Very small particles, such as silt and clay, can be moved by virtually any flow in most streams, and these are transported through the stream network relatively rapidly once they are introduced into streams. In most of the streams supporting salmonid spawning, however, sand-size particles can be transported as suspended material only during higher flows, and remain stored on and in the streambed between storms. Transport and storage of sand-size material (often referred to as "fines" by fisheries biologists) is particularly important to the spawning habitat of salmonids, and its fate in stream systems is discussed by Everest et al. (this volume).

Coarse sediment particles moving through the stream system are transported discontinuously, being alternately stored and mobilized over varying periods which differ with the type of storage location and the size of particle. Larger bed material moves by saltating or rolling along the bottom as bedload (Graf 1971). Gravel, cobbles, and boulders can be moved in this manner only by larger storms, and so can spend significant periods in storage in stream systems. This coarse material is generally molded by streamflow to form the streambed in many streams of the Pacific Northwest, and is emphasized here.

The capacity of a stream to store sediment depends on overall valley and channel dimensions and on the presence of channel obstructions such as large woody debris, channel bends, and bedrock outcrops. The steeper the channel slope, the coarser the bedload stored in valley bottoms.

The storage of sediment buffers the system so that large influxes or deficits of sediment are muted downstream, and their effects delayed (Pearce and Watson 1983). The impacts of large increases in sediment load at points further downstream, such as channel widening and filling of pools, may be lessened as slugs of sediment successively fill downstream storage sites. Gradual contribution of sediment from storage can also help to preserve spawning gravels during periods of low sediment input.

Gravel Bars. Most of the readily available sediment in moderate to large streams is stored on bars--sediment accumulations within the channel that are one or more channel widths long (Figure 2) (Church and Jones 1982). Bars may lie in the center of the channel, along one side, or across the entire width, thereby forming riffle-pool sequences. Shallows over bars are known as riffles; deeps located between the bars are pools. Differential patterns of entrainment, transport, and deposition of sediment during floods set up the gross morphology of the channel bottom, which then determines the flow characteristics at lesser flows. Bar-forming processes can accompany flow over movable boundaries in straight, simple channels, or they can be induced by convergence and divergence of flow around large obstructions or bends.

Bars can best form where the channel is wide enough to accommodate them (bankfull width/depth ratios greater than about 12) (Jaeggi 1984), and stream gradient is low enough to allow deposition (less than about 2%) (Ikeda 1975, Florsheim 1985). In steeper and narrower channels, bars and smaller deposits tend to form exclusively around obstructions. Large central bars and braided channels commonly form where valley bottoms and channels widen downstream of steep, narrow valleys and canyons. They may also form upstream of channel constrictions due to backwater effects of hydraulic control during storms. Bars usually grow and shrink seasonally because of local imbalances between deposition and erosion; but, other than in braided channels, bars tend to keep the same location as long as channel boundaries remain intact and obstructions in place (Leopold et al. 1964, Lisle 1986).

Floodplains and Terraces. Floodplains, which are most common along channels with relatively low gradients, are long-term storage sites for sediment. Floodplains are the low-relief surfaces of alluvium extending from the banks of the low-water channel to the base of valley walls or terraces. The name is appropriate, because during floods, part or all of the floodplain becomes the bed of the river. Coarse sediment is incorporated into floodplains when lateral stream migration leads to the stranding of gravel bars, while fine sediment is added by overbank deposition of suspended sediment (Leopold and Wolman 1960). Terraces are benches or steps in river valleys that usually represent former levels of valley floor or floodplain.

In many fish-bearing streams of the Pacific Northwest, steep valley walls constrain the development of floodplains to narrow zones along the channel or prevent floodplain development entirely. Such geologic controls are frequent along headwater streams, and most floodplains of third- and fourth-order streams form as discontinuous ribbons along the valley floor broken by narrow, steep gorges. The floodplains of larger streams are usually more extensive, and on major river systems can be miles across.

Residence periods for sediment stored in floodplains is quite long. In Rock Creek, a 16.3 km^2 basin in coastal Oregon (Dietrich and Dunne 1978), and in Redwood Creek, California (725 km^2) (Madej 1984), sediment storage periods on floodplains were estimated at thousands of years. Because of the large storage capacity of main-stem floodplains, significant changes in volumes of stored sediment require extreme floods and sediment inputs such as occurred in northern California in 1964 (Kelsey 1980).

Woody Debris. Woody debris forms abundant storage sites for sediment in forest streams as large as fourth order (20 to 50 km^2), where storage is otherwise limited by steep gradients and confinement of channels between valley walls. Annual sediment yields from small forested watersheds are commonly less than 10% of the sediment stored in channels (Megahan and Nowlin 1976, Swanson and Lienkaemper 1978). In Redwood Creek, California, Pitlick (1981) found that woody debris in redwood-dominated tributaries stored 74% of the sediment in the channel and 56% of the sediment produced by recent landslides; debris in Douglas-fir dominated basins stored 37% of in-channel sediment and 8% of recent landslide material. Redwood-produced debris accounted for greater sediment storage, because it decomposes more slowly than logs from species found in Douglas-fir forests and thus was longer lasting and more abundant. Pearce and Watson (1983) found that a volume of sediment equivalent to 50 to 220 times the average annual input remained stored behind debris jams in a New Zealand stream five years after its introduction by a massive landsliding episode.

Channel-forming Flow

As depth of flow increases, near-bed velocity also increases, and streams can mobilize and transport the coarse sediment stored in the bed and banks. Nearly all gravel channels are mantled by an armor layer containing particles larger than the underlying sediment. The larger particles in the armor layer partly shield the finer particles from being dislodged by the flow, but are themselves more vulnerable to entrainment because they protrude into the high-velocity flow. As a result, large and small particles in the armor layer have nearly equal mobility, and so become entrained at nearly equal discharges (Andrews 1983). Steep channels usually contain coarser bed material than gentle reaches, because the coarse sediment can be transported into and through the reach during common peak flows.

The form of a natural channel is believed to be shaped primarily during flows of a certain range of magnitude, the "channel-forming discharge" (Wolman and Miller 1960). Smaller discharges occur more frequently, but transport less sediment per storm, while larger discharges have higher transport rates but are infrequent. In gravel channels, the magnitude of the channel-forming discharge commonly lies between the mean annual discharge and the discharge that occurs once or twice every one to two years (Parker and Peterson 1980, Andrews 1980). A useful approximation of the most important channel-forming discharge in sand and gravel-bedded streams in most cases is one that just fills the channel (Leopold et al. 1964).

Where the channel bed sediment has been carried down from upstream, all sizes are more likely to be moved by annual peak flows. If a reach of stream is near a source of large rocks, such as bedrock cliffs or coarse landslides, large particles coming into a stream reach may exceed the size that the channel can carry and some particles in the bed may not be moved during annual peak flows. If boulders were introduced by a landslide into a gentle reach, for example, they would remain there until they were broken up or until further deposition and a resulting increase in stream gradient caused them to move. Once transported, particles tends to break down, the rate depending on the strength of the rock. For example, some sandstones break down so quickly that gravel-size material is generally lacking in the bed, while harder volcanic rocks usually break down more slowly and form coarse channel beds.

Gravel tends to be transported from one bar to the next during large floods (Leopold et al. 1964), with little deposition between bars. In stable channels, bed material may be transported annually and bars and meanders may shift, but bed elevation and the variables describing the average morphology and hydraulics of the channel change little from year to year.

Fine particles (sand-size and smaller) are also primarily transported at higher flows. At moderate flows, sand can be transported around bars and accumulate in pools and other quiet zones around the periphery of bars (Jackson and Beschta 1982). If fines make up more than 50% of the bed material, however, the armor layer can be covered by sand dunes. This sand can remain in transport at waning stages of floods after coarser material has stopped moving, or it can become entrained at rising stages before the armor layer moves (Ikeda 1985, Jackson and Beschta 1982). This can result in the filling of pools or deposition of fine sediments in a discontinuous sheet over the bed surface.

Channel Structure: Obstructions and Bends

Channel obstructions, ranging from single logs lying along a streambank to major bedrock bends, greatly diversify channel morphology and hydraulic conditions and add to channel stability (Keller and Swanson 1979). By influencing hydraulic conditions, these structural features store and sort sediment, enhance scour and deposition of the bed material, diversify velocity and depth, and fix the position of bars and pools (Lisle 1986). Consequently, structural elements are vitally important in managing forest watersheds to preserve fish habitat.

The presence of bedrock and boulder obstructions is determined by local geology and erosion processes; woody debris is supplied to many headwater streams by tree throw, bank undercutting, and debris torrents.

Pool Formation. Most of the pools in forested streams form around structural elements. Figure 3 shows a stream reach in Jacoby Creek, northern California (drainage area, 36 km^2; width, 14 m). At this site, Lisle (1986) found that 92% of the pools were scoured around bedrock bends and large obstructions of bedrock, woody debris, and rooted bank material, and bars were deposited upstream and downstream. In Prairie Creek, California, and its tributaries, 50 to 90% of the pools were associated with woody debris (Keller and Tally 1979).

Large obstructions, of which woody debris is often the most abundant in small channels, may fully or partly block the flow, thus regulating the scour and deposition of sediment and creating areas of high and low velocity in their vicinity. Obstructions and bends produce strong secondary currents that scour the bed, generally producing the deepest pools and scour holes (Galay et al., in press). Figure 4 illustrates the deep scour in the bed of a fourth-order stream in the vicinity of a large boulder that partly blocks the channel.

Pools vary in shape and size as a function of obstruction characteristics such as size, degree of channel constriction, vertical displacement relative to bankfull depth, and horizontal angle of deflection (Beschta 1983a, Sullivan 1986, Lisle 1986). Where logs or boulders form dams across the channel, deep, short plunge pools are scoured downstream. Where obstructions are high but only partly span the channel, scoured pools are longer and shallower (Sullivan 1986). The hydraulic significance of an obstruction generally increases as its length and width relative to channel width increase.

Stable structural features promote stable channels as long as the sediment throughput and flow regime are not too erratic. Bedrock bends and large obstructions can stabilize the most important elements of channel morphology by controlling the location of pools and bars (Figure 3) (Lisle 1986). Moreover, the geometry of obstructions and bends can set downstream channel courses. Channels tend to flow from one pools scoured around a large obstruction or bend to the next with fairly straight intervening courses.

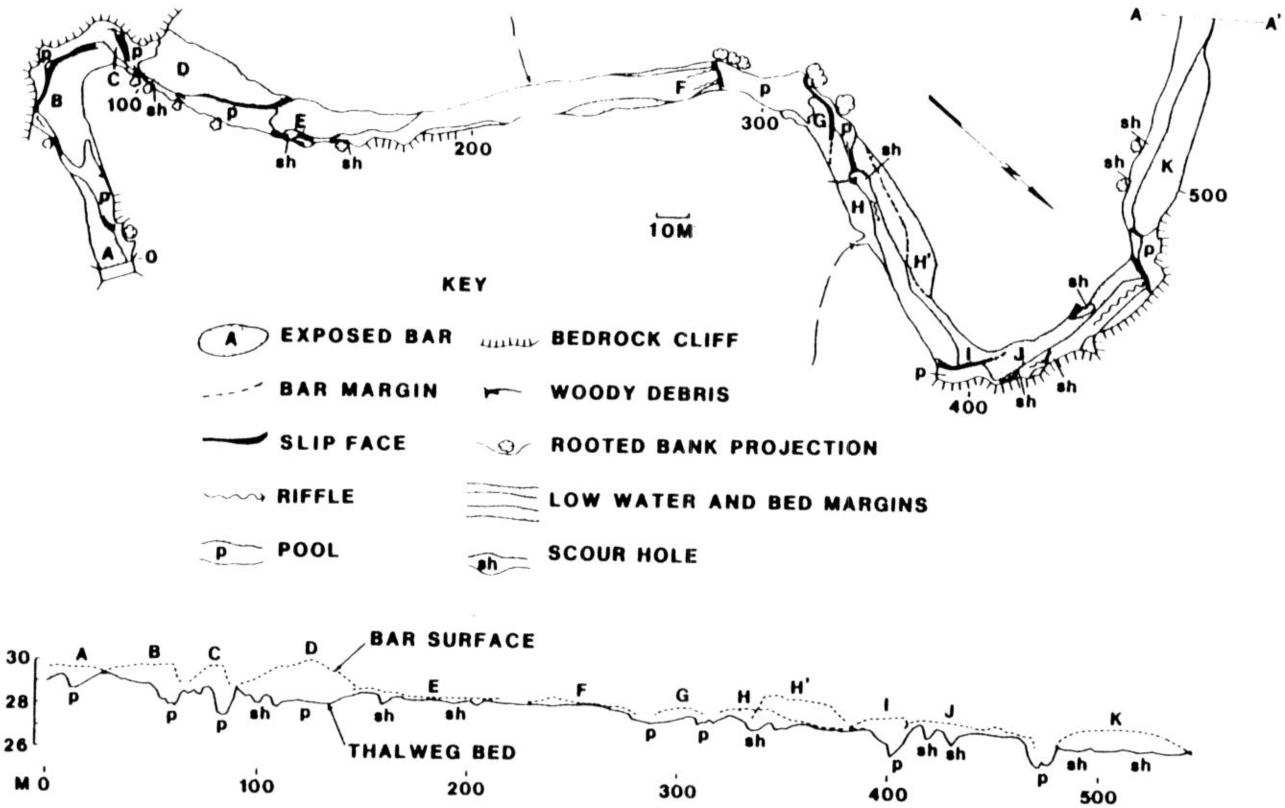


Figure 3. Map and longitudinal profile of Jacoby Creek, northwestern California, showing the association between obstructions and bends, on the one hand, and bars and pools on the other. Pools are located in bends and next to obstructions; bars are located upstream and downstream (from Lisle 1986).

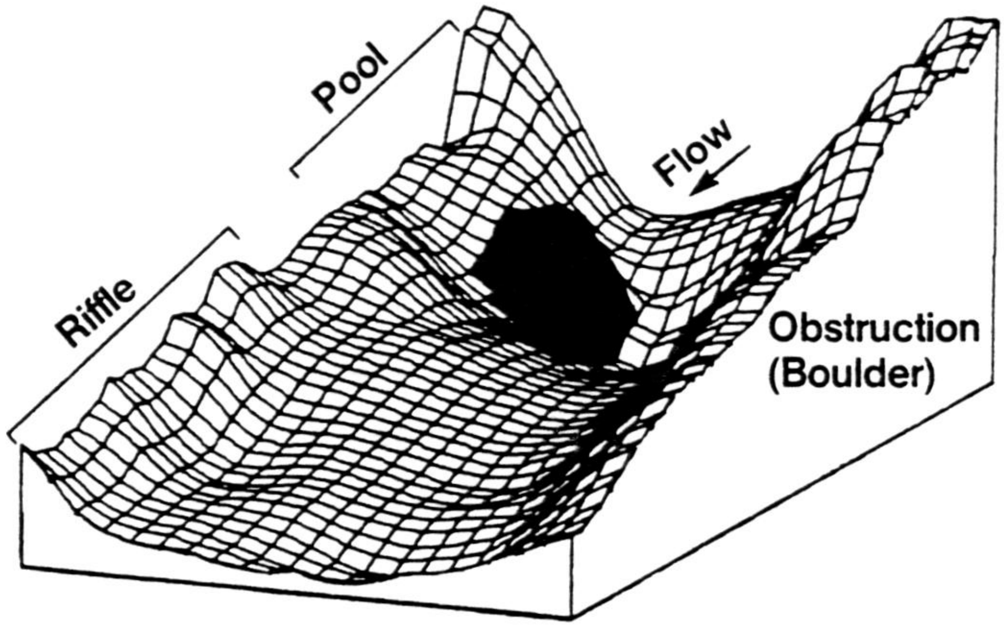
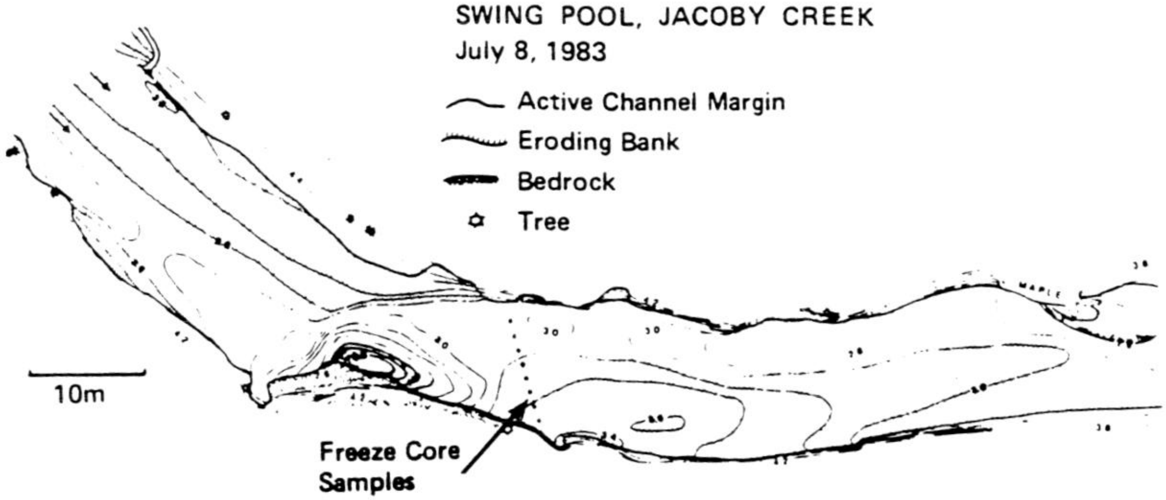


Figure 4. Streambed topography of Big Creek, a fourth-order stream in western Washington, illustrating scour and pool formation in the vicinity of a large boulder obstructing the channel (from Sullivan 1986).

Woody debris in streams protects banks from erosion at some sites, but diverts high velocity flow into banks elsewhere, and thus is an important factor in determining the local distribution of bank erosion and pool formation. Debris in most stream reaches, including those that have been disturbed, is dynamic, with some pieces shifting from year to year (Toews and Moore 1982). Moving woody debris can shift loci of scour and deposition, and thereby cause bank erosion and change channel morphology. Sediment inputs from bed or bank erosion caused by unstable debris are often compensated for by nearby deposition, unless bank erosion triggers landsliding. In a small stream with abundant debris in New Zealand, Mosley (1981) found that sediment moved sporadically with the breakup of debris jams, and most was deposited in storage sites immediately downstream. Thus the effect of blow downs on the total sediment yield is difficult to predict.

Most stable stream channels represent a sort of dynamic equilibrium (Schumm 1977) where the location of scoured pools may change from year to year as debris and bank conditions change, but an average balance of channel features is maintained through a reach. The proportion of riffles to pools, for example, appears to remain relatively constant from year to year in many stream reaches, although sequential data from stream reaches is limited.

Sediment Sorting. Obstructions also tend to control the sorting and distribution of different sizes of gravel on the streambed. Bends and large obstructions often divert flow across the channel instead of directly downstream. Where this occurs, the more easily entrained fine



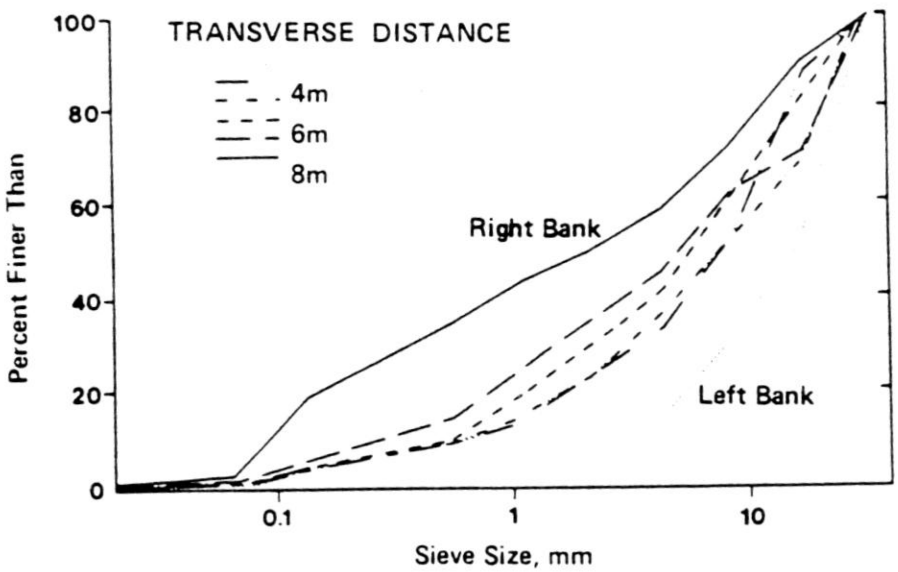


Figure 5. (Top) Location of bed cores (marked with dots downstream of the pool) taken from Jacoby Creek, northwestern California. (Bottom) Size distribution of bed cores (low transverse distances) are coarser than left-bank cores because of secondary currents set up by the bedrock obstruction upstream (Lisle, unpublished data).

particles tend to move along the bottom in the direction of flow that angles across the stream, while coarse particles react more to the force of gravity and tend to move in the direction of the slope of the bed (Dietrich and Smith 1984). The divergence of the pathways of coarse and fine particles results in one side of the streambed having less fine material than the other (Figure 5). Consequently, relatively clean spawning gravels can be maintained in a stream containing abundant fines because of the sorting that occurs at large obstructions or bends.

Bank Stability

Bank stability is largely controlled by the grain size of the bank material, the vegetation cover on the banks, and the amount of bedload carried in the channel. Weak banks formed of sparsely vegetated, noncohesive alluvium tend to collapse, and thus are usually associated with wide, shallow channels. Cohesive banks tend to form deep, narrow channels.

Banks are highly vulnerable to erosion as the stream adjusts to inputs of bedload sediment. Channels can remain stable only if bedload transport occurs at some distance from the banks, because bedload particles entrained along the bank tend to travel down the bed sloping toward the center of the channel, causing net erosion of the channel margin (Parker 1978). Increased bedload transport causes the channel to widen its zone of bedload transport (Figure 6). If this zone abuts an erodible bank, the bank erodes and the channel widens until near-bank transport stops. Once initiated, bank erosion can be self-perpetuating by introducing more sediment through bank cutting (Curry and Kondolf 1981). Under such conditions, and where the valley bottom is wide enough, the channel can become braided. Individual channels in braided reaches are very unstable because their bank materials are weak, and channels are finely adjusted to conditions that can rapidly change as they lose or capture discharge and sediment load from upstream.

Banks can be strengthened considerably by dense root systems. Therefore, plant species composition (grasses, trees, or shrubs) and vigor of riparian vegetation are very important to bank stability. Channels commonly widen in passing from meadows, where herbaceous plants form dense root mats, to forests, where roots are less dense. Roots in streambanks are usually dense only in the top several feet. As the underlying looser material erodes, the banks become undercut and chunks of bank material intermittently topple into the channel (Thorne and Lewin 1979). Thus even heavily vegetated streambanks can be easily eroded. However, large woody debris in bank failures can inhibit further erosion by buttressing the banks and slowing near-bank velocities. More important, this woody debris and deeply undercut streambanks along heavily vegetated streambanks can provide excellent summer and winter habitat for salmonids.

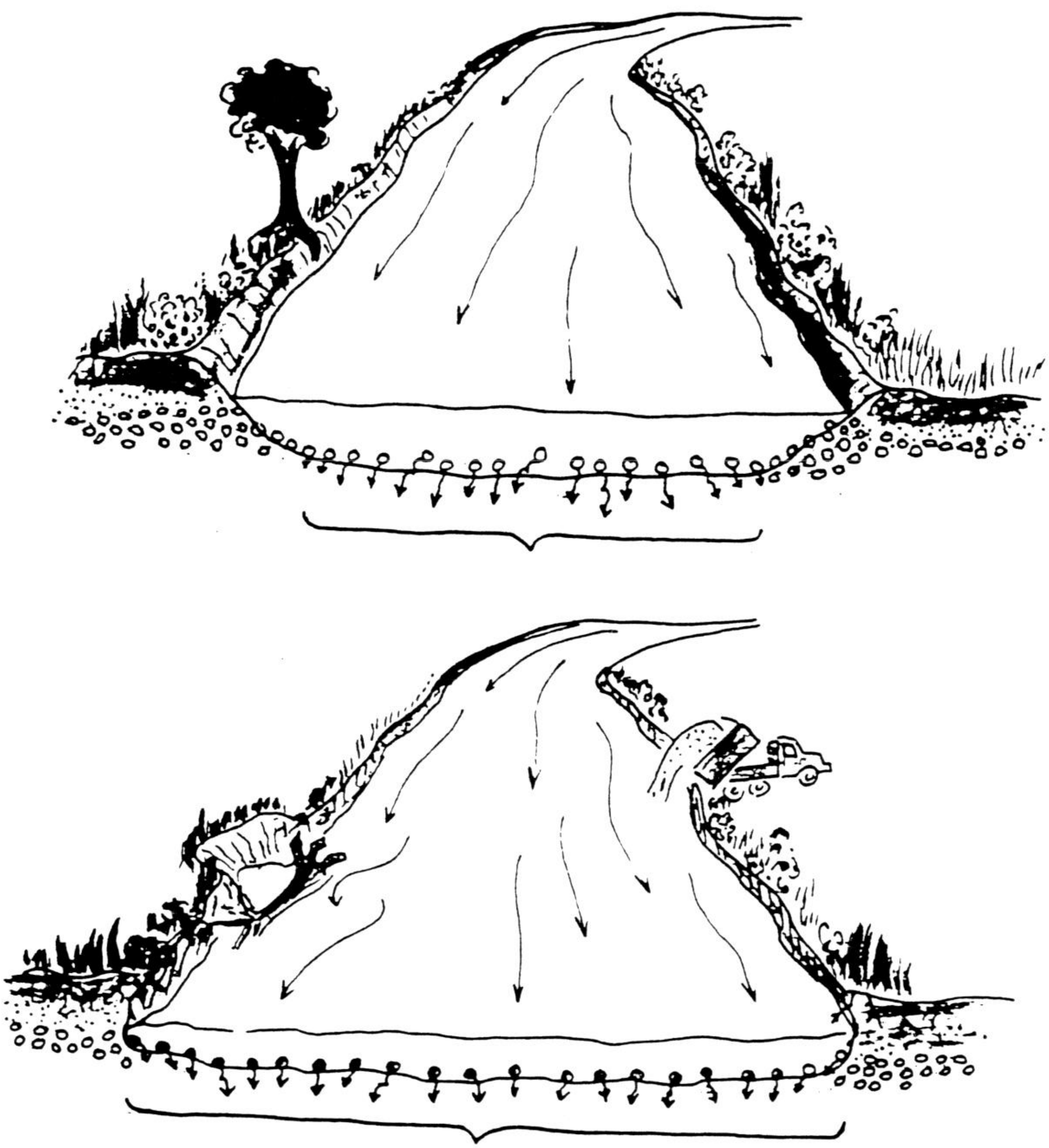


Figure 6. In a stable channel (top) no bedload is transported along the streambanks. When bedload supply increases (bottom), transport begins along the banks. As bedload particles roll down from the banks toward the center of the channel, the banks become depleted of sediment and erode.

PATTERNS OF MORPHOLOGY AND HABITAT WITHIN A WATERSHED

Channel Form

Channel morphology and hydraulic conditions tend to change progressively along the channel network. Flow generally increases in the downstream direction as small streams funnel water and sediment into progressively larger streams. Channel width, depth, and velocity generally increase downstream with the increasing volume of flow, while channel gradient and particle size commonly decline with distance from the divide (Leopold and Maddock 1953). Therefore, water discharge, sediment characteristics, and structural features can change greatly along the stream network.

As a result of the changes in sediment and flow within watersheds, particular channel features generally occur in specific locations within a watershed (Figure 7). Fish communities also change together with stream channel and flow characteristics along the stream network (Vannote et al. 1980). For example, zonation of fish communities along a gradient of stream order has been noted in mountain regions (Sheldon 1968). Changes in species composition are caused by changes in habitat and may be reflected as species addition or replacement, or by a change in relative abundance (Gorman and Karr 1978). For example, Platts (1974) found that in streams of the Idaho batholith the number of species generally increased with decreasing channel gradient, although fourth-order streams contain more species than either third- or fifth-order streams do. The dominant species often varies by stream order, although there is overlap in species use between stream orders.

Lower Basin. Channels of larger rivers meander back and forth across extensive floodplains where low-gradient channels (less than 1%) are generally formed in fine sediments (sand-size and smaller). Over extensive periods, channels migrate laterally across the floodplain by eroding banks along the concave side of meander bends and depositing sediment along the convex bank and over the floodplain surface (Leopold and Wolman 1960). This portion of the river network is important spawning and rearing habitat for some salmonid species such as chinook salmon (Everest et al., this volume). Because large woody debris is more mobile in large streams, its effect on channel morphology is reduced (Keller and Swanson 1979).

In most of the Pacific Northwest, larger rivers are currently affected more by dams, diversions, and agricultural practices than by the management of forests, which tends to be confined to the steeper, upper reaches of basins. Historically, however, channels of larger rivers have been extensively altered with significant habitat degradation as a result of log rafting and snagging for navigation (Sedell and Luchessa 1982, Bisson et al., this volume).

Upper Basin. Headwater streams are confined between narrow, discontinuous floodplains adjoining valley walls. In these steep, small streams, channel shape is a function of both stream and hillslope processes. Channel shape closely reflects the presence of bedrock outcrops, and the channel form is largely controlled by bedrock, woody

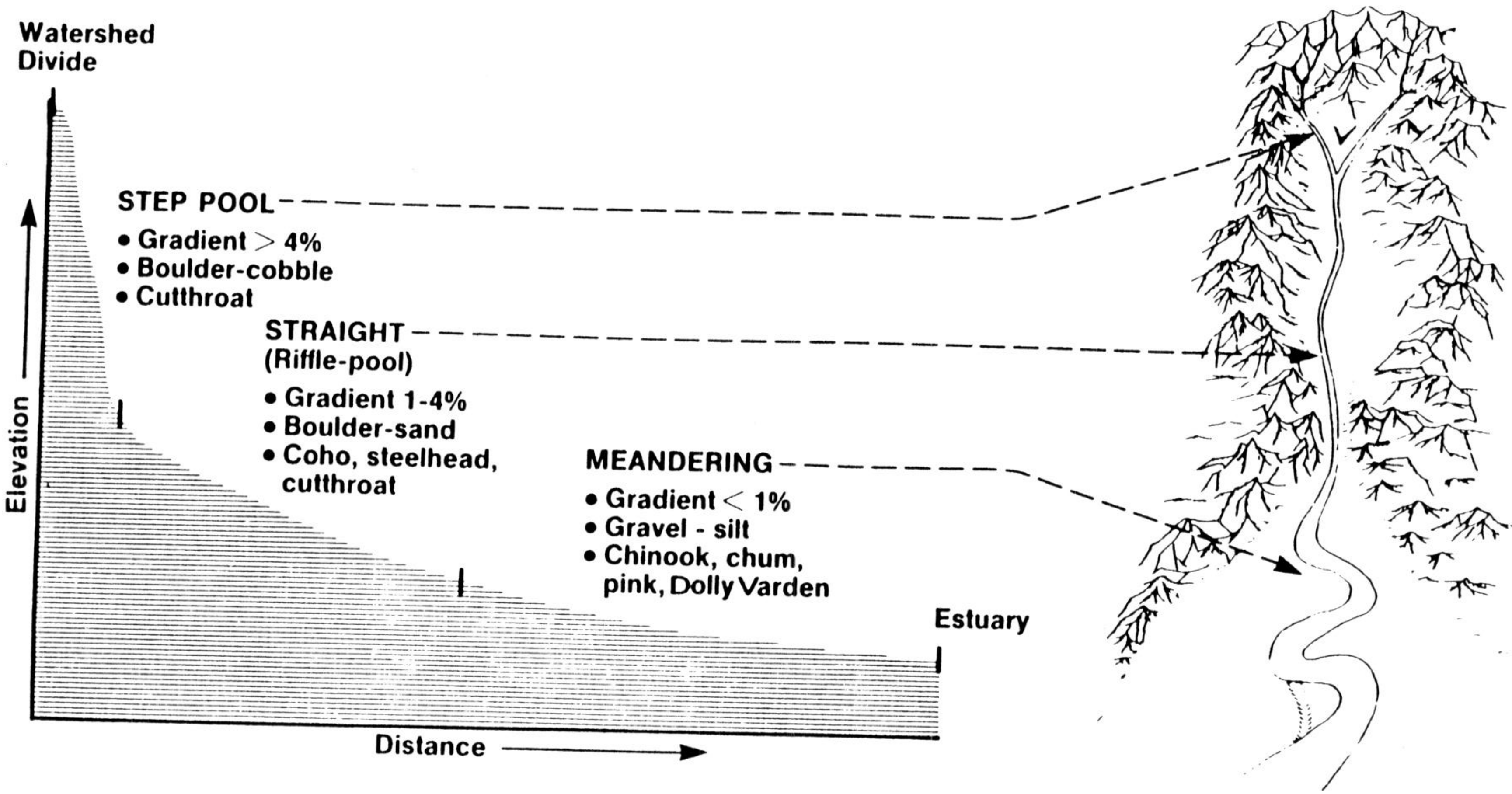


Figure 7. Patterns of channel morphology and fish use of watersheds.

debris, and coarse sediment. The influence of obstructions on channel shape is particularly apparent in these streams, since local anomalies due to changes in geology or vegetation are frequently encountered and large woody debris is abundant (Keller and Swanson 1979). Forest processes and management practices have the most direct effects on channel form and fish habitat in these streams.

Channels in headwater streams are usually moderately steep (greater than 1%) and composed of coarse bed material. Channel shape is characterized by riffles, pools, and boulder cascades, which vary in slope, roughness, and hydraulic characteristics (Bisson et al. 1982). The formation of pools and riffles is closely associated with channel bars and with scour and deposition around channel obstructions and bends, while boulder cascades are steep stream segments of very coarse deposits associated with channel constriction between valley walls or large obstructions.

Channel Units. Boulder cascades have slopes greater than 4%, and a large portion of their surface area is composed of cobbles and boulders that protrude through the flow, giving flow through this unit a characteristic "whitewater" appearance (Bisson et al. 1982). The steepest reaches of headwater streams are composed almost exclusively of boulder cascades, and they are usually the most common channel unit in small (second- to third-order) streams. This channel feature is also termed a step pool where water flows over steps of boulders or logs and falls into short, shallow pools (Heede 1972). Flows are not usually great enough to move large material, and logs typically remain in place until they rot. These types of stream reaches generally mark the upper limit of the range of anadromous fish, but resident trout may be found in their lower reaches in the wakes of boulders and cobbles that protrude from the bed.

Where gradient is lower, sediment eroded from upstream is stored in floodplains, and channel form is a function of streamflow processes interacting with structural features and streamside vegetation. Lower gradient channels (slopes greater than 0.2% and less than about 4%) store gravels over most of their beds and banks. Such channels commonly contain bars, bends, pool-riffle sequences, and abundant spawning and rearing habitat (Figure 8). Riffles, like the steeper reaches, have coarser substrate and flow that is relatively shallow and fast (Figure 9). Conversely, pools, as low points in the bed profile between bars, have a water surface gradient that is gentler than the reach average, relatively fine substrate, and flow that is generally deeper and slower. Flow characteristics in each of these units are a function of their characteristic shape and position within the channel, and of the volume of flow (Sullivan 1986). Riffles and pools can be readily identified in the field, and, because of the diversity of conditions they provide, are vital components of fish habitat.

Short cascades also occur at points along streams of up to fifth-order where valley walls or obstructions impinge on the channel and cause local steepening of channel gradient. Here, cascades are generally short (less than 2.5 channel widths in length) but resemble the headwater reaches in slope and roughness (Sullivan 1986). Cascades

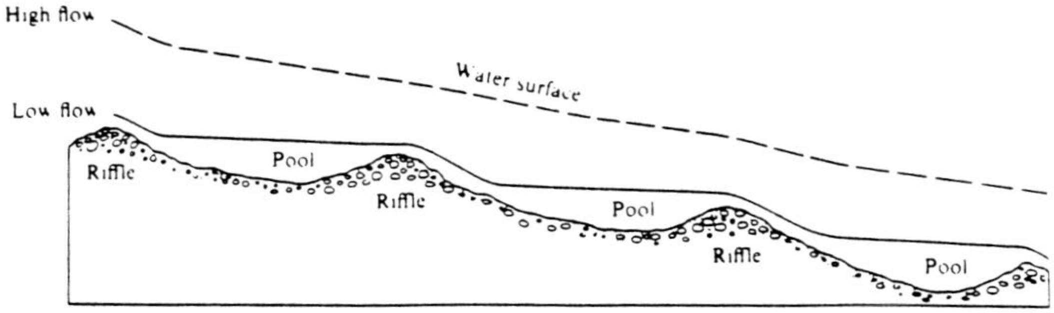


Figure 8. Channel topography and water depth characteristics of a riffle-pool sequence at high and low flows (from Dunne and Leopold 1978).

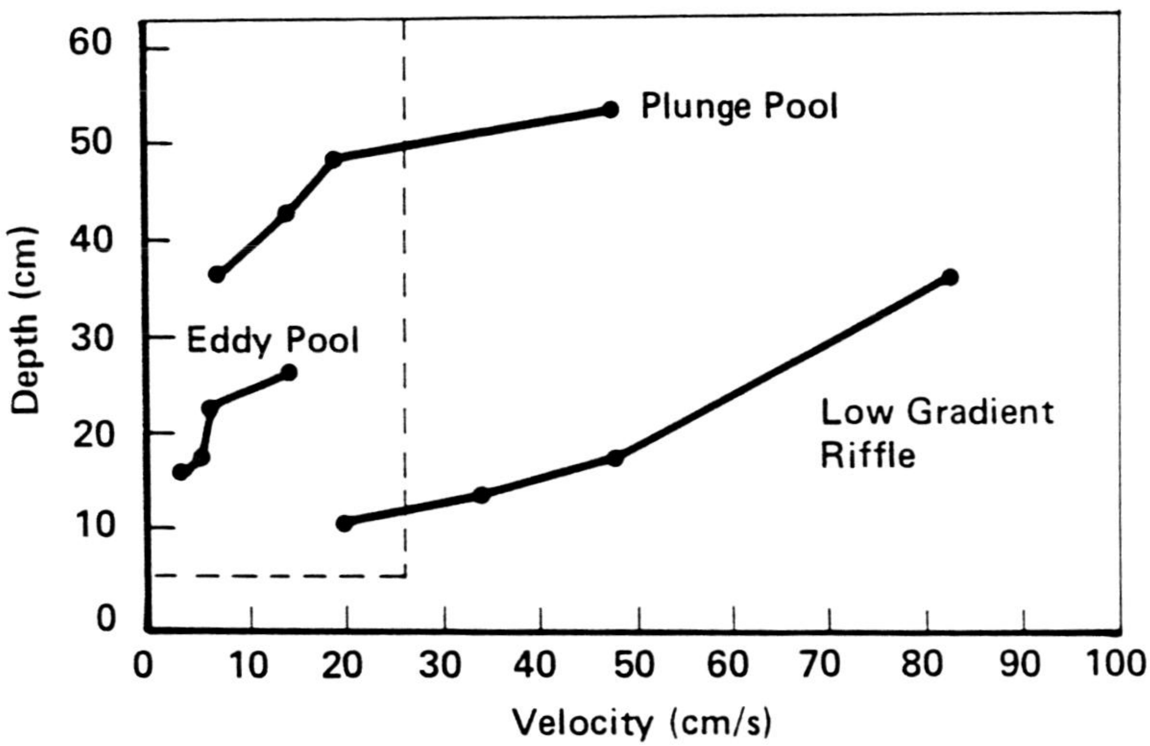


Figure 9. Average velocity and depth characteristics of selected channel units. Each line traces the centroid of the unit over a range of flow conditions, with the leftmost point representing summer low flow. Moving to the right are summer baseflow, winter baseflow, and stormflow, respectively (from Sullivan 1986).

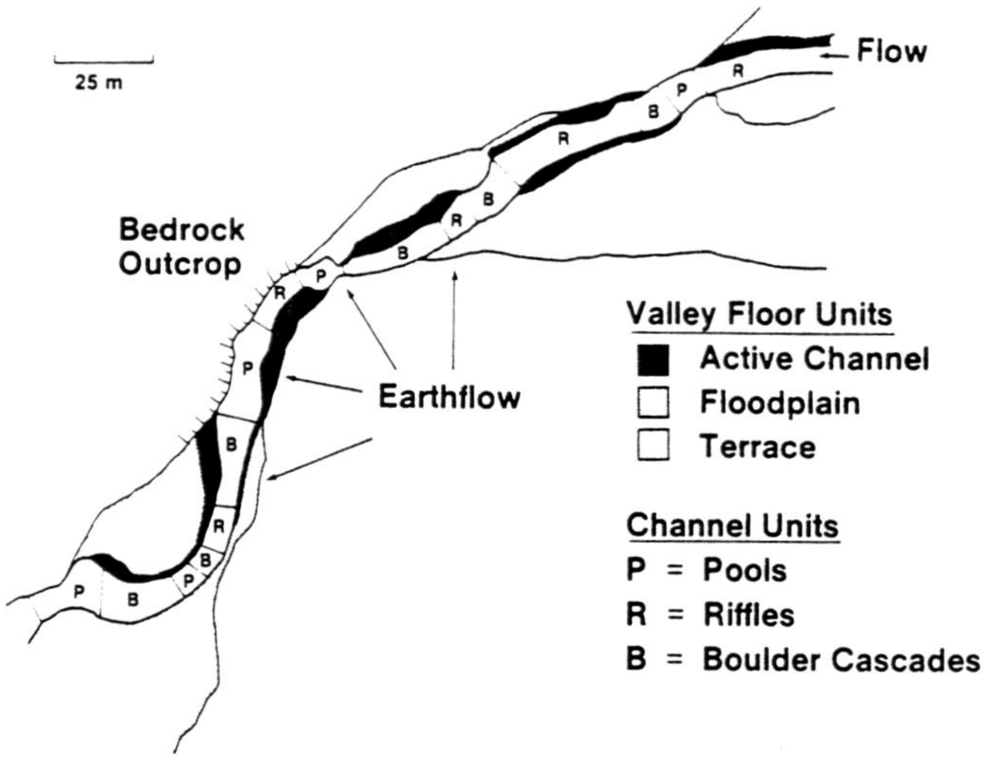


Figure 10. Arrangement of channel and valley floor units in the vicinity of an earth-flow toe, French Pete Creek, Oregon (from Grant 1986).

associated with obstructions occur intermingled with riffles and pools (Figure 10).

Because of the abundance of large obstructions in forest streams, riffle-pool sequences are commonly irregularly spaced. Pool spacing in Jacoby Creek, California, for example, ranges from one to fifteen channel widths, although pools are most frequently observed at intervals of three to five channel widths (Figure 11) (Lisle 1986). Some pools are very closely spaced (one to three channel widths) where obstructions are closely spaced.

Valley Constraints

The distribution of channel units and valley floor surfaces is determined by the extent of valley wall constraint. Channels constrained between valley walls have more high-gradient channel units (boulder cascades). Unconstrained reaches have low-gradient pools and riffles bordered by floodplain and terrace deposits on the valley floors (Figure 10) (Grant 1986).

Although the floodplain lies outside the active channel margins, it affects aquatic organisms in several ways. Vegetation adjacent to channels can provide shade and organic matter, thus influencing stream temperatures and food supply. The nature of riparian zone vegetation is determined by floodplain characteristics. Also, floodplains and other

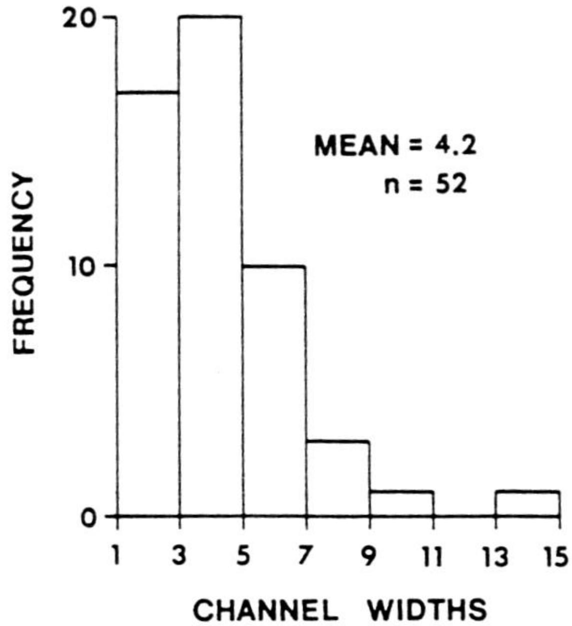


Figure 11. Frequency distribution of the spacing between pools, measured in channel-width distances in Jacoby Creek, California. Pools are irregularly spaced because they were formed at irregularly spaced obstructions and bends (from Lisle, unpublished data).

intermittently wetted areas provide seasonal access to off-channel habitats. The degree to which the floodplain provides refuge areas during times of high water depends on the extent to which the potential refuges are physically linked to the main stem.

Patterns of Fish Habitat

Selection of Microhabitats. Microhabitats are the collection of specific features within a stream chosen by an individual fish. Microhabitat use reflects trade-offs: the need to be near food sources must be balanced against flow conditions, the proximity of cover and the threat of predation, stress of competition, and so forth. Physical criteria for selection of feeding stations have not been completely defined, but velocity, depth, and substrate composition are generally considered important (Bovee and Cochnauer 1977, Reiser and Bjornn 1979). Although a fish may prefer a particular velocity or depth, there is a tolerance range for each variable. Each combination of velocity, depth, and substrate is usable only when all are within the tolerance range. The most preferred sites are generally occupied by the largest, dominant fish. Less preferred and marginal sites are occupied by sub-dominant fish, and those fish unable to occupy suitable sites may be forced to emigrate (Chapman 1966).

The tolerance of species to a range of flow conditions has been evaluated by measuring the hydraulic characteristics observed at feeding stations: fish are observed in natural streams, their feeding stations marked, and velocity, depth, and substrate are measured at

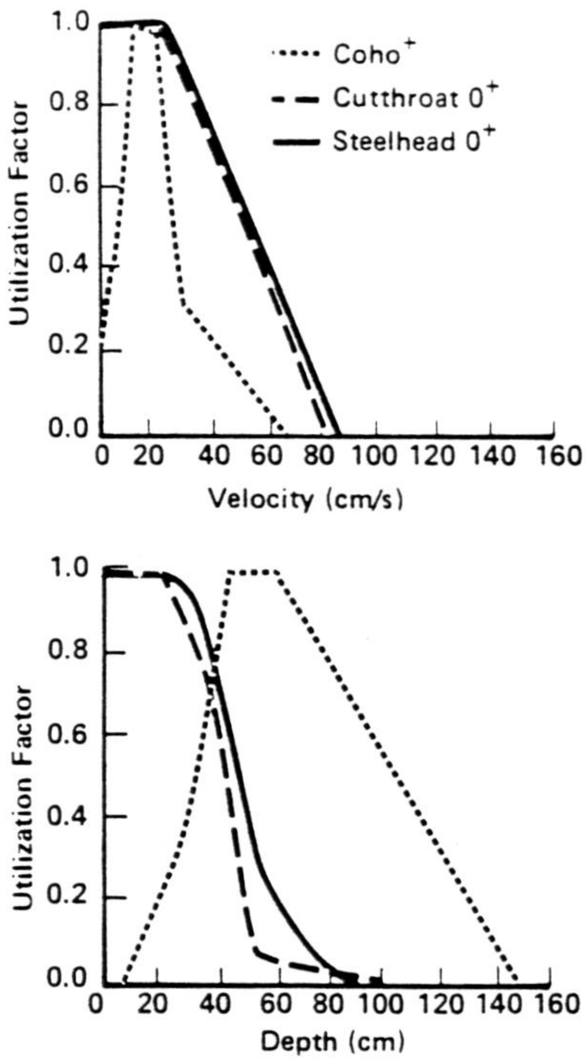


Figure 12. Utilization factor, an index of preference, of salmonid populations in relation to velocity and depth. The data shown were collected for several species of salmonid fry in streams in Washington by the Washington State Department of Game, Olympia, for use in the Instream Flow Incremental Method model developed by the U.S. Fish and Wildlife Service. (See Bovee and Cochnauer 1977 and Bovee 1982 for a description of the IFIM methodology and the utilization factor.)

each station. Most observations show that salmonids occupy a wide range of conditions, and that these ranges are defined by frequency distributions for each selection variable. For example, the utilization factor (an index of preference) for velocity and depth varies with species (Figure 12). Despite the differences in distributions that are evident in Figure 12, there is also considerable overlap in the tolerance of species and age groups to the same hydraulic conditions. If the available area is limited, species may compete for available area.

Velocity may often be the factor limiting available habitat space for salmonid fry, because fish can sustain position for extended periods only in velocities that are fairly slow. Coho salmon are particularly sensitive to velocity (Bustard and Narver 1975, Fausch 1984), while steelhead trout use a wider range of velocity (Everest and Chapman 1972, Sheppard and Johnson 1985). Focal point velocity generally increases with age as fish grow larger, and also varies seasonally in response to changing water temperature (Bustard and Narver 1975).

Although the specific distribution of depths occupied differs greatly between streams, older (larger) fish tend to occupy sites in deeper water. Depth may be the most important factor limiting available rearing habitat for older age groups of salmonids (Dolloff 1983).

Substrate functions as a factor in rearing habitat in several ways. Substrate particle size regulates the production of invertebrates (Reiser and Bjornn 1979). Particles on the bed also serve as visual reference points that individual fish use to orient to feeding stations (Keenleyside and Yamamoto 1962). Most salmonids are associated with coarse channel substrate of gravel to cobble size, although selected substrate size varies with species (Bovee 1978, Sheppard and Johnson 1985, Moyle and Baltz 1985). Coarse channel beds provide a mottled backdrop against which fish are camouflaged from terrestrial predators (Everest and Chapman 1972). Most species avoid bedrock or boulder substrate. Streams with sand or silt substrate usually have fewer fish because of lower food production (Bjornn et al. 1977).

Fish Utilization of Habitat Units. Because channel units vary in velocity and depth and bed material, they may differ in habitat suitability relative to species or age groups. The available habitat or usable area within streams can be identified as areas in which hydraulics, substrate, and cover conditions are within the tolerance ranges for each species and age group. Since habitat requirements vary, any statement about the suitability of a stream for fish must be qualified with reference to the species, age group, time of year, and presence of competing populations.

Species and age groups segregate within stream reaches because of their tendency to use channel units with hydraulic conditions matching their habitat requirements (Figure 13). During summer rearing, age 0+ coho salmon generally inhabit the slower, moderately deep pools, where they swim in midwater positions. Individuals are segregated by social hierarchies that determine the location of individual foraging stations (Chapman 1966). Older age groups of several species tend to occur in the deepest pools (Dolloff 1983), although Bachman (1984) found the largest brook trout in the best feeding sites in riffles. Fish use boulder cascades similarly to riffles (Bisson et al. 1982). Features or structures that form deep pools are critical habitat elements, particularly in small streams at times of low streamflow. Young-of-the-year trout inhabit riffles and cascades, where individual fish are usually oriented in relation to the rocks that protrude from the bed--either in their wakes, in front of, or sometimes underneath them (Hartman 1965, Ruggles 1966, Everest and Chapman 1972). Individual trout are spatially

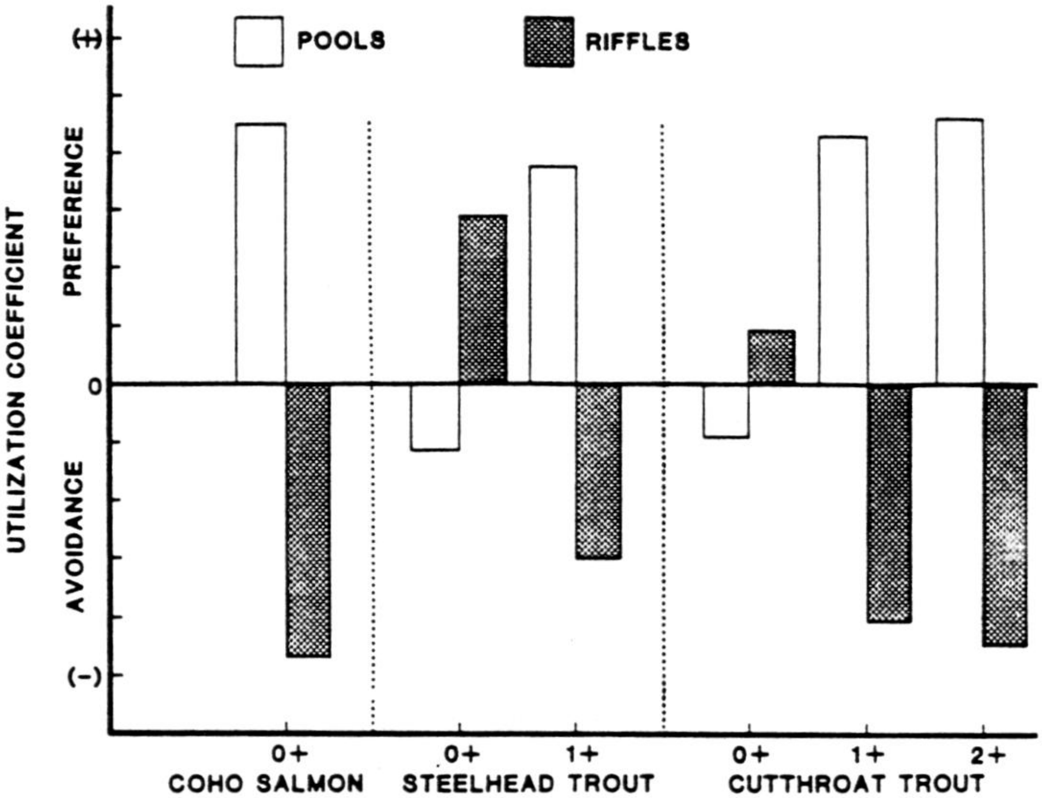


Figure 13. Relative habitat preferences of salmonids in streams of western Washington (from Bisson and Sedell 1984).

segregated as a result of the discrete nature of the most suitable microhabitats confined within the larger main stem (Chapman 1966).

Although species segregate within stream reaches, the same portions of streams could be occupied by individuals of different species, because tolerance ranges for velocity, depth, and substrate overlap among species and age groups. For example, coho will occupy sites in the riffles when steelhead are absent (Mason and Chapman 1965, Bisson et al. 1985), and steelhead trout will occupy pools when coho are absent (Hartman 1965). Interspecific and intraspecific competition, therefore, plays an important role in regulating the distribution of fish within the usable area of streams and may account for the high degree of spatial segregation of species and age groups within stream reaches.

Although habitat availability is generally related to channel units, the location of usable area is very dynamic within a stream reach. During low flows, much of the stream's total water volume may reside in pools (Beschta and Platts 1986). As flow declines to critical low levels in summer, woody debris and large bed particles can help to maintain habitable depths for fish by slowing and deepening the flow (Lisle 1986).

As discharge increases, the expanding channel area and changing hydraulic patterns create new usable areas while eliminating others. Average velocity and depth increase in all parts of the stream with increased flow, but at different rates (Figure 9; Sullivan 1986). With increasing flow the usable area tends to move from the middle of the channel to the edges, to which it is restricted during stormflow. Thus the habitat suitability of channel units changes seasonally in response to changing velocity and depth, and channel units that are capable of holding large numbers of coho fry during the summer are largely unsuitable during the winter (Grette 1985, Sullivan 1986). Protrusion of objects of different geometries into the flow creates numerous hydraulic "nooks and crannies" of slower water that provide cover from predators and high winter flows. In confined streams with steep gradients where winter habitat is otherwise lacking, debris jams can provide refuge from high velocities by ponding water during high flow.

Many salmonids emigrate from headwater streams to escape the extreme fluctuations in discharge and high average velocities that occur through the winter (Tschaplinski and Hartman 1983). Fish that remain in the main-stem channel move to locations different from those they had occupied during the summer months. Coho continue to use the slower pools, which during winter are primarily found along the channel margin and in the eddy pools downstream from large obstructions; steelhead trout abandon the riffles and move into the gravels in the bed at the deepest point in the pools or hide themselves in the interstices of the rocky substrate of the streambed (Hartman 1965, Edmundson et al. 1968, Bustard and Narver 1975). In some areas large numbers of fish emigrate to small channels on floodplains and terraces, where they overwinter (Peterson and Reid 1984).

<u>Habitat Assessment</u>. Mundie (1974) and others have recognized that processes essential to fish production, including suitable hydraulic characteristics, food production, and cover features, tend to be grouped within riffle-pool sequences. Because of this association, channel unit surveys at this scale are widely used in habitat assessment (Platts et al. 1983). The proportion of channel area composed of riffles and pools is a useful index of habitat quality, and a stream with approximately 50% pools is generally considered to possess good habitat attributes (Ruggles 1966, Platts et al. 1983). Under most conditions, however, the proportion of pool area can vary from 30 to 70% total stream area. Pool quality indexes may also be useful in assessing habitat, but these have been developed mainly from the habitat needs of fish of catchable size in specific regions and may not be widely applicable (Platts et al. 1983).

Habitat assessment using different types of pools and riffles as microhabitat units has helped to sort out the hydraulic complexity of channels with abundant amounts of large woody debris. The classification scheme developed by Bisson et al. (1982) recognizes six types of pools and three types of riffles based on causative factors and water surface gradient. Each unit represents a different microhabitat, which differs from others in characteristics of velocity and depth (Sullivan 1986). Therefore, microhabitat surveys based on channel characteristics (Figure 14) are a useful estimate of the habitat available to a variety of

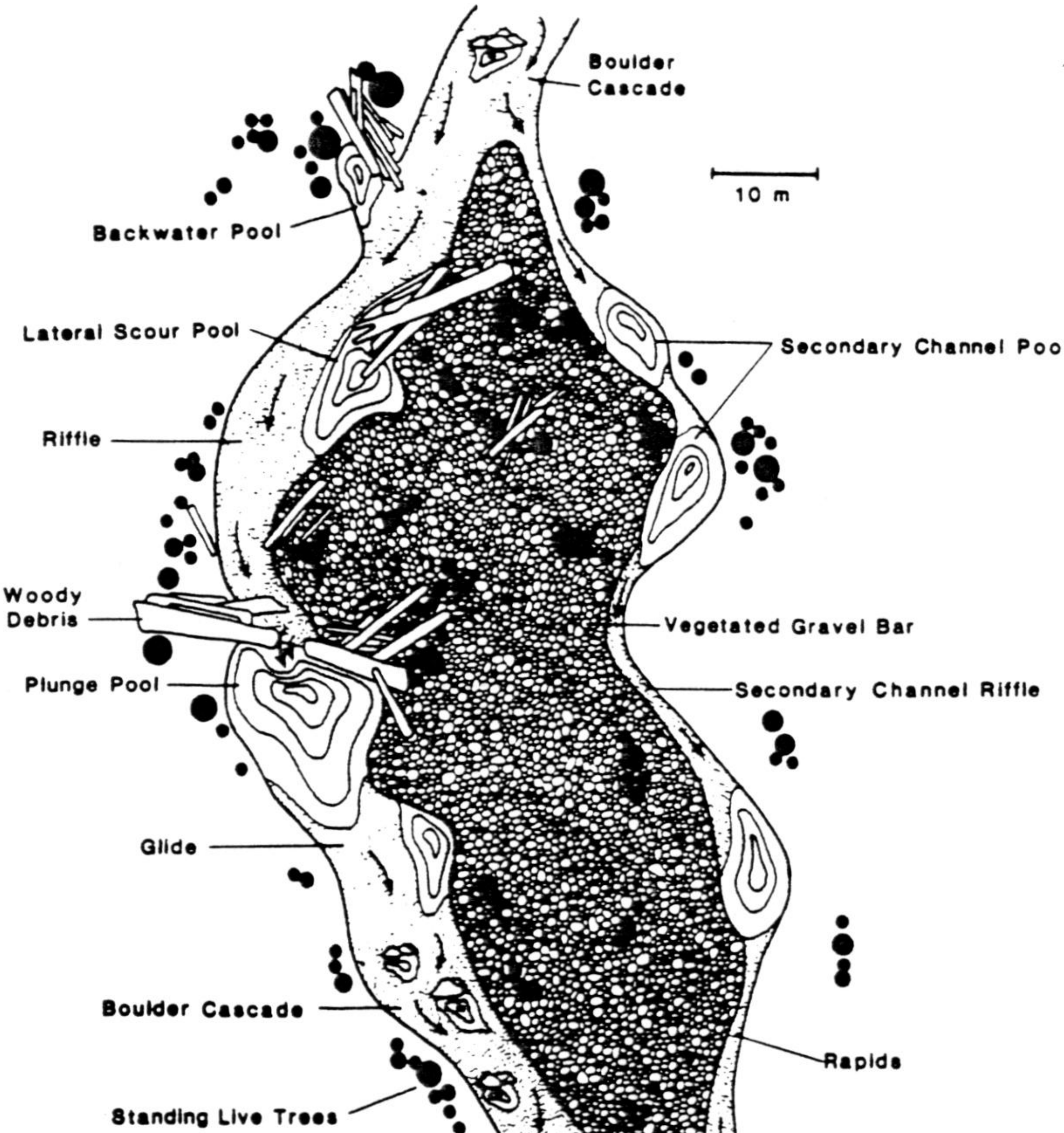


Figure 14. Channel unit map of microhabitats in a stream reach in a fourth-order stream, western Washington (from Bisson et al. 1982).

species and can be used to assess habitat availability at most flows. Data requirements are minimal, and this method can be applied over extensive areas.

Another quantitative method of assessment based on the hydraulics of flow at channel cross sections is the Instream Flow Incremental Methodology (IFIM) developed by the U.S. Fish and Wildlife Service (Bovee and Cochnauer 1977, Bovee 1982). This method has gained wide use in evaluating the effects on fish habitat of changes in flow regimen likely to be caused by diversions or dams. Although the method produces good results for specific reaches, data requirements are very intensive for each stream reach examined, precluding its use for more general habitat assessment.

It should be noted that both microhabitat surveys and the IFIM are capable only of predicting available usable area within stream reaches and therefore fish community distribution. Neither method can adequately predict stream productivity, which also depends on other factors such as the availability of food resources, competition and predation, and the presence or absence of spawning populations.

Regional Variability: Geology and Climate

A channel's shape is controlled largely by processes that operate outside of the channel. The controlling influence of large-scale factors of climate and geology on the fluvial system means that stream channels are likely to look and behave differently where different geologic and hydrologic processes are active. The properties, size distribution, and availability of sediment and the seasonality, intensity, and duration of hydrologic events are strongly influenced by geology and climate. Furthermore, the topology of the drainage network, mode of sediment delivery from hillslopes, and the presence or absence of bedrock in the channel are determined by geologic and climatic factors.

Hence regional differences in channel morphology can be significant. For example, northern California and southwestern Oregon have large amounts of rain on a landscape composed of pervasively sheared bedrock. This has resulted in highly unstable terrain and streams with exceptionally high total suspended sediment yields (2,000 to 3,000 t/km^2 per year; Karlin 1980) and beds commonly composed largely of gravel and sand which are easily transported during annual floods. On the other hand, the climate of the western Cascades of Washington and Oregon is less intense, and the volcanically derived rocks are more stable. Cascade streams have relatively low sediment transport rates (30 to 80 t/km^2 per year; Larson and Sidle 1980) and stable beds composed largely of cobbles and boulders which move only during more extreme events.

WATERSHED DISTURBANCE

Water discharge, sediment input, and the abundance and type of channel obstructions can change following either natural (e.g., wildfires or volcanic eruptions) or man-caused disturbances. Storms can also be viewed as a type of disturbance, though their primary effect may be to cause changes triggered by other disturbances such as logging or wildfire.

Forest management activities can lead to changes in channel morphology by altering sediment production (affected by increased mass failures and surface erosion), debris loading (affected by logging activities), and local hydrology (affected by road-related drainage alterations and tree harvest). While most natural disturbances tend to occur in localized areas in the Pacific Northwest over a relatively short period, logging-related disturbances have affected broad parts of the region over the past several decades. Differences between natural and anthropogenic disturbances include different patch sizes (natural ones tend to be larger), geometries, and frequencies of occurrence.

Among the three major factors controlling channel morphology in forest streams--sediment, flow, and obstructions--increases in sediment load have most frequently been blamed for channel changes after watershed disturbance. Common channel changes accompanying increased sediment loads are channel widening and braiding, decreased riffle-pool amplitude, aggradation, and decreased bed particle size. Increasingly, attention has also focused on the effects on channel morphology of artificial removal of large woody debris during stream cleaning following logging. Such changes in channel structure can cause immediate changes in local reaches, while changes in the input of water or sediment, if large enough, can cause downstream channel adjustments. To the extent that any of the factors controlling channel morphology change, the channel morphology will change to reflect the new balance.

Effects of Large Floods

The extremely large floods (e.g., the flood of December 1964 in northern California and Oregon) may leave an imprint on the channel that persists long after the storm event. Erosion and sediment transport processes such as debris avalanches, debris flows, and the movement of large boulders in channels typically occur during extreme conditions of runoff and soil moisture. Thus, as unusually large volumes of sediment enter channels from hillslopes and tributaries and the entire bed surface is mobilized, the channel is molded into depositional and erosional forms that reflect the magnitude of high stream flows and sediment inputs. Even though both managed and unmanaged watersheds are affected by large storms, the response of managed watersheds tends to be greater (Grant et al. 1984).

The large flood leaves a legacy in large volumes of sediment transferred from hillslopes to channels, widened channels, large bars, depleted woody debris (except where new landslides enter the channel or logjams form), and riparian zones stripped of trees (Kelsey 1980, Lisle 1981a). During subsequent, lower flow events, this stored sediment is reworked by the stream, and channel banks rebuild as riparian vegetation becomes reestablished (Lisle 1981b, Beschta 1983b). Smaller flows may exert more influence on the inner portion of the channel (the portion providing summer habitat for fish) just after a large flood than before, because the fine sediment left by the flood can be mobilized by relatively low flows. As a result, pools fill and riffles decrease in gradient (Lisle 1982, Jackson and Beschta 1984).

The order in which hydrologic events and watershed disturbance occur is therefore very important in determining the relative effects of a given event (Beven 1981). The effect of a large flood depends partly on how erodible the watershed and channel are when the flood occurs and the period that has passed since the last large flood. Since each flow event that moves sediment changes the channel to some degree from the condition left from the previous event, the ability of an event of a given magnitude to leave its imprint on the channel depends on the amount of work it does on the channel relative to the amount of work done by succeeding events (Wolman and Gerson 1978). Large floods can appear to be most responsible for the condition of a channel if one has occurred in the recent past; moderate floods may appear more effective if a long period has passed since the last large flood. As a result, the shape of any channel is partly a function of hydraulic and sediment transport processes that have operated on different scales depending on the magnitude of past floods.

The effect of large storms may be particularly important in altering channel morphology where the land is steep, the streams are small, bed material is coarse, runoff is highly variable, and there is much sediment available during high runoff (Lisle 1981a). These conditions are common to mountainous, forested areas dominated by mass erosion and rainfall-runoff, such as the Pacific Northwest. Furthermore, the chance occurrence of major floods creates high uncertainty in predicting the effects of disturbance associated with land use. For example, there were six major floods in northern California between 1950 and 1975, preceded by a fifty-year period without major floods (Harden et al. 1978).

Effects of Forest Management

Forest management may cause an increase in the influx of coarse sediment and floatable organics to the stream system, the generation of more erosive flows, a weakening of streambanks, and the removal of obstructions that regulate the routing of sediment and flow through the stream network. With these changes, channels may widen, bed sediments may be transported more frequently, and the volume of sediment in temporary or long-term storage on floodplains, bars, and within the channel may increase, thus decreasing pool area. The extent to which any of these changes occurs depends largely on the geologic and climatic regime, position in the watershed, and management practices.

In this section we briefly discuss mechanisms by which sediment, flow, and woody debris loading can be changed by forest management and processes of channel adjustment. Our discussion will focus on changes in channel morphology rather than the forest practices that may cause them, since these are discussed in some detail in other papers in this volume (Swanson et al., Everest et al., Bisson et al.).

In addition to determining how management activities affect channel-forming processes, an assessment of management impacts must also consider: (1) What are the regional differences in channel behavior arising from geology, climate, and land use? (2) What is the sequence of watershed disturbance, channel adjustments, and recovery? (3) How much of a disturbance is necessary to cause important changes in fish habitat? Watershed disturbance can lead to many different types of changes in the input or output of sediment, water, or structural elements in channel systems, but some combinations of changes are more common than others. If these more common changes are recognized and understood, there is a basis for predicting effects at other sites.

Changes in Sediment Load. The amount of sediment contributed to streams is affected by management-induced changes in rates of hillslope erosion processes, such as increases in landslide frequency, and by introduction of completely new processes, such as sheet-wash erosion on road surfaces. The manner in which forest management affects sediment loading is discussed in other papers in this volume (Swanson et al., Everest et al.).

Disturbance of parts of a watershed can accelerate certain erosion processes and thus affect the volume, timing, and grain size of sediment contributed to streams. For instance, sediment produced by overland flow on road surfaces is usually fine grained and is produced in varying volumes by each rainfall event (Reid and Dunne 1984), while road fill failures are less frequent, coarser, and individually more voluminous.

Changes in Sediment Storage. An increase in erosion rate on hillslopes usually results in an increase in the volume of sediment contributed to streams, and thus sediment of transport-limited grain sizes is likely to accumulate locally until transport capacities increase. Different parts of a drainage basin respond to a given change at different times. For example, management-induced changes are likely in sediment transport processes on hillslopes, but the results of these changes are translated to streams at the rate that sediment is transported downslope, introducing a lag time that may range from minutes to decades.

When coarse sediment from a new source enters the stream, it travels as slow-moving bedload, and may take tens or hundreds of years to reach the mouth of a moderate-size basin (Beschta 1983b, Madej 1984). The channel at the basin mouth will not fully respond to the change on the hillslope until the sediment has arrived there, and an unknown proportion of the sediment may be lost to long-term storage on the way through the stream system.

Changes in Peak Flow. It can be argued that soil compaction, ditching, increased rain-on-snow melt rates, and overstory removal in managed forested watersheds should increase peak discharges in streams and thereby cause channel instability. Testing of this hypothesis has yielded mixed results, however. The ability to detect peak flow increases varies with the magnitude of changes in runoff regime and the regional differences in soils, geology, and climate. Furthermore, it is difficult to determine the effects on channel morphology of increased flow alone, because in most logged streams sediment input, woody debris, or banks may also be disturbed (Beschta and Platts 1986). Nevertheless, increases in runoff without significant increases in sediment load after urbanization have caused channels to enlarge (Dunne and Leopold 1978). Although generalization is difficult, the effects of increased sediment availability by landsliding appear to be more important than possible flow changes brought about by management practices (Beschta 1984, Grant et al. 1984).

Under natural conditions, infiltration rates on forest soils are usually high enough to prevent overland flow, but compaction of road surfaces and skid trails can result in overland flow. Because overland flow delivers runoff to streams more rapidly than subsurface flow, land use practices that make the ground more impervious or bring subsurface flow to the surface usually increase peak runoff and sediment transport. Increased peak flows have been demonstrated on small basins where road densities are high (Harr et al. 1975). The interception of subsurface flow by roadcuts can also increase runoff rates (Megahan 1972, King and Tennyson 1984).

Saturated areas capable of generating overland flow are also likely to increase in managed basins, since removal of the forest cover decreases evapotranspiration rates and thus increases the water stored in soils. As a result, soils are more quickly saturated during storms, and smaller rainfall volumes are sufficient to generate overland flows. However, evapotranspiration rates from mature forests are low in winter when rainfall is heaviest. Therefore, this effect is only important early in the season when soil moisture would be quite low under natural conditions, and does not increase peak runoff significantly after the first few storms saturate the ground (Harr et al. 1975, Ziemer 1981). Lengthening of the saturated period, however, may play an important role in earth-flow movement in terrain susceptible to this type of mass movement.

Research results suggest that clearcut logging can alter snow accumulation and melt enough to increase the size of peak flows caused by snowmelt during rainfall (Harr 1986). This effect can occur during storms throughout the winter season and over a wide area of the Pacific Northwest. This suggests that susceptibility to hydrologic change varies based on elevation, climate, and stand age within basins. The extent to which increased peak flows from this source have affected channel morphology has not been demonstrated, although Lyons and Beschta (1983) listed it as a possible cause of channel widening of the Middle Fork Willamette River. Additional research is clearly needed to determine the extent of peak flow changes in managed watersheds and to clarify its possible effects on channel morphology.

Changes in Debris Loading. Effects of timber harvesting on large woody debris in streams and strategies to manage woody debris and riparian areas are detailed in the companion paper by Bisson et al. (this volume). In recent years, streams were usually cleared of large woody debris during and after logging. Natural debris was frequently removed along with logging slash, leaving most streams depleted of

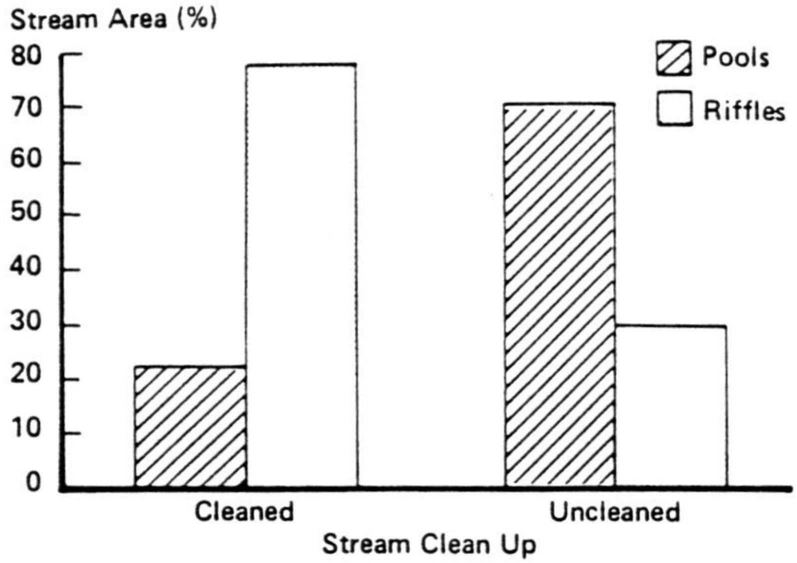


Figure 15. Proportion of stream area in riffles and pools before and after removal of woody debris following logging (Bisson, unpublished data).

woody debris. Debris torrents can also deplete debris by transporting it downstream. Through either mechanism, both hydraulic and habitat complexity are reduced as a result of the loss of woody debris.

Immediately following debris removal, there is an initial release of large quantities of sediment (Beschta 1979) and considerable rearrangement of whatever floatable woody debris remains (Bilby 1984). Within a stream reach these adjustments may result in a smoothing of channel gradient where the deepest pools are filled and higher gradient riffles flattened. In most areas, a semblance of the riffle-pool morphology persists following debris removal, but characteristics of those features may change.

The extent and duration of changes in riffle and pool morphology with debris removal appear to depend on the sediment regime of the stream, and reflect such factors as increases in sediment input concurrent with debris removal, the history of storms since debris removal, and the presence of other pool-scouring obstructions and bends. Therefore, the documented changes in morphology in response to debris removal have varied in the Pacific Northwest from little change from preexisting conditions to extreme changes. In some northern California streams that have been cleaned, sediment filled pools and channels widened, resulting in the complete disappearance of pools and severe loss of cover and habitat diversity. In other cleaned streams, total pool volume may decrease as riffles elongate (Figure 15). For example, Bisson and Sedell (1984) documented loss of pool area in a fourth-order, gravel-bedded stream in western Washington following debris removal. Elsewhere in western Washington, streams that have been cleaned of debris or have experienced debris torrents have

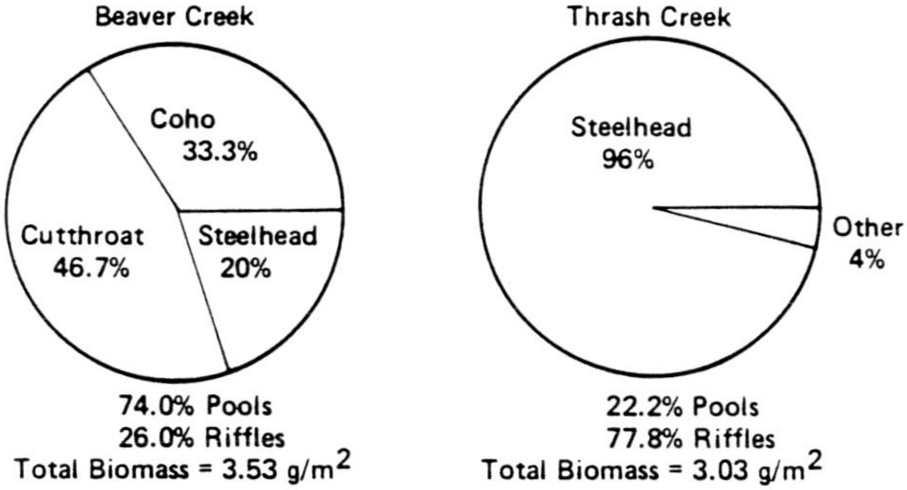


Figure 16. Fish populations in two streams in western Washington with different proportions of pool area (Bisson, unpublished data).

developed fewer but larger pools, resulting in the same overall pool area as existed prior to debris removal (Grette 1985).

Bank Instability. Felling and yarding operations often disrupt banks of low-order streams, or leave the banks bare of vegetation and woody debris and susceptible to erosion. Toews and Moore (1982) measured a threefold increase in bank erosion along a reach of Carnation Creek, British Columbia, that had been cleared of all riparian vegetation and cleaned of stable debris along the channel margin. Possible loss of root strength of banks after harvesting riparian trees has not been adequately investigated.

Removal of streamside vegetation and weakening of banks may result in increased channel width. Lyons and Beschta (1983) documented increased channel widths in the Middle Fork Willamette River and tributaries after the large 1964 storm damaged riparian corridors. Die-off of willows after residential pumping of floodplain groundwater along the Carmel River was associated with channel widening of 100% or more (Curry and Kondolf 1981). Cattle grazing of meadows commonly leads to channel widening and destruction of fish habitat through removal of streamside vegetation and trampling of the banks (Platts 1981).

Changes in Fish Habitat. Changes in the pool-riffle ratio in a stream reach may alter fish community structure by changing the type of habitat available. For example, where pool volume decreases, species or age groups of salmonids requiring deep pools may be eliminated or reduced. On the other hand, increased riffle area favors species such as steelhead trout and young-of-the-year age groups of trout and salmon. Therefore, stream reaches with different morphologies are likely to support different fish communities, as illustrated in Figure 16. Not only do the species differ between the streams shown in Figure 16, but the cutthroat and steelhead trout populations in Beaver Creek are composed of several age groups while steelhead populations in Thrash Creek are primarily age 0+. Species diversity is often lower in streams with low hydraulic diversity. Channels with little structural complexity offer poor habitat for fish communities as a whole, even though the channel may be stable.

Where channels are not stable, frequent changes in habitat structure may reduce fish populations. For example, Scrivener and Andersen (1984) found that the coho salmon population in Carnation Creek, British Columbia, decreased several years following logging as unstable debris in disturbed channels was frequently redistributed during winter storms.

A shift in the riffle-pool composition does not necessarily decrease the rearing capacity of a stream reach if species adapted to new habitat conditions have access to the stream. Often, clearcut streams can be very productive as reduced habitat space associated with changes in channel morphology and debris loading may be compensated for by increased food production in streams cleared of overstory vegetation and exposed to increased light (Scrivener and Andersen 1984). For example, the population biomass shown for each stream in Figure 16 is similar despite a significant difference in pool habitat. Nevertheless, overall population success of species that spend more than one season in streams could be reduced if overwintering habitat is eliminated. Research is needed to determine the winter habitat requirements of species and the extent to which the availability of overwintering habitat in headwater streams limits their populations.

BASIN-SCALE CASE STUDIES

Despite widespread concerns about the effects of logging on channel morphology, there are surprisingly few well-documented studies. There are even fewer studies that link changes in morphology with changes in habitat and fish populations in river basins. Reasons for this are varied. The broad spatial and temporal scales over which most channel changes occur require both at-a-site and basin-scale monitoring or evaluation in order to determine the type and extent of channel responses. Furthermore, historical records or ongoing studies are needed to document time trends. Many of these methods which have been applied are time consuming and expensive, they often do not yield results for many years, and results have limited geographic applicability. Relating changing fish populations to changes in habitat has also proved difficult, because factors other than channel changes associated with forest management have contributed significantly to decreasing fish populations. Fishing pressure, construction of hydroelectric dams and diversions, and urban and agricultural land use practices contribute to the general decline of fish runs that has been observed over the last three decades in the Pacific Northwest. Thus, even though habitat and population changes can be demonstrated within forest stream reaches, the relationship between fish populations, habitat conditions, and land use within basins has not been adequately documented.

Nonetheless, there are several examples on a basin scale that illustrate how channels located in different geologic settings respond to and recover from disturbances of different types and intensities. Here, we present four case studies from the Pacific Northwest. Placing studies of channel morphology changes side by side makes it possible to compare and contrast differences in disturbance processes, channel sensitivities, and time scales and mechanisms of channel recovery. These differences highlight the important controls exerted on channel response by local factors of geology, hydrology, and vegetation.

Our four examples are located on the Toutle River in Washington, the Middle Fork Willamette River in Oregon, the South Fork Salmon River in Idaho, and the Trinity and other rivers in northern California. In each case, we examine (1) individual site characteristics that may play a role in determining the nature of channel response, (2) documented channel changes, including changes in channel geometry, bed morphology, and patterns of sediment or organic debris accumulation, and (3) evidence of channel recovery. The changes in input variables and subsequent channel changes are summarized in Table 1. Since no one study measured all these characteristics, there are obvious gaps in this cross-site comparison. Furthermore, in none of our examples were fish populations systematically related to changes in channel morphology. These gaps clearly point up the need for additional research.

Northern California

Region Characteristics. Streams in northern California have the highest rates of sediment production in the conterminous United States (Judson and Ritter 1964), as the result of high rates of uplift, pervasively sheared bedrock, high seasonal rainfall, and disruptive land use practices in the period from about 1950 to 1970. A series of six large floods occurred during the period from 1950 to 1975. One flood in particular, the historic flood of December 1964, caused extensive landsliding and gullying, particularly on cutover land (Kelsey 1980, Janda 1978). Floods of similar frequency and magnitude occurred from 1861 to 1890, but apparently produced much less sediment than the present series, because intensive logging, tractor yarding, and road building in old-growth forests had not occurred (Harden et al. 1978). Local geology and vegetation produced a wide variety of effects. For instance, deep gullies were formed in the deeper soils of grasslands, and debris torrents and avalanches were more prevalent on steep, forested slopes with thin soils (Kelsey 1980).

Channel Changes. The combination of unusually high flow events and large inputs of sediment of all grain sizes produced substantial changes in stream channels that persist in some areas to the present. Channels aggraded up to 4 m and widened as much as 100% (Hickey 1969, Kelsey 1980, Lisle 1981a). Bed material size commonly decreased in aggraded reaches except where coarse landslide debris was introduced. Channel courses were changed, and many became braided. Riparian corridors were stripped, and large volumes of woody debris were introduced by landslides and eroding banks. Much of the woody

Table 1. Case histories of channel response and recovery after disturbance.

Area	Type of Disturbance	Channel Response	Recovery Period (years)	
			Channel	Riparian
Northern California	Logging-induced landslides, surface erosion; large floods	Widening, aggradation, loss of riparian vegetation	5-60	100-200
Middle Fork Willamette, Oregon	Logging-induced landslides, debris flows; large flood	Widening, aggradation, loss of riparian vegetation	10-20	100-200
South Fork Salmon River, Idaho	Logging-induced landslides, surface erosion; large floods	Aggradation, deposition of fines, infilling of pools	10	Little impact
Mount St. Helens blast area	Large increases in fine sediment; LOD added, then salvaged	Aggradation, fining of the bed, filling of pools	8-25?	100-200

debris was swept away and accumulated in huge jams in channels and on floodplains or was floated out to sea.

The effects of fish populations and their habitats are poorly documented. However, populations generally declined during this period (Rankel 1979), and observed changes in channel morphology point to reduced productivity in many streams. Increased fines, greater depths of scour and fill, and loss of heterogeneity in bed material in aggraded reaches probably decreased spawning success and impacted benthic invertebrates. Critical surface flow in summer was lost to subsurface flow through increased thicknesses of bed material (Jones 1980). Pools were filled and riffles became less pronounced (Lisle 1982). Riparian vegetation in widened channels became more isolated from streams in summer, resulting in fewer terrestrial insects falling into the water and increased stream temperatures. Remaining suitable habitat around woody debris was probably reduced by debris removal from dispersed locations along banks.

Channel Recovery. Since the floods, channels have recovered to various degrees and at different rates in the following sequence (Lisle 1982). Suspended sediment concentrations declined to stable levels after a few years as landslide scars and gullies stabilized and became armored (Anderson 1970). Channels degraded to stable levels equal to or higher than preflood levels within time spans ranging from five years to two decades or more. Riffle-pool sequences recovered to some degree at this stage, but full recovery awaited subsequent steps (Lisle 1982). Alluvial channels narrowed as they degraded (Figure 17), but channels with nonalluvial banks were not observed to narrow with degradation (Figure 18), both because hillslope processes were slow in replacing eroded streambank material and because newly formed banks and riparian vegetation were vulnerable to erosion at high flows confined within the steep valley walls (Lisle 1981a). Riparian vegetation became established along active channels and helped to reconstruct banks by trapping and stabilizing fine sediment. The absence of large floods since 1975 has greatly helped this process so that riparian stands are increasingly less vulnerable to high flows. New large woody debris is probably accumulating at dispersed locations and being anchored along riparian corridors with reestablished vegetation. However, extensive postflood cleanup of debris and the loss of old sources of debris may have caused a long-term deficit in natural concentrations.

In summary, large floods and damaging forest practices exacted a heavy price on fishery resources. Most small channels (up to fifth order) have recovered to the point where riparian trees are reestablished and new debris is accumulating. Fish populations in channels that have physically recovered remain low in the Klamath-Trinity system, for example, because of severe depletion of stocks by overfishing, long periods of poor habitat conditions, or continued poor conditions of main-stem and estuarine habitats. Many larger channels, which in this region of low summer flows could have important potential for rearing habitat, will probably remain aggraded and widened through the end of this century (Madej 1984).

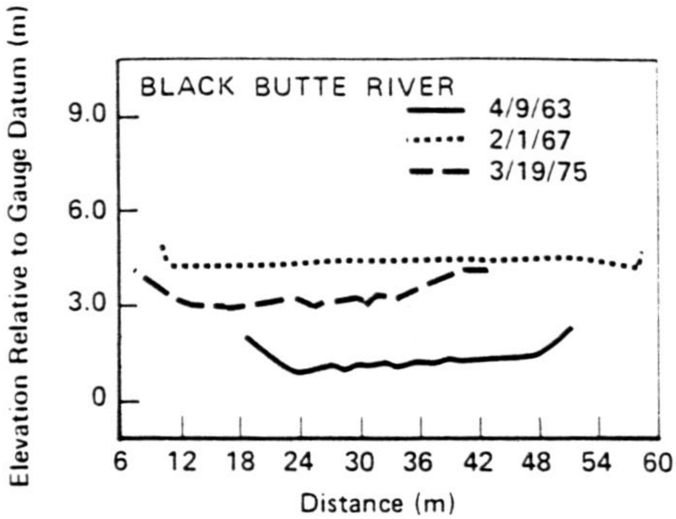


Figure 17. Channel cross sections surveyed at the gauging station at Black Butte River, northwestern California, before and after the 1964 flood (data from U.S. Geological Survey). The channel aggraded and widened after 1964, and has since incised partially into flood deposits, creating a narrower channel (Lisle, unpublished data).

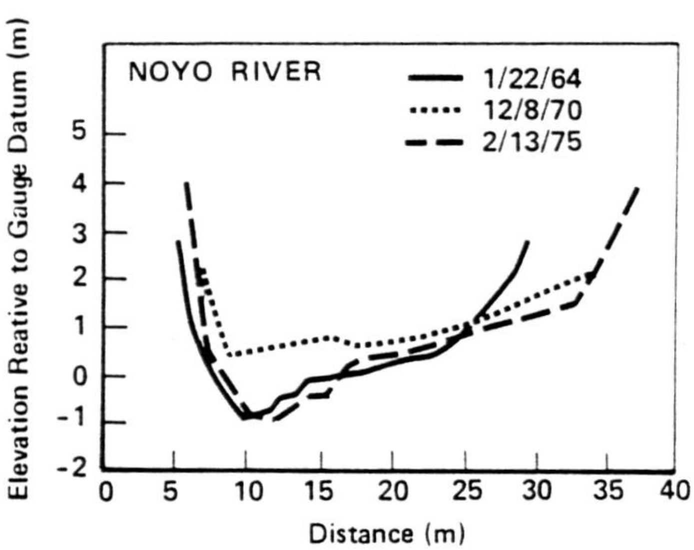


Figure 18. Channel cross sections surveyed at the gauging station of Noyo River, northwestern California, before and after the 1964 flood (data from U.S. Geological Survey). The channel aggraded and then degraded since 1964, but has remained wide (Lisle 1982).

South Fork Salmon River (SFSR)

Region Characteristics. The South Fork Salmon River is a large (3,300 km^2) drainage in central Idaho underlain exclusively by granitic rocks of the Idaho batholith. Elevations range from 640 to 2,740 meters, and side slopes are steep and mantled by shallow, coarse-textured soils developed on deeply weathered granite saprolite. Vegetation is primarily ponderosa pine and Douglas-fir. Historically the SFSR contained Idaho's largest salmon run: prior to 1960 the river produced 30% of Idaho's chinook salmon harvest (Platts and Megahan 1975). This discussion of the effects of logging, roads, and storms on fish habitat and channel morphology in the region is based on research described in the following sources: Arnold and Lundeen 1968, Megahan and Kidd 1972, Michelson et al. 1973, Platts 1975, Platts and Megahan 1975, Platts 1979, Megahan et al. 1980, Cole and Megahan 1980, and Harmon et al. 1986.

Most studies in the SFSR have focused on the upper South Fork above its confluence with the Secesh River. Channel beds were historically covered with gravel and have had very low concentrations of coarse woody debris. Extensive logging activities in this 1,030 km^2 subbasin from 1950 to 1965 resulted in 15% of the basin area in logging sales and 1,000 km of roads by 1965. The logging and road construction accelerated erosion from shallow granitic soils to the extent that by 1967, sediment loads had increased 350% over prelogging levels. Severe storms in 1962, 1964, and 1965 contributed to the increased erosion, particularly from roads. Because of concern over declining fisheries, a moratorium on logging was imposed in 1966, and a watershed rehabilitation program was initiated. Cautious reentry into the basin was implemented in 1978.

Channel Changes. The products of accelerated erosion, consisting mostly of coarse sand, resulted in excessive bedload sedimentation during the 1960s that buried many of the prime spawning and rearing areas. Photographic analysis indicated significant aggradation of channels and filling of pools with fines (Megahan et al. 1980). Dunes of sand covered gravels and the surfaces of spawning areas with concentrations of fines.

Channel Recovery. The moratorium on logging imposed in 1966 and institution of watershed rehabilitation measures apparently resulted in a reversal of the trend of extensive channel sedimentation. Channel cross sections in spawning areas monitored from 1966 to 1979 showed a total decrease in average riverbed elevation ranging from 8.6 cm to 46 cm, averaging 12 cm (Megahan et al. 1980). Differences in channel response between riffles and pools are not reported; however, sequential air photographs show that a considerable volume of material was transported out of pools during this period (W. Megahan, pers. comm.). Percentage of fines in spawning areas in 1979 had decreased from 30% to 8%, while gravel content increased from 32% to 68% over the same period. Rearing areas showed a similar, though smaller, decrease in fines and increases in coarse rubble and gravel.

These results suggest that in a relatively high energy stream system draining an area producing fine-grained material, the volume of sediment in transport is likely to vary as a function of the rate at which sediment is supplied from hillslopes. Channel changes during the 1960s were the result of excessive delivery of sediment from hillslopes, largely caused by logging-related surface and mass erosion aggravated by a series of large storms. The supply of sediment exceeded the river's capacity to transport it, and deposition of fines and riverbed aggradation ensued. The moratorium on logging effectively reduced supply of sediment, and stream energies were sufficient to remobilize the deposited material and transport it out of affected reaches. Because riparian vegetation remained intact despite the sedimentation, banks and streambeds remained stable, facilitating recovery of the riffle-pool morphology.

Middle Fork Willamette (MFW)

Basin Characteristics. This 700 km^2 drainage basin in the western Oregon Cascades has been the site of several studies on the effects of storms and logging on first- through sixth-order stream channels (Lyons and Beschta 1983, Beschta 1984, Grant et al. 1984, Grant 1986). The Middle Fork Willamette basin is located in a deeply dissected and weathered volcanic platform composed of volcaniclastic rocks and lava flows of Miocene age. Annual precipitation is approximately 1,500 mm per year, falling as both rain and snow during the winter months; the highest streamflows occur during rain-on-snow events (Harr 1981). Elevations range from 260 to 2,660 meters, and sideslopes are steep and mantled with soils ranging in texture from clay to stony depending on underlying bedrock and topographic position. Vegetation is primarily Douglas-fir and western hemlock in the lower elevations and Pacific silver fir in the higher. Stream gradients are steep, ranging from an average of 7% in the fourth-order tributaries to 1% in the main-stem Middle Fork Willamette. Bedload material ranges from cobble to boulder size in the tributaries and gravel to cobble in the main stem; little sand is present. The basin has been extensively logged and roaded over the past forty years, with approximately 15% of the total basin area harvested as of 1975 (Lyons and Beschta 1983).

Channel Changes. Along the main Middle Fork Willamette, Lyons and Beschta (1983) reported increased channel width over the period 1959 to 1967, a span of time that included the major storm of December 1964. The observed increases in channel width can be attributed both to delivery of large volumes of sediment from landslides, most of which were associated with roads and clearcuts, and the scouring effect of the flood as it entrained large woody debris and removed riparian vegetation (Lyons and Beschta 1983, Grant et al. 1984). Most riparian canopy removal along fourth- and fifth-order tributaries occurred downstream from landslide sites. In smaller streams, debris flow passage essentially stripped the channel and banks of wood and scoured the channel to bedrock in many places, although photographic interpretation suggests that increased sediment supply was more important than peak flow scouring in causing channel enlargement (Grant et al. 1984).

Over twenty years after the 1964 event, the legacy of the flood is still very much in evidence. Large boulder and cobble bars that date from the 1964 flood still line the channel over most of its length. This material appears to be considerably coarser than much of the sediment in the channel bed, indicating that it is probably immovable by moderate flows. The incision of the channel into flood deposits and the development of multiple channels and braids have removed many 1964 deposits from active transport by most discharge events. Hence some channel changes due to accelerated erosion in the 1960s will probably persist for many centuries.

The extent to which the original frequency and distribution of pools, riffles, and woody debris were changed during the storm is unknown. In a comparison of bed morphology of two tributary streams twenty years after the storm, pools and large woody debris accumulations, many of which formed channel-spanning debris dams storing large quantities of sediment, were slightly more frequent in undisturbed streams than in landslide-impacted streams. Sample size was small, however, and differences in morphology could have been due to watershed differences.

Channel Recovery. Unvegetated channel width along the main-stem Middle Fork Willamette has generally decreased over the period from 1972 to 1979 as a result of regrowth of riparian vegetation (Lyons and Beschta 1983). Riparian species composition, however, has shifted from conifer dominated to alder and willow dominated, and dense stands of deciduous trees now line the channel. This shift is important in determining the type and characteristics of coarse woody debris and litter input to the stream, stream shading, bank stability, and possibly even low-flow biological water demand. Assuming that no large storms similar to the 1964 event "reset" the system, it may take several centuries for the valley bottom vegetation to return to its pre-1964 condition.

The 1980 Eruptions of Mount St. Helens: The Blast Area

Thus far we have discussed sites where logging practices have played a major role in provoking channel responses. It is also instructive to examine the results of an extremely catastrophic natural disturbance in order to explore the extremes of channel response. For this purpose we have selected Mount St. Helens.

Region Characteristics. 1980 eruptions of Mount St. Helens blanketed large areas with material mostly the size of sand and finer, up to about a half meter deep. (See Lipman and Mullineaux 1981 for descriptions of the 1980 eruptions.) The gradient in thickness of deposits over several major drainages provides a grand experiment in the effects of different levels of fine-sediment input on fish habitat. Other special circumstances include the lack of change in runoff (except in the western portion of the blast area). This summary focuses on the blast area north of the crater where a pyroclastic surge toppled most of the trees in the old-growth Douglas-fir forest and covered the ground with sandy ash and blast material. It does not address the North Toutle drainage, which received the large debris avalanche from failure of the cone on May 18, 1980. The effects of the eruption on channel morphology and fish populations of the North Toutle basin are described in detail by Martin et al. (1984), and recovery of anadromous fish habitat in this area is described by Jones and Salo (1986). Effects of ashfall on fish habitat outside the blast area are generally regarded as slight or short-lived (Lehre et al. 1983, Lisle et al. 1983).

Channel Changes and Recovery. Sandy blast and airfall deposits entered channels during the May 18, 1980 eruption, and later from sheet, rill, and gully erosion at an average rate of about 25 x 10^3 tonnes per km^2 per year (Swanson et al. 1983). Erosion rates then declined after the first two years after the eruption, and most blast material has been delivered to stream channels (Lehre et al. 1983, Collins and Dunne 1986). More recently, increased debris torrents and avalanches have delivered coarser debris to channels.

In summer 1980, channels of all sizes were filled with fine material, although steep reaches remained scoured to preeruption armor layers (Lisle et al. 1983). Most reaches of lower order channels degraded to gravel after the next high runoff season. Higher order channels (fourth order or larger) are in various stages of exhausting their supply of unarmored deposits of fine material. Thus, low gradient, main-stem channels downstream of the blast area are still aggraded with fine material throughout, while fine sediments in most other channels are confined to pools, active bars, quiet channel margins, and among woody debris. Extensive bank erosion has not been common, except downstream of debris avalanches and torrents. Streambanks were well buttressed by root networks of the downed trees, and vegetation along banks was the first to recover, because the steep banks were immediately able to shed the smothering blast and airfall deposits.

Some debate has accompanied the development of a management plan for woody debris in the blast zone. The strategy adopted by the state of Washington and the U.S. Forest Service was to remove most of the large woody debris from stream channels in order to capitalize on its timber value, to prevent local scour of streambanks by flow deflections created by debris, to reduce overbank flooding which might entrain additional fines, and to hasten the flushing of fines by removing obstructions. However, in a 1982 experiment to assess the importance of woody debris in restoring fish habitat, the Forest Service removed woody debris from some reaches and left it in others. Preliminary results suggest that, for the most part, debris in channels has served to enhance fish habitat by scouring pools, providing cover, maintaining depth during low flow, and diversifying hydraulic conditions.

Channel Recovery Following Disturbance

The four case histories illustrate the changes in channel morphology that can result in a response to increased sediment supply, whether natural or man-caused, and large floods. Two factors stand out as having an important effect on rate of recovery: the particle size of the increased supply of sediment and the form and structure of the riparian zone. For example, under natural conditions, both the Middle Fork Willamette and the South Fork Salmon might be considered to be "supply-limited" systems: the particle size and volume of sediment carried by the streams are limited by what is delivered to the channel instead of what the channels are capable of carrying. However, long-term channel responses to accelerated erosion are different in the two basins. In the case of the MFW, delivery of very coarse material to the main stem, coupled with channel widening, has resulted in a major shift in the characteristics of deposits on the valley floor. Because the sediment is so coarse, some bars of material deposited during the 1964 event will probably require an event of similar magnitude to be transported downstream. The channel has been transformed from a supply-limited to a transport-limited system, a change from which it may take centuries to recover.

On the other hand, the SFSR is an example of how a stream can recover from excessive sediment input. Here, the transport capacity of the channel was able to handle the influx once supply had been reduced. This resiliency is probably due both to the relatively fine size of input material relative to the original coarseness of the channel bed and to the absence of direct physical disturbance to the channel. Channel gradients and geometries had evolved to transport gravel, and sand deposition was short-lived because the sand could be transported during relatively frequent, moderate-size events.

This contrast demonstrates that channel response to disturbance is likely to be strongly controlled by geological factors that determine both the suite of sediment transport processes delivering material to channels and the size of the delivered material (Nolan and Marron 1985). The rate of recovery is also strongly influenced by the condition of the riparian zone. The relatively fast recovery of the riffle-pool morphology in the South Fork Salmon River was probably facilitated by the lack of disturbance of the riparian zone. In northern California rivers, riparian zones were eroded during channel widening and disruption of channel morphology. The recovery of stable channels that provide habitat for fish has been coupled with reestablishment of stable bars and banks and maintenance of woody debris.

STRATEGY AND TACTICS FOR MANAGING FORESTS AND FISH

Forest practices may alter the morphology of channels to which anadromous fish have evolved. Ideally, then, management activities should be designed to leave stream systems in as close to their natural state as possible. The aim of stream preservation elements of forest management practices, therefore, should be to minimize the changes in the sediment and flow regime of a watershed accompanying timber harvest, and to avoid disruption of the normal routing of sediment and flow within channels that can result from removing large woody debris. Minimizing changes in these factors will reduce impacts on channel shape and stability and fish habitat. As a result, this general strategy will serve to maintain hydraulic and habitat diversity sufficient to maintain diverse populations of salmonids species. To accomplish these goals, the forest manager needs an array of techniques that can be employed to prevent changes associated with various forest management activities, as well as an appreciation for the dominant erosion and transport processes operating within the basin of interest.

Many different management methods are already in use which minimize sediment production. Because of the inherent lag time between the management-related changes on hillslopes and the response of the channel system, the most useful way to control potential impacts on the channel is to control the changes in hillslopes that may trigger channel response. The general methods briefly described below are included as best management practices (BMPs) under forest practice operating guidelines in most states of the Pacific Northwest. For each state, the rules adopted represent the common denominator of our understanding of the dominant problems associated with forest management throughout a region or subregion. Many of the guidelines address the factors that ultimately determine channel morphology and fish habitat.

Hence many of the rules in most states are aimed at preventing erosion from roads, particularly landslides, by addressing road location, layout, construction, and maintenance practices. Provisions for buffer strips along streams are also included, although riparian zone guidelines were initially largely aimed at temperature control. Many states are currently revising forest practice guidelines to add a channel morphology component to riparian zone management that will ensure both bank stability and the recruitment of large woody debris into streams.

While forest practice guidelines provide generally applicable methods for stream protection, it must be remembered that there can be large differences in geology, climate, and disturbance history between basins within a region, and these will result in differences in the susceptibility of hillslopes and streams to change. Therefore, we emphasize that recognizing the factors that control channel morphology in individual watersheds can go a long way toward suggesting the appropriate techniques to apply in each, and we include watershed evaluation as a useful tool for forest management in a basin. Evaluation of basins should suggest the kinds of control methods that are both relevant and cost effective, and these will vary from area to area. The experiences of local land management agencies can be very useful in identifying specific problems and techniques of channel protection that may be applied in a locality.

At the Planning Stage

Control of adverse impacts at the planning stage is relatively straightforward. In most areas the dominant sediment sources in logged areas are landslides and debris torrents related to roads, and much is already known about prevention of mass failures (see discussions by Swanson et al., this volume). In most cases landslide frequency can be kept low by minimizing the construction of midslope roads, diverting road drainage from potentially unstable sites, ensuring that ditches and culverts remain functional, and constructing full-bench roads that minimize fill. A preliminary survey of natural slopes and nearby managed areas is very useful in identifying the types of sites that are least stable; once identified, they can be avoided, or appropriate engineering techniques applied.

Also significant is the contribution of fine-grained sediment from surface erosion on heavily used roads (Reid 1981). This can be reduced by ensuring that flow lengths are as short as possible on the bearing surface of the road, by in- or out-sloping the surface or by constructing frequent dips or water bars. Planning yarding methods and unit layouts to minimize road density can go far to alleviate input from road-surface erosion. In some cases, paving of roads, which eliminates road-surface erosion, can be justified economically by virtue of increased traffic, more rapid transit times, and decreased maintenance for both roads and vehicles.

Maintaining riparian stands with large trees is usually the most effective way to ensure an adequate supply of woody debris. Bisson et al. (this volume) describe possible strategies for management of woody debris and riparian zones. Future supplies of large woody debris need to be considered over periods of cutting cycles, because woody debris is likely to become depleted through time if not replenished. Recruitment of second-growth conifers into streams is a slow process extending over the duration of the lengthy rotation age of streamside stands (Grette 1985). Merchantable conifers within riparian zones may be a necessary source for large woody debris during future cutting cycles, even where the abundance of woody debris is currently adequate.

Resource Assessment

In order to predict possible changes in channel morphology resulting from management activities, we must be able to identify the normal state, determine the potential impacts, and evaluate changes already in progress.

An initial evaluation should include both definition of the stable channel state and identification of the hydrologic and sediment-production regimes with which it is in balance. This is most easily done by dividing the hillslopes and streams in the area of interest into groups according to bedrock and topography (and drainage basin area or stream order in the case of the streams), choosing representative samples from each group, and measuring those factors susceptible to change. In the case of streams, estimates of fish populations, pool area, channel bed material, and debris loading are useful (Platts et al. 1983), while hillslopes should be examined for the distribution of erosion processes and runoff-producing areas. These data from undisturbed streams will provide the basis for defining the natural state.

Forest management has been under way in many areas for long periods, and undisturbed slopes and streams may be rare. If undisturbed areas exist, it may be possible to evaluate the nature of ongoing changes by comparing the characteristics of disturbed and undisturbed streams and hillslopes using the method described above. If undisturbed areas cannot be found, sequential aerial photographs may provide clues to earlier conditions. Identification of changes both in the channels and on the hillslopes is important in interpreting ongoing or future effects.

It may also be useful to establish sites for repeated measurement of the morphological elements most likely to be affected by forest management. Yearly measurements of channel cross sections and bed-material composition, for example, are very useful in documenting change, or lack of it. Habitat assessment using techniques based on channel morphology and streamflow (Platts et al. 1983, Bisson et al. 1982) may also be useful for documenting effects on fish habitat.

Because sediment influx is often a primary trigger for altering channel morphology, an evaluation of the rates and character of sediment input before disturbance and an estimate of the input resulting from implementation of the management plan can be quite useful in assessing the potential effects of management. This type of evaluation is known as a sediment budget (Dietrich et al. 1982), and the method has recently been applied during short-term studies to evaluate the effects of low-head hydropower diversions in the Pacific Northwest. To construct a sediment budget, the types of sediment sources present in the area of interest are identified, the grain sizes they introduce are sampled, and their rates of input are measured. Rate measurement can take the form either of mapping the spatial frequency of discrete sources, such as landslides, and determining the age of scars by dating the colonizing vegetation or examining aerial photographs; or of determining the depth of erosion through time due to more continuous sources, such as bank erosion, by measuring the root exposure on datable plants (Reid 1981, Reid et al. 1981). In any case, ample evidence is usually available to estimate approximate erosion rates without requiring monitoring, and thus assessment can often be carried out over a period of weeks.

Sediment budgets can also be constructed for conditions following implementation of a proposed management plan. In this case, evaluation must address both the new erosion processes likely to be introduced and those already present whose rates will be altered. For this, examination of areas undergoing similar management and estimates based on measured process rates in similar areas are useful.

Repairing the Effects of Past Impacts

Because of the long history of forest management in many areas, impacts may already be present in areas of concern to fisheries management. In some cases, loss of habitat has been so severe that it has been considered necessary to restore a semblance of the undisturbed channel environment. Preserving and manipulating preexisting woody debris and adding new structural elements can be effective in enhancing fish habitat, at least in the short term, because such features can directly control channel form and preserve habitat even in the face of unfavorable hydrologic and sediment regimes.

Where woody debris has been removed from streams and loss of habitat has been severe, hydraulic complexity can be restored by introducing large woody debris or by constructing artificial structures designed to mimic the effects of natural obstructions in streams. Stream improvement techniques such as placement of gabions, log sills, and boulder groupings can increase natural salmonid production in marginal

Table 2. Need for structural elements in relation to stream gradient.

Stream Gradient	Priority for Habitat Improvement
<1%	Low to moderate: Spawning gravels are abundant, although structure can help to clean gravels. Inherent tendency to form pools and bars. Structure forms deep pools and increases cover.
1% to 10%	High: Bars and pools are formed only around obstructions. Spawning gravel is scarce, but often of good quality.
>10%	Low: Step pools can form good rearing habitat. Obstructions are relatively ineffective in creating habitat. Chronic problems of fish passage. Subject to debris torrents.

and degraded areas (Reeves and Roelofs 1982, House and Boehne 1985 and 1986). However, artificial structures are often costly, and each structure affects only a small area. Furthermore, despite increasing commitment by management agencies to habitat improvement projects, surprisingly few detailed studies have documented the physical and biological changes in stream environments and salmonid populations that would indicate the success of those efforts (House and Boehne 1985).

In order to be successful, stream improvement projects must be considered in view of the characteristics of the watershed, valley, and stream in which they are to occur (Reeves and Roelofs 1982). For example, the need for structural elements varies with channel gradient, as summarized in Table 2. The type of habitat units that form in the vicinity of obstructions is dependent on the relationship between streambanks and the flow characteristics induced by obstructions during high flow (Sullivan 1986). Thus, consideration of the principles of hydraulics and proper engineering techniques in placement of artificial structures are essential if their adequate performance is to be ensured (Orsborne and Anderson 1986). More research is needed to assess the effectiveness of various rehabilitation efforts in improving long-term productivity of headwater streams.

SUMMARY

Stream channels are composed of a mosaic of channel units such as riffles and pools which have distinctive shapes and locations within the stream channels. Riffles and pools have distinct differences in average velocity, depth, and substrate. Channel morphology reflects a balance between the influx of sediment, water, and woody debris to a stream, the stream's ability to transport sediment and woody debris, and the strength of the banks. The channel morphology and flow characteristics adjust if any of these factors change.

The amount of stream area suitable for freshwater rearing and spawning of salmonids is strongly dependent on the hydraulic characteristics of streams, which in turn reflect the relationship between streams and their valleys. Hydraulic characteristics directly influence the available space and therefore the distribution of fish within streams, since juvenile salmonids are limited by the velocity and depth conditions that they can inhabit. Species and age groups differ in the types of conditions in which they compete most effectively, resulting in segregation of species and age groups within stream reaches. Hydraulic diversity created and maintained around channel obstructions enhances species diversity by providing habitat space for a variety of species and age groups.

Forest practices can affect all of the factors that control channel morphology. For example, forest management can increase the influx of coarse sediment to the stream system, generate more erosive flows, alter sediment and water routing through the stream network, weaken the streambanks, and change debris loadings. With these changes, channels may widen, bed sediments may move more frequently, and the volume of sediment in temporary or long-term storage on floodplains and within channels may increase, thus decreasing pool area. Minimizing changes in these factors will reduce impacts on channel shape and stability and fish habitat. A review of channel changes documented in four basins that experienced increased sedimentation during the past three decades (Trinity and other northern California rivers, South Fork Salmon River, Middle Fork Willamette River, and Toutle River) suggests that two factors stand out as having an important effect on rate of recovery: the particle size of the increased supply of sediment (determined by geological factors) and the condition of the riparian zone.

The extent and persistence of changes in channel morphology and aquatic habitat that result from logging, wildfire, or other disturbances are likely to show considerable regional variation. Observations and conclusions about system behavior must be related to the specific geologic setting in which those observations were made. Consequently, management strategies for protecting aquatic resources must be based on an understanding of the specific physical processes common to a particular region. Control methods that are both relevant and cost effective may vary from area to area, and thus local evaluation of potential impacts is important.

Despite the need for site-specific control methods, our general understanding of stream systems suggests that adoption of best management practices (BMP) has provided a much needed basis for reducing the effects of forest operations. The intent of BMPs is to minimize potential impacts on water quality, channel morphology, and fish habitat on a regionwide basis. Best management practices attempt to minimize sediment input and hydrologic change, and preserve the morphologic complexity of channels. It is hoped that these strategies will maintain the hydraulic diversity necessary to satisfy temporal and spatial requirements of the variety of salmonid species that inhabit streams in the Pacific Northwest.

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LITERATURE CITED

Allen, K. R. 1969. Limitations on production in salmonid populations in streams. In T. G. Northcote (ed.) Symposium on Salmon and Trout in Streams, p. 3-20. H. R. MacMillan Lectures in Fisheries. University of British Columbia, Vancouver.

Anderson, H. W. 1970. Principal components analysis of watershed variables affecting suspended sediment discharge after a major flood. In Symposium on the Results of Research on Representative and Experimental Basins, p. 404-416. IAHS Publ. 96. Christchurch, New Zealand.

Andrews, E. D. 1980. Effective and bankfull discharges in the Yampa River basin, Colorado and Wyoming. J. Hydrol. 46:311-330.

_________. 1983. Entrainment of gravel from naturally sorted riverbed material. Geol. Soc. Am. Bull. 94:1225-1231.

Arnold, J. F., and L. Lundeen. 1968. South Fork of the Salmon River special survey: Soils and hydrology. USDA For. Serv. Intermountain Region, Ogden, Utah. 149 p.

Bachman, R. A. 1984. Foraging behavior of free-ranging wild and hatchery brown trout in a stream. Trans. Am. Fish. Soc. 113:1-32.

Beschta, R. L. 1979. Debris removal and its effects on sedimentation in an Oregon Coast Range stream. Northwest Sci. 53(1):71-77.

_________. 1983a. The effects of large organic debris upon channel morphology: A flume study. In D. B. Simons (ed.) Symposium on Erosion and Sedimentation, p. 8.63-8.78. Simons, Li and Associates, Fort Collins, Colorado.

_________. 1983b. Channel changes following storm-induced hillslope erosion in the upper Kowai basin, Torlesse Range, New Zealand. N.Z. J. Hydrol. 22(2):93-111.

_________. 1984. River channel responses to accelerated mass soil erosion. In Symposium of the Effects of Forest Land Use on Erosion and Slope Stability, p. 155-163. Environment and Policy Institute, East-West Center, University of Hawaii, Honolulu.

Beschta, R. L., and W. S. Platts. 1986. Morphological features of small streams: Significance and function. Water Resour. Bull. 22(3):369-380.

Beven, K. 1981. The effect of ordering on the geomorphic effectiveness of hydrologic events. In Erosion and sediment transport in Pacific Rim steeplands, p. 510-526. IAHS Publ. 132. Christchurch, New Zealand.

Bilby, R. E. 1984. Removal of woody debris may affect stream channel stability. J. For. 82(10):609-613.

Bisson, P. A., J. L. Nielsen, R. A. Palmason, and L. E. Grove. 1982. A system of naming habitat types in small streams, with examples of habitat utilization by salmonids during low streamflow. In N. B. Armantrout (ed.) Acquisition and utilization of aquatic habitat inventory information, p. 62-73. Western Division, American Fisheries Society, Portland, Oregon.

Bisson, P. A., J. L. Nielsen, and J. W. Ward. 1985. Experimental release of coho salmon (Oncorhynchus kisutch) into a stream impacted by Mount St. Helens volcano. In Proceedings, Western Association of Fish and Wildlife Agencies, p. 422-435. Victoria, B.C.

Bisson, P. A., and J. R. Sedell. 1984. Salmonid populations in streams in clearcut vs. old-growth forests of western Washington. In W. R. Meehan, T. R. Merrell, Jr., and T. A. Hanley (eds.) Fish and wildlife relationships in old-growth forests: Proceedings of a symposium, p. 121-129. American Institute of Fishery Research Biologists.

Bjornn, T. C., M. A. Brusven, M. P. Molnau, J. H. Milligan, R. A. Klamt, E. Chacho, and C. Schaye. 1977. Transport of granitic sediments in streams and its effects on insects and fish. Bull. 17. Forest, Wildlife and Range Exp. Stn., University of Idaho, Moscow. 43 p.

Boussu, M. F. 1954. Relationship between trout populations and cover on a small stream. J. Wildl. Manage. 18:229-239.

Bovee, K. D. 1978. Probability-of-use criteria for the family Salmonidae. Instream Flow Information Paper 4. U.S. Fish and Wildlife Service, Office of Biological Services.FWS/OBS-78/07. 79 p.

__________. 1982. A guide to stream habitat analysis using the Instream Flow Incremental Methodology. Instream Flow Information Paper 12. U.S. Fish and Wildlife Service, Office of Biological Services. FWS/OBS-82/26. 248 p.

Bovee, K. D., and T. Cochnauer. 1977. Development and evaluation of weighted criteria, probability-of-use curves for instream flow assessments: Fisheries. Instream Flow Information Paper 3. U.S. Fish and Wildlife Service, Office of Biological Services. FWS/OBS-77/63. 39 p.

Brett, J. R. 1964. The respiratory metabolism and swimming performance of young sockeye salmon. J. Fish. Res. Board Can. 21:1183-1226.

Burner, C. J. 1951. Characteristics of spawning nests of Columbia River salmon. U.S. Fish and Wildlife Service Bull. 61(52):97-110.

Bustard, D. R., and D. W. Narver. 1975. Aspects of the winter ecology of juvenile coho salmon (Oncorhynchus kisutch) and steelhead trout (Salmo gairdneri). J. Fish. Res. Board Can. 32:667-680.

Chapman, D. W. 1962. Aggressive behavior of juvenile coho salmon as a cause of emigration. J. Fish. Res. Board Can. 19:1047-1080.

__________. 1966. Food and space as regulators of salmonid populations in streams. Am. Nat. 100:345-357.

Chapman, D. W., and T. C. Bjornn. 1969. Distribution of salmonids in streams, with special reference to food and feeding. In T. G. Northcote (ed.) Symposium on Salmon and Trout in Streams, p. 153-176. H. R. MacMillan Lectures in Fisheries. University of British Columbia, Vancouver.

Church, M., and D. Jones, 1982. Channel bars in gravel-bed rivers. In R. D. Hey, J. C. Bathurst, and C. R. Thorne (eds.) Gravel-bed rivers, p. 291-338. John Wiley and Sons, New York.

Cole, G., and W. Megahan. 1980. South Fork Salmon: Future management. Symposium on Watershed Management, 1:396-405. American Society of Civil Engineers, New York.

Collins, B. D., and T. Dunne. 1986. Erosion of tephra from the 1980 eruption of Mount St. Helens. Geol. Soc. Am. Bull. 97:896-905.

Cummins, K. W., G. W. Minshall, J. R. Sedell, C. E. Cushing, and R. C. Petersen. 1984. Stream ecosystem theory. Verh. Int. Ver. Limnol. 22:1818-1827.

Curry, R. R., and G. M. Kondolf. 1981. Strategy for restoration of channel stability, Carmel River, Monterey County, California. In R. N. Coats (ed.) Proceedings of a Symposium on Watershed Rehabilitation in Redwood National Park and Other Pacific Coastal Areas. Center for Natural Resource Studies, John Muir Institute, Inc.

Dietrich, W. E., and T. Dunne. 1978. Sediment budget for a small catchment in mountainous terrain. Z. Geomorph. Suppl. 29:191-206.

Dietrich, W. E., T. Dunne, N. Humphrey, and L. M. Reid. 1982. Construction of sediment budgets for drainage basins. In F. J. Swanson, R. J. Janda, T. Dunne, and D. N. Swanston (eds.) Sediment budgets and routing in forested drainage basins, p. 5-23. USDA For. Serv. Gen. Tech. Rep. PNW-141. Pac. Northwest For. and Range Exp. Stn., Portland, Oregon.

Dietrich, W. E., and J. D. Smith. 1984. Bedload transport in a river meander. Water Resour. Res. 20:1355-1380.

Dolloff, C. A. 1983. The relationships of wood debris to juvenile salmonid production and microhabitat selection in small southeast Alaska streams. Ph.D. thesis, Montana State University, Bozeman.100 p.

Dunne, T., and L. B. Leopold. 1978. Water in environmental planning. W. H. Freeman, San Francisco. 818 p.

Edmundson, E., F. E. Everest, and D. W. Chapman. 1968. Permanence of station in juvenile chinook salmon and steelhead trout. J. Fish. Res. Board Can. 25(7):1453-1464.

Everest, F. H., and D. W. Chapman. 1972. Habitat selection and spatial interaction by juvenile chinook salmon and steelhead trout in two Idaho streams. J. Fish. Res. Board Can. 29(1):91-100.

Fausch, K. D. 1984. Profitable stream positions for salmonids: Relating specific growth rate to net energy gain. Can. J. Zool. 62:441-451.

Florsheim, J. L. 1985. Fluvial requirements for gravel bar formation in northwestern California. M.S. thesis, Humboldt State University, Arcata, California.

Galay, V. J., E. K. Yaremko, and M. E. Qauzi. In press. Riverbed scour and riprap stone protection. In C. R. Thorne, J. C. Bathurst, and R. D. Hey (eds.) Problems of sediment transport in gravel-bed rivers. John Wiley and Sons, New York.

Gorman, O. T., and J. R. Karr. 1978. Habitat structure and stream fish communities. Ecology 59(3):507-515.

Graf, W. H. 1971. Hydraulics of sediment transport. McGraw-Hill, New York. 513 p.

Grant, G. E. 1986. Downstream effects of timber harvest activity on the channel and valley floor morphology of western Cascade streams. Ph.D. thesis, John Hopkins University, Baltimore. 363 p.

Grant, G. E., M. J. Crozier, and F. J. Swanson. 1984. An approach to evaluating off-site effects of timber harvest activities on channel morphology. In Proceedings, Symposium on the Effects of Forest and Land Use on Erosion and Slope Stability, p. 177-186. Environment and Policy Institute, East-West Center, University of Hawaii, Honolulu.

Grette, G. B. 1985. The role of large organic debris in juvenile salmonid rearing habitat in small streams. M.S. thesis, University of Washington, Seattle. 105 p.

Harden, D. R., R. J. Janda, and K. M. Nolan. 1978. Mass movement and storms in the drainage basin of Redwood Creek, Humboldt County, California: A progress report. U.S. Geological Survey Open File Rep. 78-486. 161 p.

Harmon, M. E., J. F. Franklin, F. J. Swanson, P. Sollins, S. V. Gregory, J. D. Lattin, N. H. Anderson, S. P. Cline, N. G. Aumen, J. R. Sedell, G. W. Lienkaemper, K. Cromack, Jr., and K. W. Cummins. 1986. Ecology of coarse woody debris in temperate ecosystems. Adv. Ecol. Res. 15:133-302.

Harr, R. D. 1981. Some characteristics and consequences of snowmelt during rainfall in western Oregon. J. Hydrol. 53:277-304.

__________. 1986. Effects of clearcutting on rain-on-snow runoff in western Oregon: A new look at old studies. Wat. Resour. Res. 22(7):1095-1100.

Harr, R. D., W. C. Harper, J. T. Krygier, and F. S. Hsieh. 1975. Changes in storm hydrographs after roadbuilding and clearcutting in the Oregon Coast Range. Water Resour. Res. 11(3):436-444.

Hartman, G. F. 1965. The role of behavior in the ecology and interaction of underyearling coho salmon (Oncorhynchus kisutch) and steelhead trout (Salmo gairdneri). J. Fish. Res. Board Can. 22(4):1035-1081.

Hazzard, A. S. 1932. Some phases of the life history of the eastern brook trout (Salvelinus fontinalis). Trans. Am. Fish. Soc. 62:344-350.

Heede, B. H. 1972. Influences of a forest on the hydraulic geometry of two mountain streams. Water Resour. Bull. 8(3):523-530.

Hickey, J. J. 1969. Variations in low-water streambed elevations at selected stream-gaging stations in northwestern California. U.S. Geological Survey Water Supply Pap. 1879-E. 33 p.

House, R. A., and P. L. Boehne. 1985. Evaluation of instream enhancement structures for salmonid spawning and rearing in a coastal Oregon stream. North Am. J. Fish. Manage. 5:283-295.

_________. 1986. The effects of instream structures on salmonid habitat and populations in Tobe Creek, Oregon. North Am. J. Fish. Manage. 6:38-46.

Ikeda, J. 1975. On the bed configuration in alluvial channels: Their types and condition of formation with reference to bars. Geographical Review of Japan 48(10):712-730 (in Japanese).

_________. 1985. Flume experiments on mobility of sediment mixtures. In T. Spenser (ed.) International geomorphology: Abstracts of papers for the First International Conference on Geomorphology, p. 289. British Geomorphological Research Group, Manchester.

Jackson, W. L., and R. L. Beschta. 1982. A model of two-phase bedload transport in an Oregon Coast Range stream. Earth Surface Processes and Landforms 7:517-527.

_________. 1984. Influence of increased sand delivery on the morphology of sand and gravel channels. Water Resour. Bull. 20(4):527-533.

Jaeggi, M. N. R. 1984. Formation and effects of alternate bars. J. Hyd. Engr. 110(2):142-156.

Janda, R. J. 1978. Summary of watershed conditions in the vicinity of Redwood National Park, California. U.S. Geological Survey Open File Rep. 78-25. 82 p.

Jones, R. P., and E. O. Salo. 1986. The status of anadromous fish habitat in the North and South Fork Toutle River watersheds, Mount St. Helens, Washington. FRI-UW-8601. Fisheries Research Institute, University of Washington, Seattle. 53 p.

Jones, W. E. 1980. Summer steelhead (Salmo gairdneri) in the Middle Fork Eel river and their relationship to environmental changes, 1966 through 1978. California Department of Fish and Game, Administrative Rep. 80-2.

Judson, S., and D. F. Ritter. 1964. Rates of regional denudation in the United States. J. of Geophys. Res. 69:3395-3401.

Kalleberg, H. 1958. Observations in a stream tank of territoriality and competition in juvenile salmon and trout (Salmo salar L. and S. trutta L.). Rep. Inst. Freshw. Res. Drottningholm 9:55-98.

Karlin, R. 1980. Sediment sources and clay mineral distributions off the Oregon Coast. J. Sed. Petrol. 50(2):543-560.

Keenleyside, M. H. A., and F. T. Yamamoto. 1962. Territorial behavior of juvenile

Atlantic salmon (Salmo salar L.). Behavior 19:139-169.

Keller, E. A., and F. J. Swanson. 1979. Effects of large organic material on channel form and fluvial processes. Earth Surface Processes 4:361-380.

Keller, E. A., and T. Tally. 1979. Effects of large organic debris on channel form and fluvial processes in the coastal redwood environment. In D. D. Rhodes and G. P. Williams (eds.) Adjustments of the fluvial system, p. 169-197. Proceedings, Tenth Annual Geomorphology Symposium. State University of New York, Binghamton. Kendall/Hunt Publishing Company, Dubuque, Iowa.

Kelsey, H. M. 1980. A sediment budget and an analysis of geomorphic process in the Van Duzen River basin, north coastal California, 1941-1975. Geol. Soc. Am. Bull. 91(4):1119-1216.

King, J. G., and L. C. Tennyson. 1984. Alteration of streamflow characteristics following road construction in north central Idaho. Water Resour. Res. 20(8):1159-1163.

Larson, K. R., and R. C. Sidle. 1980. Erosion and sedimentation data catalog of the Pacific Northwest. USDA For. Serv. R6-WM-050-1981. Pacific Northwest Region, Portland, Oregon. 64 p.

Lehre, A. K., B. D. Collins, and T. Dunne, 1983. Post-eruption sediment budget for the North Toutle River drainage, June 1980-June 1981. Z. Geomorph. Suppl. 46, p. 143-163. Berlin/Stuttgart, Germany.

Leopold, L. B., and W. B. Bull. 1979. Base level, aggradation and grade. Proc. Am. Philosoph. Soc. 123(3):168-202.

Leopold, L. B., and T. Maddock, Jr. 1953. The hydraulic geometry of stream channels and some physiographic implications. U.S. Geological Survey Prof. Pap. 252. 57 p.

Leopold, L. B., and M. G. Wolman. 1960. River meanders. Geol. Soc. Am. Bull. 71:769-794.

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

Lewis, S. L. 1969. Physical factors influencing fish populations in pools of a trout stream. Trans. Am. Fish. Soc. 98:14-19.

Lipman, P. W., and D. R. Mullineaux (eds.) 1981. The 1980 eruptions of Mount St. Helens, Washington. U.S. Geological Survey Prof. Pap. 1250. 844 p.

Lisle, T. E. 1981a. The recovery of aggraded stream channels at gauging stations in northern California and southern Oregon. In Erosion and sediment transport in Pacific Rim steeplands, p. 188-211. IAHS Publ. 132. Christchurch, New Zealand.

_________. 1981b. Channel recovery from recent large floods in north coastal California: Rates and processes. In R. N. Coats (ed.) Proceedings of a Symposium on Watershed Rehabilitation in Redwood National Park and Other Pacific Coastal Areas, p. 153-160. Center for Natural Resource Studies, John Muir Institute, Inc.

_________. 1982. Effects of aggradation and degradation on riffle-pool morphology in natural gravel channels, northwestern California. Water Resour. Res. 18(6):1643-1651.

_________. 1986. Stabilization of a gravel channel by large streamside obstructions and bedrock bends, Jacoby Creek, northwestern California. Geol. Soc. Am. Bull. 97:999-1011.

Lisle, T. E., A. K. Lehre, H. A. Martinson, D. K. Meyer, K. M. Nolan, and R. D. Smith. 1983. Stream channel adjustments after the 1980 Mount St. Helens eruptions. In D. R. Harden, D. E.

Marron, and A. MacDonald (eds.) Friends of the Pleistocene 1982 Pacific Cell Field Trip: Late Cenozoic History and Forest Geomorphology of Humboldt County, California, p. 226-245.

Lyons, J. K., and R. L. Beschta. 1983. Land use, floods and channel changes: Upper Middle Fork Willamette River, Oregon (1936-1980). Water Resour. Res. 19(2):463-471.

Madej, M. A. 1984. Recent changes in channel-stored sediment. Tech. Rep. 11. Redwood National Park, Arcata, California. 54 p.

Martin, D. J., L. J. Wasserman, R. P. Jones, and E. O. Salo. 1984. Effects of the Mount St. Helens eruption on salmon populations and habitat in the Toutle River. FRI-UW-8412. Fisheries Research Institute, University of Washington, Seattle. 130 p.

Mason, J. C., and D. W. Chapman. 1965. Significance of early emergence, environmental rearing capacity, and behavioral ecology of juvenile coho salmon in stream channels. J. Fish. Res. Board Can. 22(1):173-190.

McNeil, W. J. 1966. Effect of the spawning bed environment on reproduction of pink and chum salmon. U.S. Fish and Wildlife Service Fish. Bull. 65(2):495-523.

Megahan, W. F. 1972. Subsurface flow interception by a logging road in mountains of central Idaho. In National Symposium on Watersheds in Transition, p. 350-356. Colorado State University, Fort Collins.

Megahan, W. F., and W. J. Kidd. 1972. Effects of logging and logging roads on erosion and sediment deposition from steep terrain. J. For. 70(3):136-141.

Megahan, W. F., and R. A. Nowlin. 1976. Sediment storage in channels draining small forested watersheds. In Proceedings, Third Federal Interagency Sedimentation Conference, p. 4.115-4.126. Water Resources Council, Washington, D.C.

Megahan, W., W. S. Platts, and B. Kulesza. 1980. Riverbed improves over time: South Fork Salmon. Symposium on Watershed Management, 1:380-395. American Society of Civil Engineers, New York.

Michelson, M., N. Kulesza, C. Stephenson, and W. S. Platts. 1973. Review and analysis of the South Fork of the Salmon rehabilitation program. Unpublished report. USDA For. Serv. Intermountain Region, Boise National Forest, Boise, Idaho.

Mosley, M. P. 1981. The influence of organic debris on channel morphology and bedload transport in a New Zealand forest stream. Earth Surface Processes 6:883-890.

Moyle, P. B., and D. M. Baltz. 1985. Microhabitat use by an assemblage of California stream fishes: Developing criteria for instream flow determinations. Trans. Am. Fish. Soc. 114:695-704.

Mundie, J. H. 1969. Ecological implications of the diet of juvenile coho in streams. In T. G. Northcote (ed.) Symposium on Salmon and Trout in Streams, p. 135-152. H. R. MacMillan Lectures on Fisheries. University of British Columbia, Vancouver.

__________. 1974. Optimization of the salmonid nursery stream. J. Fish. Res. Board Can. 31:1827-1837.

Nolan, K. M., and D. C. Marron. 1985. Contrast in stream-channel response to major storms in two mountainous areas of California. Geology 13:135-138.

Orsborn, J. F., and J. W. Anderson. 1986. Stream improvements and fish response: A bioengineering assessment. Water Resour. Bull. 22(3):381-388.

Parker, G. 1978. Self-formed straight

rivers with equilibrium banks and mobile bed. Part 2: The gravel river. J. Fluid Mech. 89(1):127-146.

Parker, G., and A. W. Peterson. 1980. Bar resistance of gravel-bed streams. J. Hydraul. Div., ASCE 106(HY10):1559-1575.

Pearce, A. J., and A. Watson. 1983. Medium-term effects of two landsliding episodes on channel storage of sediment. Earth Surface Processes and Landforms 8:29-39.

Peterson, N. P. 1982. Immigration of juvenile coho salmon (Oncorhynchus kisutch) into riverine ponds. Can. J. Fish. Aquat. Sci. 39:1308-1310.

Peterson, N. P., and L. M. Reid. 1984. Coho riverine habitat: Its evolution, distribution, and use. In Proceedings of the Olympic Wild Fish Conference, p. 215-225. Fisheries Technology Program, Peninsula College, Port Angeles, Washington.

Pitlick, J. 1981. Organic debris in tributary stream channels of the Redwood Creek basin. In R. N. Coats (ed.) Proceedings of a Symposium on Rehabilitation in Redwood National Park and Other Pacific Coastal Areas, p. 177-190. Center for Natural Resource Studies, John Muir Institute, Inc.

Platts, W. S. 1974. Geomorphic and aquatic conditions influencing salmonids and stream classification--with application to ecosystem management. SEAM Program, USDA, Billings, Montana. 199 p.

__________. 1975. Relationships among stream order, fish populations, and aquatic geomorphology in an Idaho river drainage. Fisheries 4:5-9.

__________. 1979. Relationships among stream order, fish populations, and aquatic geomorphology in an Idaho river drainage. Fisheries 4:5-9.

__________. 1981. Effects of livestock grazing. In W. R. Meehan (ed.) Influence of forest and rangeland management on anadromous fish habitat in western North America. USDA For. Serv. Gen. Tech. Rep. PNW-124. Pac. Northwest For. and Range Exp. Stn., Portland, Oregon.

Platts, W. S., and W. Megahan. 1975. Time trends in channel sediment size composition in salmon and steelhead spawning areas: South Fork Salmon River, Idaho. USDA For. Serv. Gen. Rep. Intermountain For. and Range Exp. Stn., Ogden, Utah. 21 p.

Platts, W. S., W. F. Megahan, and G. W. Minshall. 1983. Methods for evaluating stream, riparian, and biotic conditions. USDA For. Serv. Gen. Tech. Rep. INT-138. Intermountain For. and Range Exp. Stn., Ogden, Utah. 70 p.

Rankel, G. L. 1979. Inventory of reservation waters, fish rearing feasibility study, and a review of the history and status of anadromous fishery resources of the Klamath River. Final Report to the Hoopa Valley Indian Reservation, Arcata, California. Arcata Field Station, U.S. Fish and Wildlife Service.

Reeves, G. H., and T. D. Roelofs. 1982. Rehabilitating and enhancing stream habitat. Part 2: Field applications. In W. R. Meehan (ed.) Influence of forest and range management on anadromous fish habitat in western North America. USDA For. Serv. Gen. Tech. Rep. PNW-124. Pac. Northwest For. and Range Exp. Stn., Portland, Oregon.

Reid, L. M. 1981. Sediment production from gravel-surfaced forest roads, Clearwater basin, Washington. FRI-UW-8108. Fisheries Research Institute, University of Washington, Seattle. 247 p.

Reid, L. M., and T. Dunne. 1984. Sediment production from forest road surfaces. Water Resour. Res. 20(11):1753-1761.

Reid, L.M., T. Dunne, and C. J. Cederholm. 1981. Application of sediment budget studies to the evaluation of logging road impact. N.Z. J. Hydrol. 20:49-62.

Reiser, D. W., and T. C. Bjornn. 1979. Influence of forest and rangeland management on anadromous fish habitat in the western United States and Canada. Part 1: Habitat requirements of anadromous salmonids. USDA For. Serv. Gen. Tech. Rep. PNW-96. Pac. Northwest For. and Range Exp. Stn., Portland, Oregon. 54 p.

Ruggles, C. P. 1966. Depth and velocity as a factor in stream rearing and production of juvenile coho salmon. Can. Fish. Culture. 38:37-53.

Schumm, S. A. 1977. The fluvial system. Wiley-Interscience, New York. 338 p.

Scrivener, J. C., and B. C. Andersen. 1984. Logging impacts and some mechanisms that determine the size of spring and summer populations of coho salmon fry (Oncorhynchus kitsutch) in Carnation Creek, British Columbia. Can. J. Fish. Aquat. Sci. 41:1097-1105.

Sedell, J. R., and K. J. Luchessa. 1982. Using the historical record as an aid to salmonid habitat enhancement. In N. B. Armantrout (ed.) Acquisition and utilization of aquatic habitat inventory information, p. 210-223. Western Division, American Fisheries Society, Portland, Oregon.

Sheldon, A. L. 1968. Species diversity and longitudinal succession in stream fishes. Ecology 49(2):193-198.

Sheppard, J. D., and J. H. Johnson. 1985. Probability-in-use for depth, velocity, and substrate of subyearling coho salmon and steelhead trout in Lake Ontario tributary streams. North Am. J. Fish. Manage. 5:277-282.

Sullivan, K. 1986. Hydraulics and fish habitat in relation to channel morphology. Ph.D. thesis, Johns Hopkins University, Baltimore. 430 p.

Swanson, F. J., and G. W. Lienkaemper. 1978. Physical consequences of large organic debris in Pacific Northwest streams. USDA For. Serv. Gen. Tech. Rep. PNW-69. Pac. Northwest For. and Range Exp. Stn., Portland, Oregon. 12 p.

Swanson, F. J., B. Collins, T. Dunne, and B. T. Wicherski. 1983. Erosion of hillslopes affected by volcanic eruptions. In Proceedings of the Symposium on Erosion Control in Volcanic Areas, p. 183-222. Tech. Memorandum 1908. Sabo Division Erosion Control Department, Public Works Research Institute, Ministry of Construction, Japan.

Thorne, C. R., and J. Lewin. 1979. Bank processes, bed material movement, and planform development in a meandering river. In D. D. Rhodes and G. P. Williams (eds.) Adjustments of the fluvial system, p. 117-138. Proceedings, Tenth Annual Geomorphology Symposium, Binghamton, New York. Kendall/Hunt Publishing Company, Dubuque, Iowa.

Toews, D. A. A., and M. K. Moore. 1982. The effects of three streamside logging treatments on organic debris and channel morphology in Carnation Creek. In G. F. Hartman (ed.) Proceedings of the Carnation Creek Workshop: A ten-year review, p. 129-153. Pacific Biological Station, Nanaimo, B.C.

Tschaplinski, P. J., and G. F. Hartman. 1983. Winter distribution of juvenile coho salmon (Oncorhynchus kisutch) before and after logging in Carnation Creek, British Columbia, and some implications for overwinter survival. Can. J. Fish. Aquat. Sci. 40:452-461.

Vannote, R. L., G. W. Minshall, K. W. Cummins, J. R. Sedell, and C. E. Cushing. 1980. The river continuum concept. Can. J. Fish. Aquat. Sci. 37:130-137.

Wickham, M. G. 1967. Physical microhabitat of trout. M.S. thesis, Colorado State University, Fort Collins. 42 p.

Wolman, M. G., and R. Gerson. 1978.

Relative scales of time and effective ness of climate in watershed geomorphology. Earth Surface Processes 3:189-208.

Wolman, M. G., and J. P. Miller. 1960. Magnitude and frequency of forces in geomorphic processes. J. Geol. 68:54-74.

Ziemer, R. R. 1981. Storm flow response to road building and partial cutting in small streams of northern California. Water Resour. Res. 17(4):907-917.