CHAPTER FIVE

Large Woody Debris in Forested Streams in the Pacific Northwest: Past, Present, and Future

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ABSTRACT This paper reviews the form, function, and management of woody debris in streams, and reaches three major conclusions: (1) Large woody debris enhances the quality of fish habitat in all sizes of stream. (2) Removal of most trees in the riparian zone during logging, combined with thorough stream cleaning and short-rotation timber harvest, has altered the sources, delivery mechanisms, and redistribution of debris in drainage systems, leading to changes in fish population abundance and species composition. (3) There is an urgent need for controlled field experiments and long-term studies that focus on the protection of existing large woody debris in stream channels and the recruitment of new debris from the surrounding forest.

Woody debris has long been considered a potential source of logjams that could block river navigation, water-based log transport, and the upstream passage of salmon and trout on their way to spawning grounds, but is now understood to play an important role in the creation and maintenance of fish habitat throughout entire rivers. Although wood itself eventually enters the food web of the stream ecosystem as it gradually decays, the major importance of debris lies in its structural characteristics and the way these features influence channel hydraulics. Physical processes associated with debris in streams include the formation of pools and other important rearing areas, control of sediment and organic matter storage, and modification of water quality. Biological properties of debris-created structures can include blockages to fish migration, provision of cover from predators and from high streamflow, and maintenance of organic matter processing sites within the benthic community. The locations and principal roles of woody debris change throughout the river system. In steep headwater streams where logs span the channel, debris creates a stepped longitudinal profile that governs the storage and release of sediment and detritus, a function that facilitates the biological processing of organic inputs from the surrounding forest, When the stream channel becomes too wide for spanning by large logs, debris is deposited along the channel margins, where it often forms the most productive fish habitat in main-stem rivers. In all but the smallest streams there is some degree of clumping, although the size and spacing of debris clumps generally increase in a downstream direction, Debris-related fish habitat can be found anywhere in small forested streams. In large rivers it is primarily

associated with debris accumulations along the margins and secondary channel systems of the floodplain, although it also occurs behind and under very large pieces (intact boles and root wads) along main-stem gravel bars.

Changes in tree species composition, abundance, and input rates to streams resulting from forest management practices have differed according to location in the watershed, and many physical and biological processes have been altered by these changes in the river system's debris load. Several questions have not been fully explored, particularly with regard to the long-term consequences of streamside management for debris recruitment. Yet the majority of studies of streams in second-growth forests have demonstrated that the input of large, potentially stable debris from second-growth stands in which nearly all large merchantable trees had been harvested was significantly reduced relative to debris inputs from old-growth stands. Other studies have shown that loss of large debris has led to a shift in stream habitat composition that favored underyearling steelhead (*Salmo gairdneri*) and cutthroat trout (*S. clarki*) at the expense of the older troutage classes as well as both underyearling and yearling coho salmon (*Oncorhynchus kisutch*). Loss of debris has also reduced overwinter survival of all species. In order to develop procedures that will protect existing instream debris, as well as provide a continued supply of the proper quantity and quality of large woody debris for the future, it will be necessary to test scientifically a variety of management options over a wide range of stream sizes. Many management procedures have been proposed, including techniques for removing slash from stream channels after logging, determining the configuration of buffer strips, selective harvesting within the streamside management zone, and deliberately adding debris to streams for habitat enhancement. Evaluation of these proposals will require a great deal of time and effort, as well as the cooperation of many resource management organizations. However, long-term research is essential in view of the complexity of debris management issues.

A quarter century ago, Chapman (1962) summarized what was known about the effects of logging on fish populations and stream habitat in the Journal of Forestry. This account reflected the concerns of the time and was meant to bring foresters up to date on the important environmental consequences of logging in Pacific Northwest watersheds. The paper dealt mostly with sedimentation and water quality; issues related to the management of woody debris were a minor part of the overall concerns. The last twenty years--especially the last decade--have witnessed a surge of interest in the role and management of debris in streams. Woody debris is now recognized as playing an important role in controlling channel morphology, the storage and routing of sediment and organic matter, and the creation of fish habitat, Pressure to harvest timber in highly productive riparian zones, coupled with increased demands for providing large woody structures for fish habitat as well as wildlife habitat, has created direct competition between fish and wildlife managers and forest managers for this valuable resource, Is it possible to have it both ways: can we realize the commercial worth of the timber in riparian zones and also maintain an adequate source of woody debris for streams? The purpose of this paper is to summarize the various functions of debris and the ways in which riparian areas can be managed for the maintenance of healthy stream ecosystems.

HISTORICAL TRENDS

To appreciate how our attitudes toward debris have changed, we must consider debris management from a historical perspective. Beginning in the latter half of the nineteenth century and extending well into the twentieth, large streams and rivers were used extensively to transport logs from forest to mill. To prevent the logs from accumulating in large logjams, widespread reaches of rivers were cleared for log drives as well as for navigation (Sedell and Luchessa 1982). As logging penetrated upstream in the river basins, channel clearance did also. When the size of the stream became too small to transport large logs effectively, splash dams were built to permit the storage of logs and water until sufficient head was built to sluice logs downstream to a larger river. Splash dams were numerous along coastal watersheds in the Pacific Northwest (Wendler and Deschamps 1955), and the evidence of repeated log drives remains in many coastal and inland waterways (Sedell and Duval 1985). The net effect of channel clearance and splash damming was to remove extensive quantities of woody debris from medium to large size streams--a condition from which many river systems have not recovered (Sedell and Luchessa 1982).

Interest in promoting the migration of anadromous fishes to inaccessible spawning and rearing areas led post-World War II fishery managers to give more attention to debris removal in smaller streams. All along the Pacific coast, logjams were removed with the intention of opening new reaches of stream to anadromous salmonids (Narver 1971, Hall and Baker 1982). Although not now practiced on the same scale as in the 1930s and 1960s, debris removal is still a large part of salmon enhancement programs in several western states, and it is mandated by virtually every forest practices act in the western United States and Canada. The combination of debris removal for fish passage in headwater areas of watersheds, historical splash damming, and removal of snags and logjams from large rivers has led to situations where whole drainage systems no longer possess the debris load present in pristine, undisturbed river basins (Sedell and Swanson 1984). Undisturbed conditions are currently limited, for the most part, to certain high elevation areas of publicly owned commercial forests, the coastal watersheds in parts of British Columbia and Alaska, and national parks and provincial wilderness areas.

With large woody debris generally less abundant now than in the past, timber and fishery resource managers are faced with the problem of determining how much and what kind of debris to include in riparian prescriptions for adequate fish habitat maintenance. The following discussion explores (1) what we do and do not know about the form and function of woody debris in stream channels, (2) how debris can be affected by forest management activities, and (3) some alternative strategies for providing sufficient debris for the future. We hope that this information will be helpful to managers seeking ways to protect both timber and fishery resources.

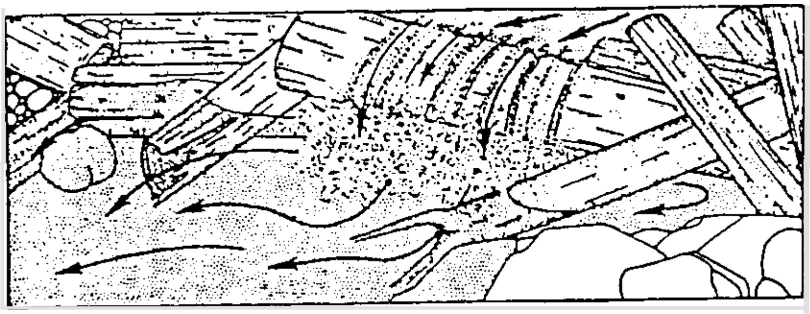
THE ROLE OF WOODY DEBRIS IN STREAMS

Physical Functions and Processes

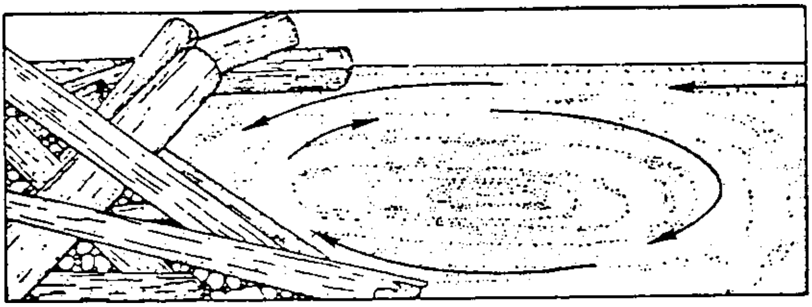
Habitat Formation and Channel Geometry. Geomorphologists speak of woody debris as "large structural roughness elements" or use similar descriptive phrases that refer to the ability of debris to control the flow of water in the stream channel (Lisle 1982). Sullivan et al. (this volume) also deal with the role of debris in shaping channel morphology. Our discussion will examine the role of debris in creating and maintaining habitat for salmonid fishes. Perhaps the single most important function of large woody debris in forming salmonid habitat is the creation of rearing pools (Figure 1). In order to live in running water, free-swimming species such as salmon and trout require feeding locations that provide maximum exposure to drifting food organisms, but call for a minimum expenditure of energy. In other words, salmonids favor rearing sites where food is plentiful and the effort of maintaining a feeding station is low (Dill et al. 1981, Fausch 1984). Riffle habitats tend to have relatively few such sites: the flow is swift enough to transport many food items, but the metabolic cost of swimming against the rapid current often outweighs the benefits of exposure to more food. Some excellent feeding sites do occur in riffles (Bachman 1984), but they are usually small in area, located behind boulders, and provide limited vision of passing food items. Some species, notably coho salmon, avoid riffle habitats almost entirely when competitors are present (Hartman 1965, Bisson et al. 1982, Dolloff 1983) and rely instead on pools with ample cover provided by large woody debris (although exceptions are known: see Stein et al. 1972, Bisson et al. 1985).

It is primarily because pools possess lower current velocities that most stream fishes inhabit them. In addition to the slower movement of water, pools are usually deeper than riffles. The greater depth affords fish a better chance of escaping from terrestrial predators, and also allows coexisting fish species or age classes to "stack"--that is, occur in layers within the water column (Fraser 1969, Allee 1982).

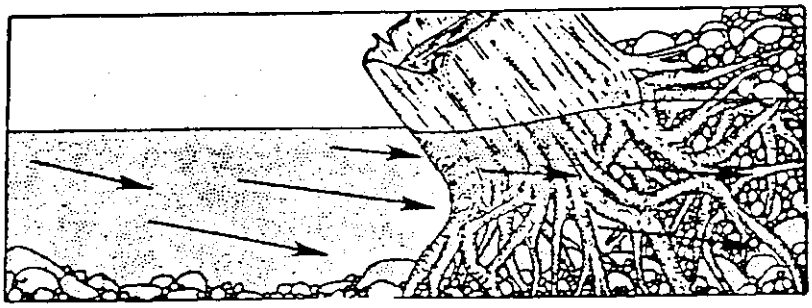
Woody debris is responsible for the location of many of the pools in Pacific Northwest streams (Swanson et al. 1976, Keller and Swanson 1979). In small streams (up to about third-order) single pieces of large debris or accumulations of smaller pieces anchored by a large piece often create a stepped longitudinal profile (Figure 2) consisting of an upstream sediment deposit, the debris structure, and a downstream plunge pool (Heede 1972). Lisle and Kelsey (1982) suggested that numerous debris accumulations can increase pool frequency, and Grette (1985) noted a significant correlation between the number of pools and debris pieces in low gradient western Washington streams. In addition, pool frequency and volume have decreased in stream channels from which slash and naturally occurring debris have been removed following



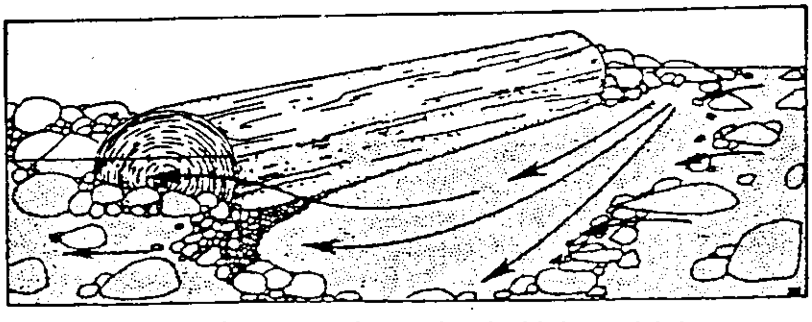
Plunge pool associated with large debris.



Dammed pool associated with large debris.



Lateral scour pool associated with root wad.



Lateral scour pool associated with large debris.

Figure 1. Examples of salmonid rearing pools formed around large woody debris (from Bisson et al. 1982).

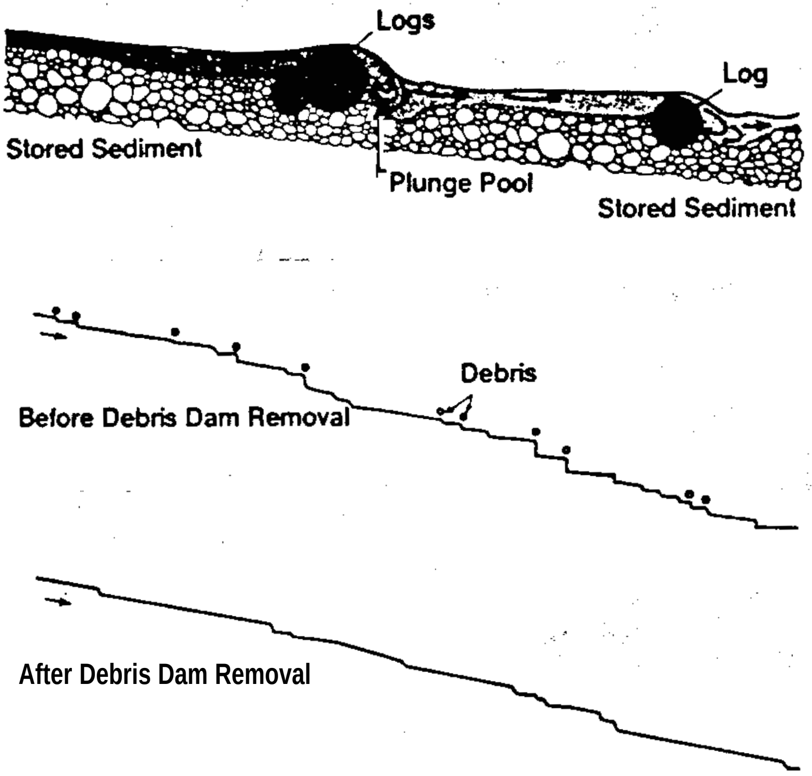


Figure 2. Top: Stepped longitudinal profile consisting of stored sediment, large woody debris, and plunge pool (redrawn from Keller and Swanson 1979). Bottom: Changes in the longitudinal profile of a small stream caused by removal of debris dams (from Bilby 1979).

logging (Toews and Moore 1982, Bilby 1984a, Bisson and Sedell 1984; also see Figure 2).

The size and location of pools are also strongly influenced by debris position. The size of a single log or accumulation of logs spanning the channel can affect the size of the associated pool. In an experimental flume study, Beschta (1983) simulated logs of different diameter and found that larger structures created longer and deeper pools, provided they were suspended above the streambed. Bilby (1985 and unpublished data) showed that pool area was positively correlated with the volume of the debris that anchored the pool, and that the correlation improved with increasing channel width in streams up to approximately 20 m wide (Figure 3). Many pools, however, are not created by scouring action of flow along the channel thalweg, but rather by eddies behind debris and other structures located at the channel margin (Figure 4). These pools, often called backwater or eddy pools, are common features of both small and large streams and are used extensively by salmonids for rearing in spring (Stein et al. 1972), summer (Mundie 1969, Lister and Genoe 1970, Gibson 1981, Bisson et al. 1982, Dolloff 1983, Sedell et al. 1984, Bryant 1985), autumn (Sedell et al. 1982, Murphy et al. 1984), and winter (Bustard and Narver 1975a, 1975b, Tschaplinski and Hartman 1983).

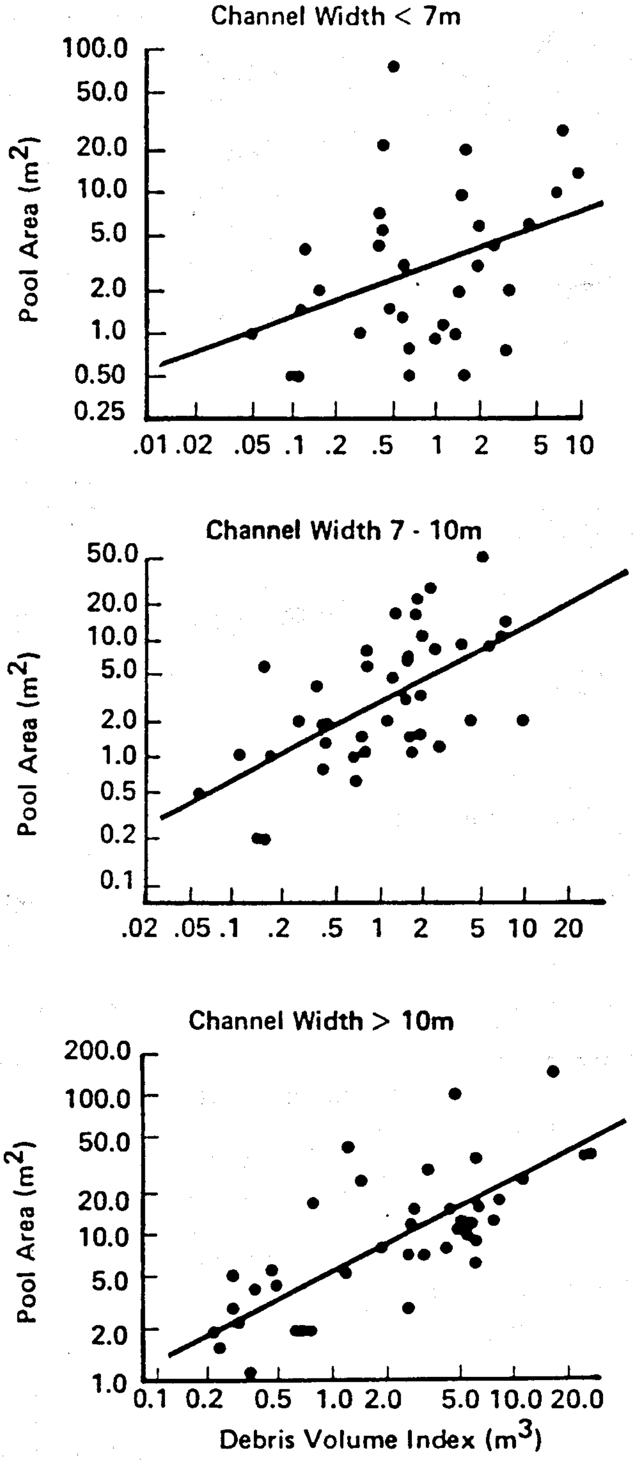
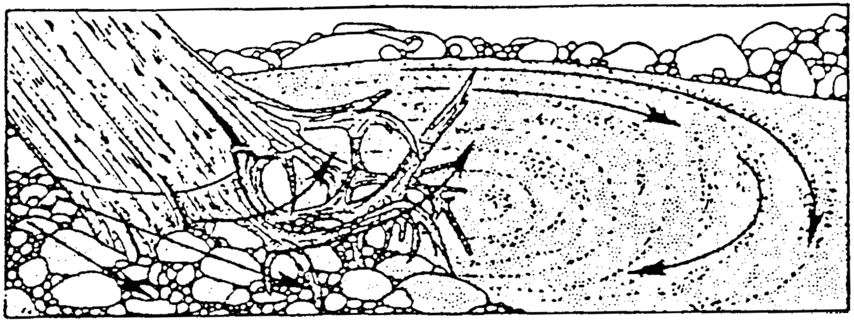
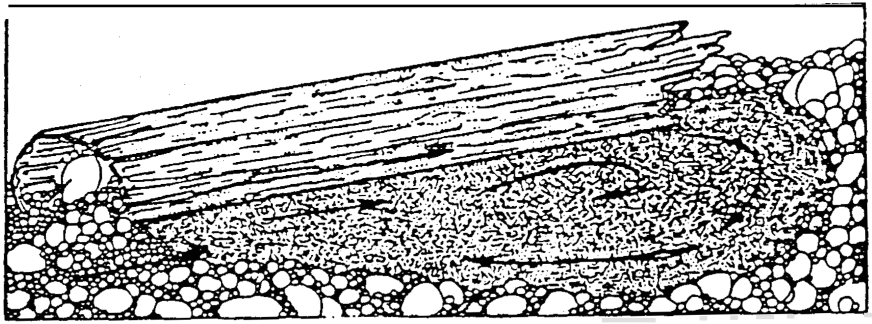


Figure 3. Relationship between pool size and the volume of the stable debris piece associated with the pool, in streams with different channel widths. Each point represents the pool area and estimated volume (debris volume index) of the debris piece anchoring a pool in a number of western Washington streams. The debris volume index was calculated as the volume of a cylinder having as its dimensions the diameter at the midpoint of the log and the total length of the piece (from Bilby 1985 and unpublished data).



Backwater pool associated with root wad.



Backwater pool associated with large debris.

Figure 4. Examples of backwater (eddy) pools associated with large woody debris found along the margins of streams (from Bisson et al. 1982).

By providing a physical obstruction to water flow, woody debris increases the complexity of stream habitats (Figure 5). Logs extending partly across the channel deflect the current laterally, causing it to diverge and widen the streambed (Zimmerman et al. 1967). Sediment stored by debris also contributes to hydraulic complexity, especially in organically rich channels along low gradient alluvial valley floors. These areas are often wide, shallow, and possess a high diversity of riffles and pools (Keller and Swanson 1979, Keller and Tally 1979). Even where the stream becomes too large to permit logs to span the main channel, debris accumulations along the banks cause meander cutoffs and create well-developed secondary channel systems (Keller and Swanson 1979, Swanson and Lienkaemper 1982). In addition to increasing the spatial diversity of stream habitats, debris also influences variation in channel depth by producing scour pools downstream from flow obstructions (Keller and Tally 1979, Hogan 1985). Debris therefore maintains a diversity of physical habitat by (1) anchoring the position of pools along the thalweg, (2) creating backwaters along the stream margin, (3) causing lateral migration of the channel and the formation of secondary channel systems in alluvial valley floors, and (4) increasing depth variability.

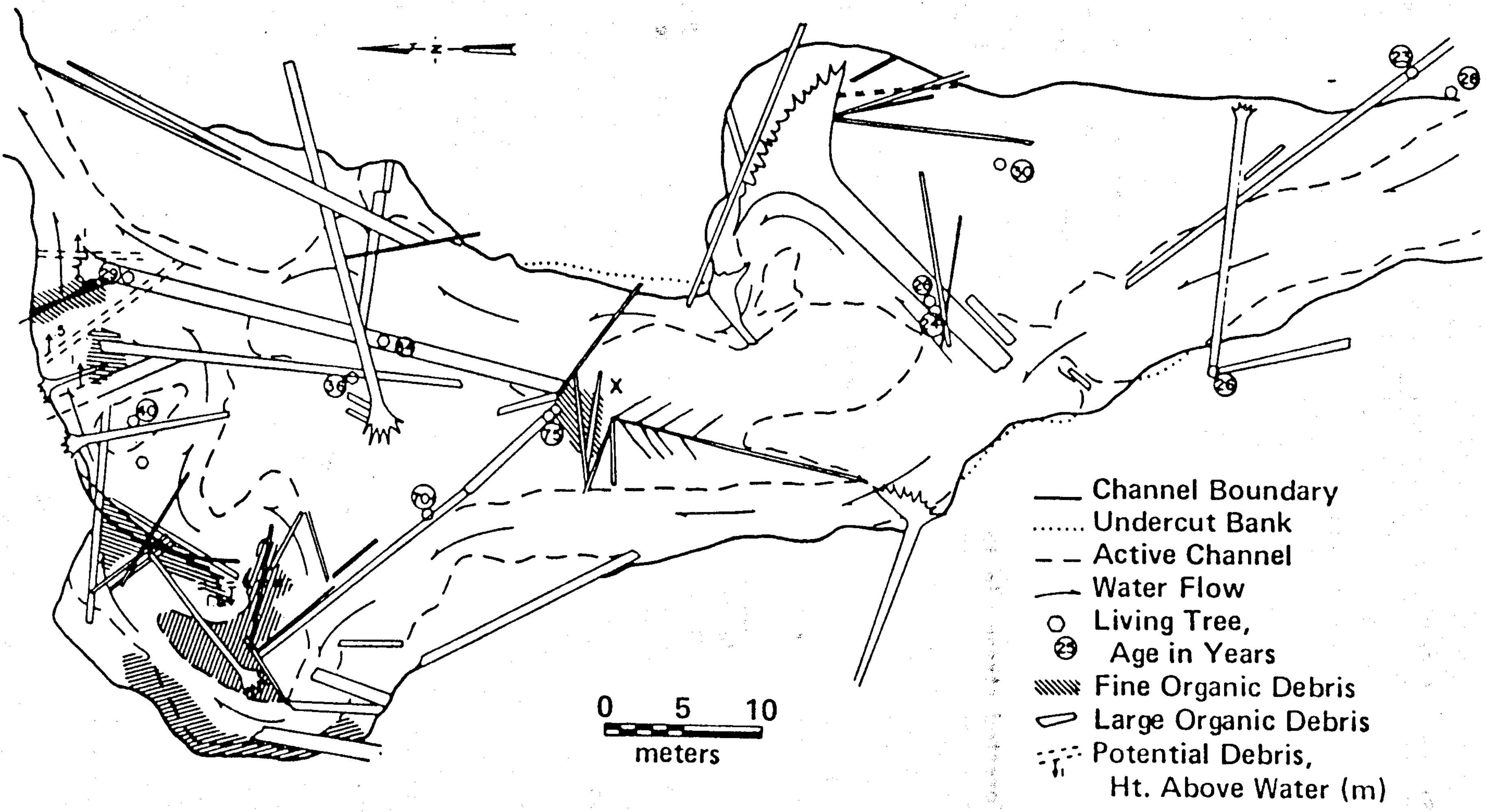


Figure 5. Map of a hydraulically complex stream channel formed around several accumulations of large woody debris: Bonnie Creek, Alaska (from Swanson et al. 1984).

Storage of Sediment and Organic Material. Large woody debris creates important storage areas for inorganic sediment (Megahan and Nowlin 1976, Bilby 1981, Nanson 1981, Marston 1982, Megahan 1982) and organic material (Naiman and Sedell 1979, Bilby and Likens 1980). The stability and storage capacity of debris is enhanced by the presence of branches and roots, which help to anchor the debris and serve as a matrix to trap and consolidate sediment and fine particulate organic matter (Triska and Cromack 1980). Megahan (1982) found that large pieces of debris are able to store higher quantities of sediment in small headwater streams in the Idaho batholith than other kinds of structures, such as boulders or streambank root systems. Short-lived debris dams in small streams can form pools and break up before their impounded storage is filled with sediment (Lisle 1986, in press). In this manner, pool volume is maintained during the transport of sediment and debris downstream,

Forested streams in the Pacific Northwest have high natural volumes of debris compared with other areas of North America (Harmon et al. 1986). Sediment deposits formed upstream from debris accumulations serve several important functions for fish populations. These functions include food production sites (which will be discussed in the section "Biological Functions and Processes"), formation of spawning riffles, and retention of fine sediment. Although the scouring action of water resulting from current deflection can cause gravel instability downstream from a debris accumulation (Helmers 1966, Sheridan 1969), the low gradient sediment deposits upstream from the accumulation can provide suitable spawning substrate. Such deposits are used for spawning in sediment-poor drainages (Everest and Meehan 1981). The scouring of gravels caused by flow obstructions has been suggested to benefit spawning in sediment-rich streams by creating secondary currents that sweep fine sediment away from spawning beds (Sedell and Swanson 1984), and by creating scour pools with tail-outs appropriate for redd construction (Sedell et al. 1982).

Storage of fine sediment and organic matter behind large debris or accumulations of smaller debris significantly delays the transport of this material downstream (Froehlich 1973, Marston 1982). In first- and second-order headwater channels, debris can prevent large quantities of fine sediment from being suddenly deposited on downstream spawning areas (Megahan 1982, Duncan et al. 1984). Wilford (1984.) found that large woody debris on the upper streambank stores considerable amounts of sedimentat the base of unstable hillslopes. Further evidence for the role of debris in sediment storage has come from debris dam removal studies, in which sediment and organic matter transport rates increased severalfold after debris dams were pulled from stream channels (Baker 1979, Beschta 1979, Bilby 1981, MacDonald and Keller 1983, Heede 1985). The chief benefit of the sediment storage capacity of debris to fish habitat therefore appears to be the moderating influence of debris on sediment transport rates, the effect of which is to buffer the channel against rapid changes in sediment loading that could degrade spawning gravels, fill rearing pools, and reduce invertebrate populations.

Modification of Water Quality. Rate of decomposition of woody debris is a function of the surface area of material available for microbial decay, the chemical composition of the wood itself, and the ambient stream temperature (Aumen et al. 1983, Harmon et al. 1986). Large pieces of debris possess a low surface area-to-volume ratio, a high lignin content, and do not exert a rapid oxygen demand on stream water. In contrast, accumulations of fine particulate organic matter possess a very large surface area-to-volume ratio, relatively high nutrient content (when derived from leaves, needles, etc.), and provide ample substrate for microbial decomposition. If the stream gradient is low enough to facilitate a lengthy exposure of water to decomposing debris without reaeration, dissolved oxygen levels may decline between thresholds recommended for fish survival. Such was the case following extensive intrusion of logging slash and fine organic matter into a small stream in the Alsea watershed of Oregon (Hall and Lantz 1969), and may also be true in beaver ponds and other impounded waters where fine organic matter accumulates (Dahm and Sedell 1985). In most rapidly flowing forested streams, however, reaeration is sufficient to maintain the oxygen concentrations of surface water near saturation (Ice 1978). Within the gravel, the slow movement of water coupled with high concentrations of fine organic matter is more likely to lead to anoxic conditions. Low oxygen levels in spawning gravels have been traced to high accumulations of organic fines in Oregon coastal streams (Koski 1966, Hall and Lantz 1969, Ponce 1974, Ringler and Hall 1975).

Leachates from woody debris retard microbial decomposition and consequent oxygen demand but can themselves become toxic to fishes in certain situations, although the amounts of debris required to produce enough toxic extract to cause stress or mortality are unlikely to occur naturally or, apparently, in most logging situations. Only where massive accumulations of fresh debris are subjected to prolonged exposure to water would toxicity be likely to develop. In the headwaters of the Quinault River in western Washington, organic acid leachates from large amounts of western redcedar (*Thuja plicata*) slash have been linked to low stream water pH and depresse fish populations (Allee and Smith 1974). In addition to low pH, foliage terpenes and heartwood tropolones become toxic at high concentrations (Peters et al. 1976). Egg and fry stages appear to be most sensitive to toxic extracts (Servisi et al. 1970, Buchanan et al. 1976). Peters et al. (1976) found that aquatic insects were more tolerant of leachates from western redcedar than coho salmon were. Sitka spruce (*Picea sitchensis*) and western hemlock (*Tsuga heterophylla*) bark extracts are also toxic, but less so than extracts from red cedar (Buchanan et al. 1976). In general, however, toxicity due to leachates from debris is currently not considered a widespread water quality problem in forested streams (Sedell et al. 1985).

How the presence of debris influences runoff patterns or water clarity is poorly understood. Increases in peak storm flows in small watersheds following timber harvest have been observed in several Pacific Northwest streams (Harr et al. 1975, Harr and McCorison 1979, Hetherington 1982), but there is little documentation of the extent to which the travel time of water or the magnitude and timing of stormflow peaks are affected by woody debris in the channel. Heede (1981) demonstrated that debris dams reduced stream velocity and discharge, and Gregory et al, (1985) likewise observed that debris dams significantly delayed the timing of stormflow peaks in an intermediate size watershed (11.4 km^2) in Great Britain. The latter authors, however, noted that the influence of debris dams on water travel time was most marked at low flows and was ameliorated at high flows. The presence of large water impoundments such as beaver ponds would be expected to have a greater buffering effect on the intensity of freshets than typical debris accumulations, but documentation of such an effect is lacking. Similarly, the slowing of water drainage and its corresponding energy loss could facilitate settling of suspended sediment, resulting in improved water clarity, but scientific support for this hypothesis is also scarce.

The presence of large debris can also improve water quantity when water is scarce. In small streams on Prince of Wales Island, Alaska, debris helped to maintain water depth during critical low summer flows. As discharge declined, flow resistance created by spills and eddies around emergent debris and by ponding of water behind debris dams increased, thereby slowing the rate of decrease of depth and preserving habitat at extremely low flows (Lisle 1986, in press).

Debris has been associated with the occurrence of cool water pockets (Keller and Hofstra 1982, Bilby 1984b) that may act as thermal refuges for fishes during periods of high summer temperatures (see Beschta et al., this volume). The association of debris with a cool groundwater seep may retard the mixing of groundwater with the warmer stream water and thus maintain a larger refuge area. Bilby (1984b) found that the temperature differential in cool water pockets in a fourth-order stream in western Washington averaged 5°C.

Biological Functions and Processes

Migration Blockage. The upstream migration of adult fishes returning to spawning streams may be blocked by debris accumulations (Merrell 1951, Holman and Evans 1964), but both the severity of the blockages and the amount of spawning and rearing area forgone as the result of debris jams are less than was previously believed (Sedell and Luchessa 1982). Logjams may appear to be a complete block to migration during summer low flows, but Narver (1971) and Bryant (1983) have noted that debris accumulations are often passable at elevated streamflows. Less well understood is the importance of cover provided by large woody debris to adult fish on spawning migrations. Adult salmon and trout are often seen hiding under debris to escape from predators, and for shading during summer.

Juvenile salmonids may undergo several periods of movement in a river system prior to and including smolting (Northcote 1978). The ability of juvenile salmon and trout to jump overobstacles and swim upstream against swift currents is constrained by their small size. Debris dams could potentially deny or hinder access to rearing tributaries in both summer (Stein et al. 1972) and winter (Skeesick 1970, Cederholm and Scarlett 1982); however, the extent to which debris barriers retard upstream movement of juveniles has not been shown in case studies. It is unlikely that debris accumulations would prevent or delay the downstream passage of juveniles, including smolts, unless streamflow was completely blocked.

Cover Functions: Summer versus Winter. Over the last twenty years numerous investigations have documented the importance of woody debris as cover structures for fish; useful reviews of many of these studies are given by Bryant (1983), Sedell et al. (1985), and Harmon et al. (1986). The following discussion examines the functions of debris in providing summer and winter cover for salmonids.

In addition to creating and maintaining pools, debris provides breaks in the current that serve as foraging sites for fishes feeding on drifting food items, and also forms eddies where food organisms are concentrated. Even the small current breaks behind branches and roots can be utilized by salmonids. Dolloff (1983) has suggested that visual isolation provided by the matrix of a root system reduces the frequency of aggressive encounters in juvenile coho, thus permitting higher population densities in a given stream reach. Provision of foraging sites is important in summer, when most of the annual production takes place (Chapman 1965), but salmonids may actively feed in winter (Maciolek and Needham 1952, Reimers 1957, Chapman 1966, Chapman and Bjornn 1969, Wilzbach 1984), when breaks in the swifter winter flows may become even more essential to the maintenance of a feeding station. Wilzbach (1985) and Wilzbach and Hall (1985) have recently shown that habitat complexity, including the structural complexity created by debris, may cause a reduction of foraging efficiency (the ability to exploit available prey) by obscuring food items from drift-feeding cutthroat trout, These authors contend that the benefits gained from increased cover may be partly or completely offset by reduced food consumption, especially when prey abundance is low (Wilzbach et al. 1986).

The role of woody debris in supplying protection from predators has often been inferred, but has not been quantified in natural streams. Allen (1969) cites a few examples of instances where salmonid populations have been limited by predators, including a study of fish predation on pink and chum salmon fry in a British Columbia stream (Hunter 1959). However, the degree of protection provided by debris against aquatic or terrestrial predators is not known, nor is the relationship between the amount of debris in a stream and survival rate. Variation in predation intensity among seasons is poorly understood, and it is not at present possible to generalize whether summer or winter predation rates are higher. Clearly, the effect of debris on vulnerability to predation is a topic that deserves further research.

Provision of shelter from episodes of high flow during winter is now recognized as a major cover function of woody debris (Figure 6). As stream temperature declines and discharge increases, salmonids have been observed to seek refuge from high current velocity in protected spaces such as gravel interstices (Hartman 1965, Chapman and Bjornn 1969) and in backwaters and undercut banks (Bustard and Narver 1975a, 1975b). Large woody debris is an important source of winter

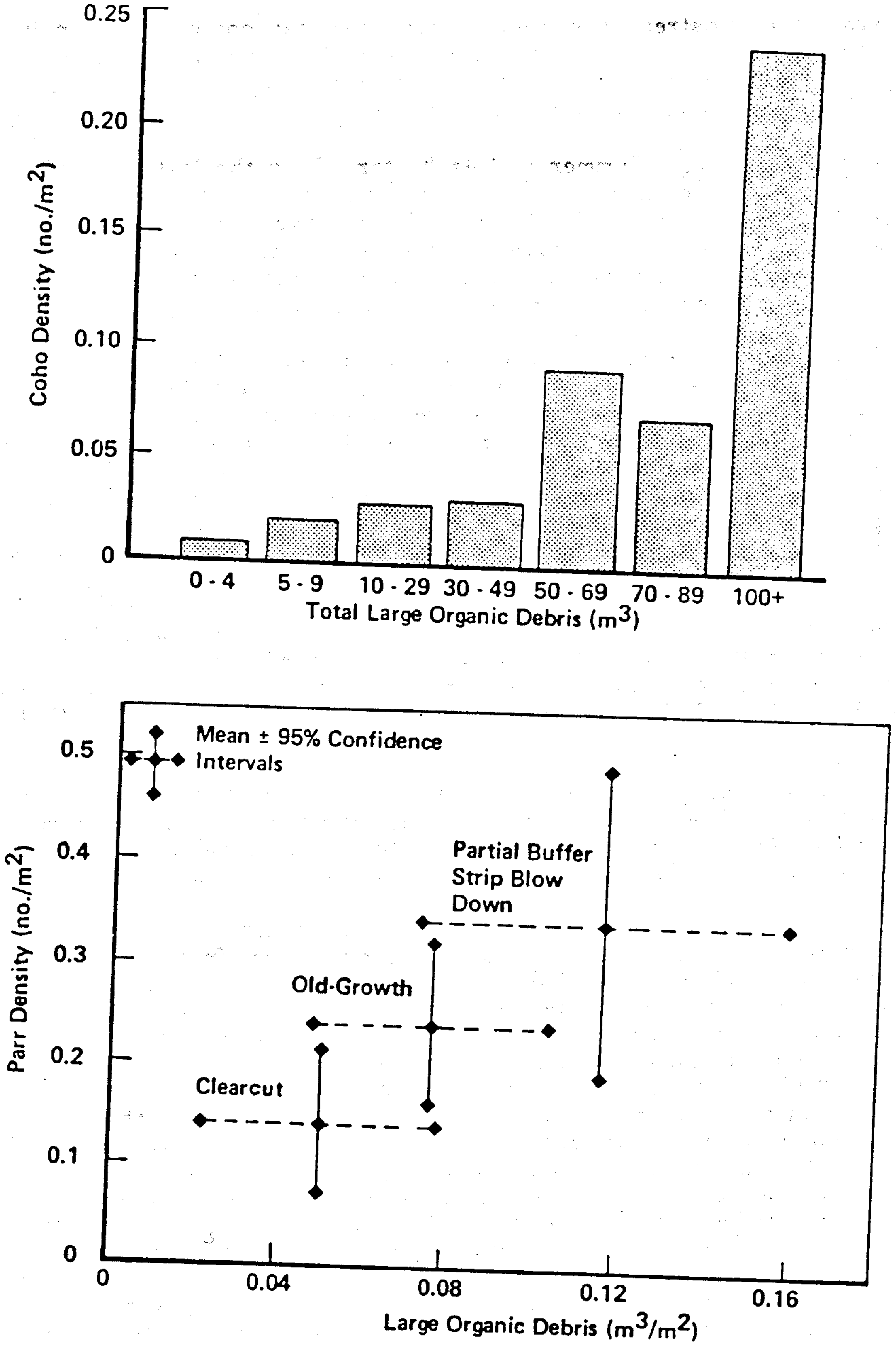


Figure 6. Examples of the relationship between woody debris abundance and juvenile coho salmon populations during winter in southeastern Alaska. In the lower graph the buffer strip sites had experienced partial blow down and actually had more debris than the old-growth sites (from Murphy et al. 1985).

cover in streams in Alaska (Murphy et al. 1985, Heifetz et al. 1986), British Columbia (Bustard and Narver 1975a, 1975b, Pollard 1981, Tschaplinski and Hartman 1983, Brown 1985), Washington (June 1981), and Oregon (Everest et al. 1984).

Debris and Food Availability, Fine organic material stored by woody debris is considered to be a more important energy source for benthic invertebrates in streams than the wood itself, although certain invertebrates are specialized for processing raw wood (Anderson et al. 1978). Most of the stored organic matter is detritus of aquatic and, primarily, terrestrial origin (Anderson and Sedell 1979, Triska and Cromack 1980), but may also include salmonid carcasses on a seasonal basis (Cederholm and Peterson 1985). A rich and diverse biological community has evolved to process this organic matter (Cummins 1974), and a detritus-based invertebrate community is believed to be the principal food resource for juvenile salmonids in most nursery streams (Mundie 1974). Without the extensive storage capacity provided by large debris, much of the organic input Prom terrestrial vegetation in forested watersheds would be rapidly transported downstream without first being reduced to detritus-size particles (Reice 1980, Bilby and Likens 1980, Triska et al. 1982).

Woody debris is largely absent from the thalweg of large rivers, but still plays an important role in the storage and processing of organic material in main river ecosystems (Vannote et al. 1980). In large rivers, the location of debris shifts to the channel margins and floodplain, and it is in these locations that both invertebrate and salmonid densities are greatest (Ward et al. 1982, Sedell et al. 1984). As in steep headwater streams, the storage of detritus by stable debris is the mechanism whereby terrestrial organic material is retained long enough to be processed by invertebrates along river margins and in secondary channels. Invertebrates living directly on the surfaces of large debris pieces probably also contribute directly to the food resources of fish populations, but the importance of the contribution has not been quantified in the Pacific Northwest. In sandy streams in the midwestern and southern United States, debris surfaces provide stable substrates that support a significant portion of the invertebrates eaten by warm-water fishes (Angermeier and Karr 1984, Wallace and Benke 1984, Benke et al. 1985).

Debris as an Enhancement Tool. Many of the early attempts to enhance stream habitat focused on restoring bank stability and preventing erosion. Debris was often considered harmful because bank cutting associated with the flow deflection caused by debris resulted in increased sedimentation rates (White and Brynildson 1967). Only a few early enhancement projects (e.g., Tarzwell 1936, Shetter et al. 1949, Boussu 1954) noted instances where debris additions improved the carrying capacity of streams for salmonids,

As knowledge of the benefits of debris for habitat improvement became more widespread, techniques of adding debris to streams (Figure 7) became more prominent in stream enhancement guidelines (Hunt 1977, Anonymous 1980, Hall and Baker 1982). Debris manipulations improved the rate of survival (Gard 1961, Hunt 1971), growth

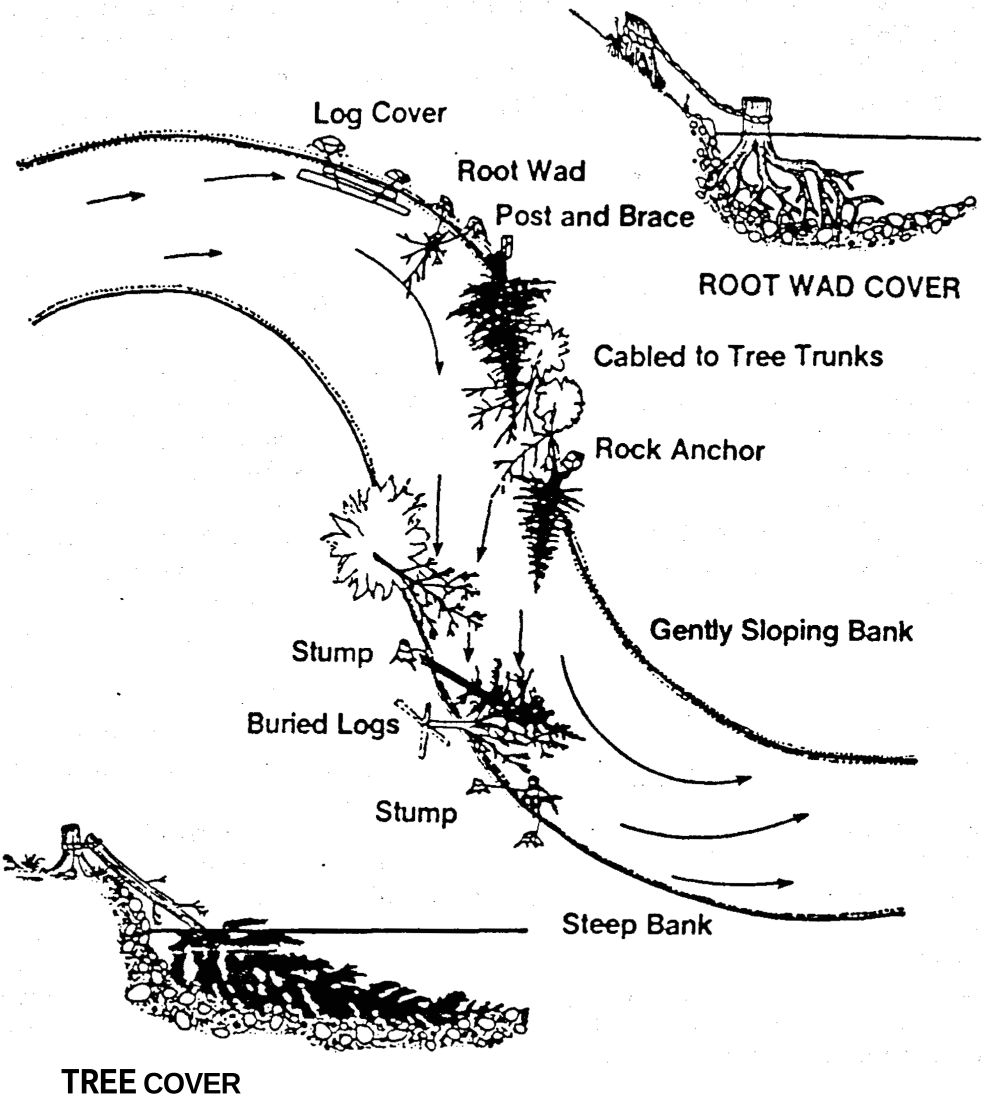


Figure 7. Use of large woody debris for enhancing salmonid habitat in streams (redrawn from Stream Enhancement Guide, Anonymous 1980).

(Tarzwell 1938), and density (Saunders and Smith 1962, Burgess and Bider 1980) of salmonids in other areas of North America, but enhancement research in the Pacific Northwest has been limited mainly to the 1970s and later. Experimental debris additions increased the summer carrying capacity of salmon and trout in streams in Oregon (Anderson 1982, House and Boehne 1985, 1986) and British Columbia (Ward and Slaney 1979). Most techniques have involved introducing stable debris to provide resting areas, overhead cover, and new pools. Deliberately manipulating debris for increased food production has not been attempted.

Because debris enhancement projects in Pacific Northwest streams are relatively recent, evaluations of the success of these projects for improving spawning or rearing habitat are rare and have not had time to report on the long-term effects of the enhancements on stream productivity. Sedell et al. (1985) have predicted that salmonid production can be increased several times by raising the debris load in debris impoverished second-growth forested streams, but this hypothesis awaits field testing, Long-term studies of the success of instream manipulations in achieving habitat improvement are needed to judge the cost effectiveness of these techniques (Hall and Baker 1982, Everest and Talhelm 1982), since it may take several years for fish populations to adjust to new habitat conditions (Hunt 1976). Also needed are clear definitions of the measure(s) of success of enhancement projects. The total density of fishes in a stream may be relatively unchanged after habitat alteration, but species and age class composition may be dramatically different (Bisson and Sedell 1984, House and Boehne 1985). In addition, densities of fish populations during summer low flows, so often used by fisheries biologists as a measure of productivity of a site, may not be good indicators of potential smolt yield after an overwintering period (Mason 1976, Hall and Baker 1982). Although debris manipulations offer excellent potential for habitat enhancement, the relative increase in fish production (as measured by improvement in standing crop or smolt yield) will need to be evaluated over a wide range of stream conditions before the benefits can be predicted.

INPUT, STORAGE, AND ROUTING OF DEBRIS IN STREAM CHANNELS: NATURAL VERSUS MANAGEMENT-RELATED IMPACTS

Input of Large Woody Debris

Input processes vary considerably, depending on riparian tree species composition, soil stability, valley form, climate, lateral channel mobility, and streamside management history. Keller and Swanson (1979) note several mechanisms through which large woody debris is transferred to stream channels, including bank failure, blow down, collapse due to snow or ice loading, snow avalanches, and mass soil movements. The contribution of each of these entry mechanisms differs in relation to channel, slope, and forest stand processes according to watershed geology and stream size. However, some generalizations are possible.

Transfer of large wood from forests to stream channels (Figure 8) can be grouped into mechanisms that involve chronic inputs (frequent and commonly irregular in time and space) and mechanisms that involve episodic inputs (infrequently spaced and often very large). Chronic input processes include natural tree mortality due to disease and insects, combined with wind throw or the gradual undercutting of root systems by the stream. Episodic input processes include very large scale insect or disease epidemics, extensive patches of blow down, debris avalanches, and massive bank erosion during a major flood. Biomasses of large woody debris in old-growth forested streams of different channel size, dominant tree species, and geographical location are given in Table 1.

Chronic inputs of woody debris greater than 50 cm diameter due to tree mortality are more common in maturing and old-growth forests than in young second-growth stands, where most or all of the trees have not attained this size. However, the inputs of smaller debris (but still

Table 1. Biomass of large woody debris in streams flowing through unmanaged old-growth forests along the Pacific Northwest coast. Sample size refers to the number of stream reaches surveyed.

Location and Dominant Riparian Tree Species	Mean Channel Width (m)	Large Woody Debris Biomass (kg/m^2)	
		Mean	Range
Prince of Wales Island, Alaska			
Picea sitchensis			
Tsuga heterophylla			
n = 4	0–5	7	2–9
n = 1	10–15	12	
Coastal British Columbia, Canada			
Picea sitchensis			
Tsuga heterophylla			
n = 1	10–15	18	
n = 3	15–20	22	21–23
West Slope Cascade Mountains, Oregon			
Pseudotsuga menziesii			
n = 19	0–5	25	2–55
n = 5	5–10	26	13–34
n = 1	10–15	23	
n = 2	15–20	10	6–14
n = 2	>20	6	2–9
Northwest Coast, California			
Sequoia sempervirens			
n = 6	0–5	134	10–180
n = 4	5–10	64	18–110
n = 1	10–15	68	
n = 1	15–20	16	
Klamath Mountains, California			
Pseudotsuga menziesii			
n = 8	0–5	15	2–46
n = 2	5–10	25	1–50
n = 1	10-15	1	

Source: Harmon et al. 1986, based on several references.

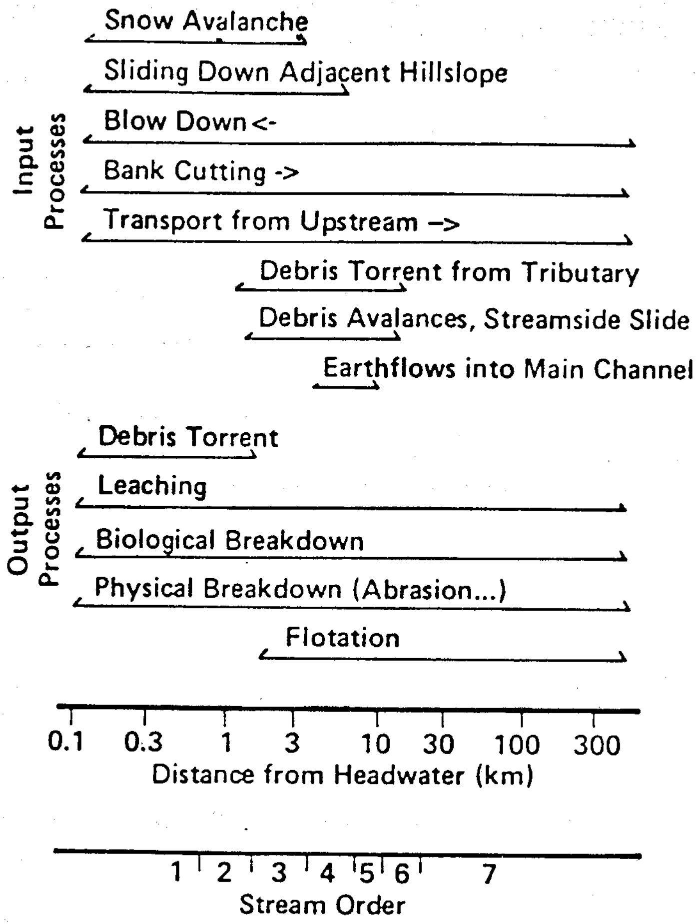


Figure 8. Debris input and transport processes according to stream order in the McKenzie River system of western Oregon. Arrows indicate direction of increasing importance (redrawn from Keller and Swanson 1979).

cm diameter) from young stands can, in some cases, equal or exceed the rate of input of small debris from old-growth forests (H. A. Froehlich, pers. comm.). The mechanisms whereby debris is delivered to the channel are variable, depending on both location and stand age. In an examination of small, low gradient coastal streams in western Washington, Grette (1985) found that the primary entry mechanism of debris in second-growth forests was by bank undercutting of living trees, while in old-growth forested streams of similar size, mortality of senescent trees was believed to be more important. In relatively steep Cascade Mountain streams in western Oregon, Lienkaernper and Swanson (1987, in press) noted that bank undercutting of old-growth Douglas-fir (*Pseudotsuga menziesii*) was infrequent and that wind was the principal agent for debris entry. Inputs of branches and treetops are usually greater in old-growth riparian zones, especially in areas prone to strong winds or heavy snowfall.

Composition of the woody material that enters streams through mortality and bank undercutting has been shown to be altered by forest succession following timber harvest. Low-to mid-elevation riparian

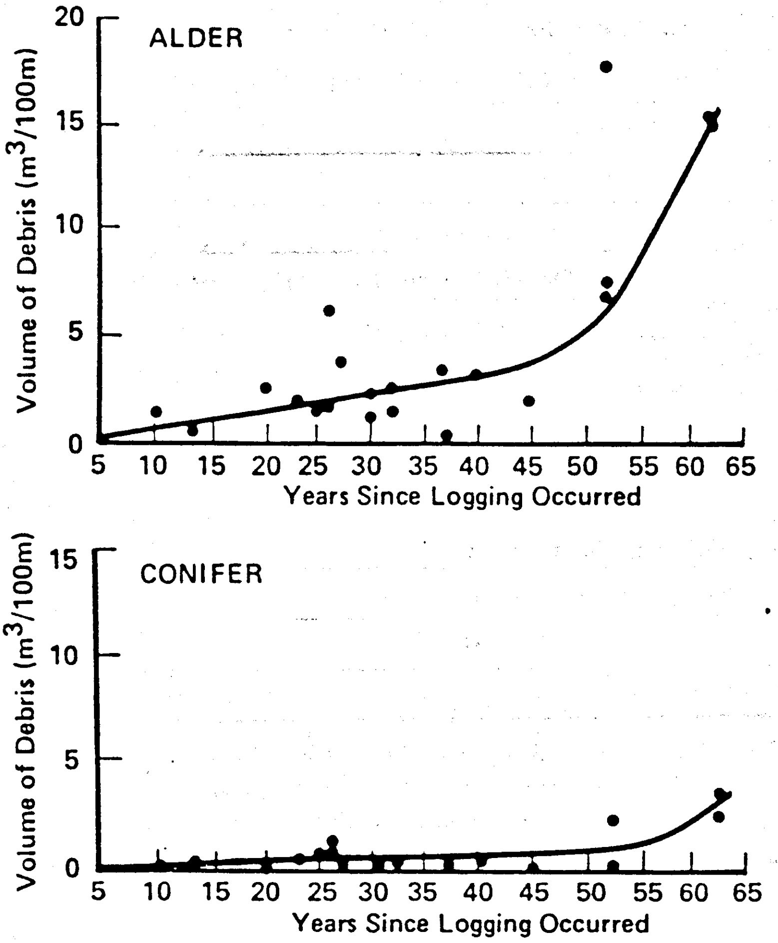


Figure 9. Inputs of red alder and conifer debris to small streams in second-growth forests in western Washington (from Grette 1985).

zones in managed second-growth forests in the Pacific Northwest are dominated by deciduous species such as red alder (*Alnus rubra*) when mature conifers are not left along the stream during logging. Grette (1985) found that the majority of trees that entered the channels of second-growth forested sites were red alder, which possessed shallow root systems and had a low resistance to undercutting. The rate of input of second-growth conifer debris in Grette's study was very slow and did not begin to increase until approximately sixty years after timber harvest (Figure 9).

Episodic inputs of debris can deposit very large quantities of woody material in the channel. Keller and Swanson (1979) note that extensive blow down, as an input process, affects streams of all sizes, although it is probably more important in small to medium size streams than along large rivers where lateral channel shifts become dominant. Inputs related to soil mass movements are confined to upstream areas where steep valley walls abut the channel (Swanson et al., this volume). Blow down generally results in large pieces of debris or often whole trees being available for stream entry--that is, some branches and portions of the root wad tend to remain intact. Debris avalanches, however, can cause considerable fragmentation, breaking trees into smaller pieces (Swanson and Lienkaemper 1978). From a fish habitat standpoint, the benefits of a nearly intact tree in providing increased stability, hydraulic diversity, and cover are generally preferable to those provided by fragments of the stem and limbs.

Large, infrequent floods can entrain debris from the channel bank and floodplain, a process that may result in the addition of far greater amounts of debris to stream channels than normal bank undercutting. In general, capture of dead and down debris, as well as living trees, is a function of the magnitude of the discharge event; the larger the flood, the greater the potential for capturing new material. Entrainment of debris from the vegetated banks and floodplain is an important process along low gradient, alluvial valley floors where channel meandering is strongly impacted by streamflow (Keller and Swanson 1979). Decreased channel stability, induced by addition of small floatable debris pieces or removal of stable pieces, may cause channel meandering and accelerate the capture of new debris from the riparian zone soon after channel disturbance (Bryant 1980, 1985). This process may help to replenish wood exported from the stream reach during the flood itself, but is unlikely to occur where valley form prohibits lateral movement of the channel (e.g., in high gradient, cascade-dominated streams flowing through narrow valleys),

Forest management tends to cause episodic debris inputs associated with harvest cycles and related activities (Swanson and Lienkaemper 1978). Debris inputs during timber harvest may include slash (roots, branches, tops, and other unmerchantable fragments), vegetation incidentally forced into the channel during falling and yarding, and large trees that accidentally slide into the stream from a steep hillside. Actual amounts of woody material that enter the channel during logging vary according to valley form, harvesting and yarding methods, and streamside management requirements (Table 2). Froehlich (1973) reported increases in debris concentrations in small, steep western Oregon streams that ranged from 0 to 400% above background, depending on the method of harvest and the presence of a buffer strip. In some of the same streams, Lammel (1972) found that approximately 10% of the weight of natural debris (i.e., not logging related) was material less than 10 cm diameter, but after harvesting and yarding, small diameter debris became proportionately more abundant from inputs of branches. Similar increases in small debris pieces after logging have been documented in streams in British Columbia (Toews and Moore 1982, Hogan 1986) and Alaska (Meehan et al. 1969, Bryant 1980). Recently, Swanson et al. (1984) found that coarse and fine debris loading averaged three and six times greater, respectively, in southeastern Alaska watersheds logged from six to ten years previously than in streams in unlogged forests (Table 2). Most of these studies were conducted in streams whose watersheds were logged before enactment of rigorous stream cleaning regulations. Additional logging debris can enter streams after channel cleaning when high flows entrain slash left along the streambank after channel cleaning (Lestelle 1978, Osborn 1981, Bilby 1984a). Toews and Moore (1982) found that alders killed by herbicide in the riparian zone and then felled next to Carnation Creek on Vancouver Island were subsequently captured by the stream during high flow. The general pattern of debris input during and soon after

Table 2. Biomass (kg/m^2) of large (>10 cm diameter) and small (<10 cm diameter) woody debris in streams in forested and clearcut watersheds in western Oregon and southeastern Alaska Stream widths ranged from 1 to 8.5 m. Sample size refers to the number of stream reaches surveyed.

Condition of Stand Adjacent to Study Stream	Before Logging		After Logging	
	>10 cm	<10 cm	>10 cm	<10 cm
Western Oregon				
Old-growth forest (n = 10)	39	3		
Clearcut:				
Free-fall (n = 3)	25	3	57	12
Cable-assisted directional fall (n = 4)	50	4	46	12
Free-fall with buffer strip (n = 3)	39	3	36	3
Southeastern Alaska (Prince of Wales Island)				
Old-growth forest (n = 4)	9	1		
Clearcut:				
Free-fall (n = 3)			28	6

Source: Swanson et al. 1984.

logging to the edge of the stream is therefore characterized by a brief but marked increase in the frequency of small debris entering the channel. Whether or not this smaller material remains in the stream will depend on the extent of cleaning, local channel and bank topography, and seasonally influenced streamflow changes.

Storage and Transport of Woody Debris

Location in the Channel. The location, stability, and longevity of debris strongly influence habitat quality in all sizes of fish-bearing streams, although the arrangement of woody debris varies according to stream size and valley morphology (Swanson et al. 1976). Spacing of individual debris pieces or clumps of pieces can be strongly influenced by dominant input processes. When the dominant input is from bank undercutting of living trees or the direct fall of dead trees, debris tends to be spaced at fairly random intervals along very small channels where discharge is insufficient to carry the debris pieces downstream (Figure 10). In most fish-bearing streams, however, there is some degree of clumping, and the magnitude and spacing of debris clumps generally increase in a downstream direction. In intermediate and large size alluvial streams--those greater than about 15 to 20 m wide (usually third- to fifth-order)--woody debris entrained by bank undercutting and direct fall is transported downstream during storms and deposited on obstructions in the channel and on the outside of river bends near

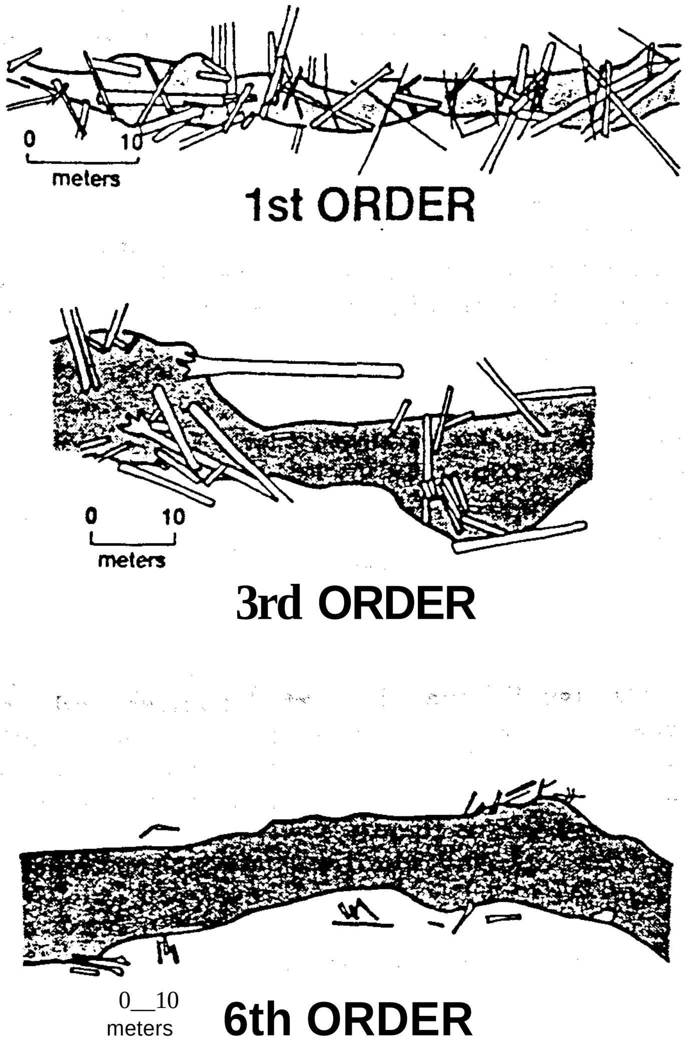


Figure 10. Distribution and abundance of large woody debris in streams of different size: McKenzie River system, Oregon (from Swanson et al. 1982, based on stream maps drawn by G. W. Lienkaemper).

the high water line (Figure 10). Keller and Swanson (1979) have shown that deposited debris may greatly increase channel width, produce midchannel bars, and facilitate the formation of meander cutoffs. Short, braided stream reaches and secondary channel systems thus formed are important rearing sites for salmon and trout in Pacific Northwest rivers (Sedell et al. 1984). Large streams flowing through steep, narrow valley walls (e.g., ravines) often do not possess zones of deposition and are dominated by boulder substrates with little or no large woody debris.

Debris clumps that result from episodic inputs such as debris avalanches, extensive blow down, or entrainment of large amounts of material from the floodplain during a major flood tend to be more widely spaced and the volume of the clumps greater than those observed in streams where these processes are not important. Large logjams are deposited at the terminus of a debris torrent—that is, the slurry of debris, soil, and water that can occur when a landslide enters a steep headwater channel (Swanston and Swanson 1976). Much sediment and debris accumulates at the terminus of a torrent, but the torrent itself scours the channel as it travels downstream, leaving a track that may be nearly devoid of both debris and sediment (Swanson et al. 1976), and that contains very poor fish habitat. In a study of debris-torrented channels in the Queen Charlotte Islands, British Columbia, Hogan (1986) found that debris remaining in torrent tracks usually lay parallel to the direction of flow,as opposed to the more common diagonal orientation found in both unlogged and nontorrented channels. This shift in orientation was found to be responsible for a reduction in channel width and depth variability, fewer cut banks, smaller pool areas, and decreased channel stability, thus leading to a reduction in fish habitat diversity and quality. The debris dam formed by a torrent can be extensive and form a major barrier to fish passage. Such dams are commonly found near tributary junctions where small first- and second-order channels that have undergone a debris torrent empty into larger,' low gradient streams (Swanson et al., this volume).

Debris torrents usually travel short distances and may not impact large rivers unless a headwater channel discharges directly into a main stem, as in many glacial valleys. However, large woody debris can still be clumped along intermediate and large size rivers as a result of infrequent events such as major floods (Swanson and Lienkaemper 1978). Entrainment of floatable debris from the floodplain or through downstream transport from headwater source areas may lead to the formation of massive accumulations of driftwood wherever constructions of the channel or low gradient depositional zones occur. Extensive driftwood dams were prominent features in coastal streams prior to river clearance (Sedell and Luchessa 1982), but are now rare. More common are sporadic large debris accumulations deposited on upper streambanks and floodplain terraces that are inundated only during periods of high discharge. Because they are normally situated above the water line, their use by fishes is limited to high flows. However, the temporary refuge provided by inundated debris accumulations along the upper banks of streams with well-established floodplains may be very important to fish survival when current velocity in the main channel becomes excessive (Tschaplinski and Hartman 1983).

In summary, the location and configuration of debris is strongly influenced by stream size, valley morphology, and dominant input processes. Debris spacing generally proceeds from frequent, randomly placed individual pieces and small debris dams in headwater streams to less frequent but larger accumulations as stream size increases. Episodic inputs of debris tend to widen the gaps between debris accumulations and create larger debris dams when coupled with high flow events. Wood-related fish habitat is abundant in most areas of small headwater channels where stream power is insufficient to transport large pieces downstream, In intermediate to large size streams, the location of wood-related habitat is much more patchy and is often limited to areas along the main channel margin, secondary channels, and floodplain.

Stability. Stability of debris accumulations is usually assumed to be important or maintaining good habitat. If debris is stable (i.e., not prone to frequent movement), its pool anchoring, cover, and substrate storage functions are enhanced. If it is unstable, these functions are diminished (Bryant 1983). Among the foremost factors contributing to debris stability is size (Toews and Moore 1982, Bryant 1983, Bilby 1984a, 1985, Grette 1985). Size includes two components, length and diameter (Figure 11), although other aspects such as the presence of a root wad or branches can also influence where or when a piece of debris will move. Length appears to be most important to debris stability in streams where discharge is sufficient to float large-diameter logs (Swanson et al. 1984, Bilby 1985, Lienkaemper and Swanson 1987, in press). Branches and root wads add to the stability of debris pieces by increasing both the mass and the surface area available for snagging on instream obstructions; whole trees are thus potentially more stable than tree fragments. In small, low gradient streams in southeastern Alaska, Swanson et al. (1984) found that tree fragments whose length ranged to about half bank-full channel width could be floated downstream during typical winter storms, while large intact stems with root wads could remain in place for at least seventy years. Length of piece relative to channel width is therefore critical. Relatively short debris pieces can stabilize in narrow channels (Figure 11), but longer pieces are necessary for stability in wider channels. Swanson et al. (1984) noted that debris pieces whose length exceeded bank-full width may have much of the weight supported by ground outside the channel, and that long pieces are easily lodged against standing trees during high streamflow.

Other aspects of debris that influence stability include orientation, degree of burial, and the percentage of the piece that is in the water. Bryant (1983) suggested that pieces whose angle of orientation relative to the axis of flow is less than 30 degrees have inherently high stability while pieces whose angle of orientation is greater than 60 degrees have an increased probability of movement. Bilby (1984a) found that degree of burial strongly influenced debris movement in a western Washington stream: pieces with both ends anchored to the streambed or bank had a lower probability of moving than pieces with only one end buried or neither end buried. Bilby (1984a) found that the degree of burial influenced potential movement: partial burial was less effective than complete or nearly complete burial in preventing downstream transport during storms. Toews and Moore (1982) also found burial to be an important factor contributing to debris stability in Carnation Creek, as did Crette (1985) in coastal streams in western Washington. Whether or not a piece is buried depends in part on the rate of sediment input to the channel and the longevity of the piece.

Much of the debris entering streams during' timber harvest is relatively small and therefore less stable and more prone to movement than naturally occurring debris (Lammel 1972, Swanson and Lienkaemper 1978, Bryant 1980, Toews and Moore 1982, Grette 1985). New pieces of debris introduced into the channel include branches (Lammel 1972) and finely divided particles such as needles, twigs, and bark fragments (Hall and Lantz 1969). Direct felling of trees into the stream can also break existing debris, causing further instability (Toews and Moore 1982). Removal of all newly added debris after logging, a requirement

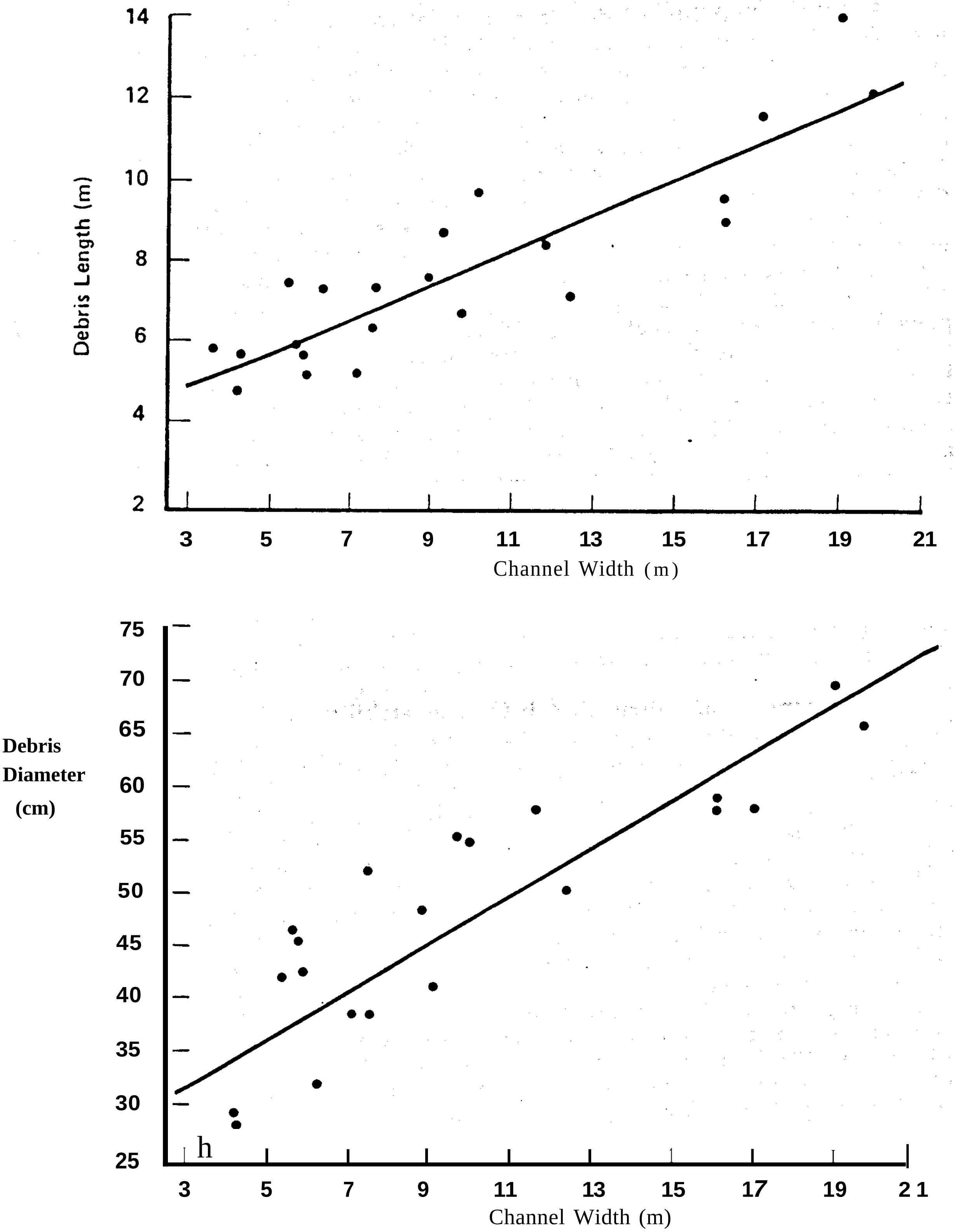


Figure 11. Relationship between the length and diameter of stable debris and channel width, Each point represents the geometric mean length or diameter of logs not held in place by other debris at each of the western Washington study streams (from Bilby 1985 and unpublished data).

of recent forest practices regulations, often involves bucking large debris into smaller pieces that are removed to the high water line. However, debris cleaning usually takes place during low flow periods and some of the material deposited on the upper bank may subsequently be re-entrained at high flows, resulting in an increase in the frequency of shorter, less stable pieces in the channel (Lestelle 1978, Osborn 1981, Bisson and Sedell 1984, Hogan 1985).

Downstream transport of small, unstable debris can lead to accumulations in debris dams that may remain in place for a few years and subsequently wash out. The debris dams themselves may pose temporary fish migration blocks, but of greater long-term consequence for fish populations is the lack of large structure in the channel after debris is transported out of the site. Bryant (1982, 1985) has demonstrated an increase in debris loading immediately following logging in southeastern Alaska streams, followed by a decline in debris abundance as accumulations gradually washed away and were not replaced by new material from the riparian zone. Toews and Moore (1982) reported a similar pattern in Carnation Creek, although for a shorter period. Both studies have observed corresponding reductions in high quality fish habitat as debris was exported from study reaches (Scrivener and Andersen 1984, Bryant 1985).

Longevity. The residence time of woody debris in stream channels is affected not only by transport processes but also by decay rates and resistance to breaking and abrasion. In coniferous forests of the Pacific Northwest, dendrochronologic dating of instream debris has documented pieces that have been in channels for up to 200 years or more (Swanson et al. 1976, Keller and Tally 1979). The decay rate of old-growth conifer debris has been estimated at 1% per year in western Washington streams (Grette 1985), although species differences occur. Anderson et al. (1978) demonstrated that western redcedar was more refractory to decomposition in streams than Douglas-fir or western hemlock, and that all three coniferous species far outlived red alder. Differences in breakdown were due to log diameter, resistance to fragmentation, and chemical constituents in the wood that affected decomposition rates.

Forest management alters the composition of riparian vegetation through the establishment of early successional stages, and debris from second-growth stands has been shown to have shorter residence times in stream channels than debris from preharvest forests. Grette (1985) found that the frequency of red alder debris in second-growth forested streams was approximately twice the frequency of alder in old-growth streams. However, the disappearance of red alder from the second-growth streams after delivery to the channel was believed to be more rapid than the disappearance of coniferous debris (primarily hemlock and spruce), because the alder debris was shorter, smaller diameter, more easily broken, and less well anchored than coniferous debris from the preharvest forest. Although the rate of input of alder debris from second-growth stands exceeded the input rate of coniferous debris (Figure 9), the reduced longevity of alder resulted in streams with less cover and fewer pools than streams in unlogged forests. Grette (1985) observed that loss of cover in second-growth streams had the most significant impact on salmonid populations in winter, when attraction to debris was very strong,

THE CHALLENGE OF DEBRIS MANAGEMENT

Debris Removal

Stream cleaning projects resulting from forest management activities are generally of two types: those intended to remove logging slash immediately following harvesting, and those intended to remove a specific blockage or series of blockages to upstream migrating adults. The former project type is usually conducted by a professional stream cleaning crew using hand operated equipment such as a chain saw winch. The latter project type is usually supervised by a fishery-biologist and sometimes involves elaborate debris removal techniques using heavy equipment and explosives. The nature of the debris removed from the stream channel and the biological impact of a particular removal project varies according to site location; however, case studies during recent years indicate that stream cleaning may have unwanted consequences for habitat quality (Sedell et al. 1985) and that removal techniques should be practiced with caution in order to minimize adverse impacts.

Thorough removal of logging slash on a widespread scale, as required by forestry regulations, has now been practiced for about a decade since the initial rules took effect (Figure 12). Changes in stream habitat and fish populations following stream cleaning have been evaluated in several areas of the Pacific Northwest. In almost every case study, debris removal has led to conditions that have resulted in loss of important habitat features and a decline in fish population abundance (Elliott and Hubartt 1978, Lestelle 1978, Bryant 1980, Osborn 1981, Toews and Moore 1982, Dolloff 1983, Lestelle and Cederholm 1984, House and Boehne 1985). These studies found that removaI of large, stable debris along with smaller pieces of slash caused a loss of channel stability and a corresponding reduction in the quantity and quality of pools and cover. A temporary increase in the abundance of small, easily floated debris has sometimes been observed after stream cleaning (Meehan et al. 1969, Toews and Moore 1982), but such increases have resulted from the entry of new slash from outside the channel, the re-entrainment of debris stacked near the high water line of the streambank during cleaning, or the breakup of wood that was in the stream prior to logging. In most cases, unstable debris was flushed from the cleaned reach within a few years, leaving channels that were lacking in structural complexity. Bisson and Sedell (1984) observed an increase in the proportion of riffles and a reduction in the number of pools in cleaned stream channels in western Washington. The increased frequency of riffles led to a relative increase in the abundance of underyearling steelhead and cutthroat trout, which preferred riffle habitats, but a corresponding reduction in the abundance of coho salmon and older age classes of steelhead and cutthroat, which preferred pools (see Sullivan et al., this volume).

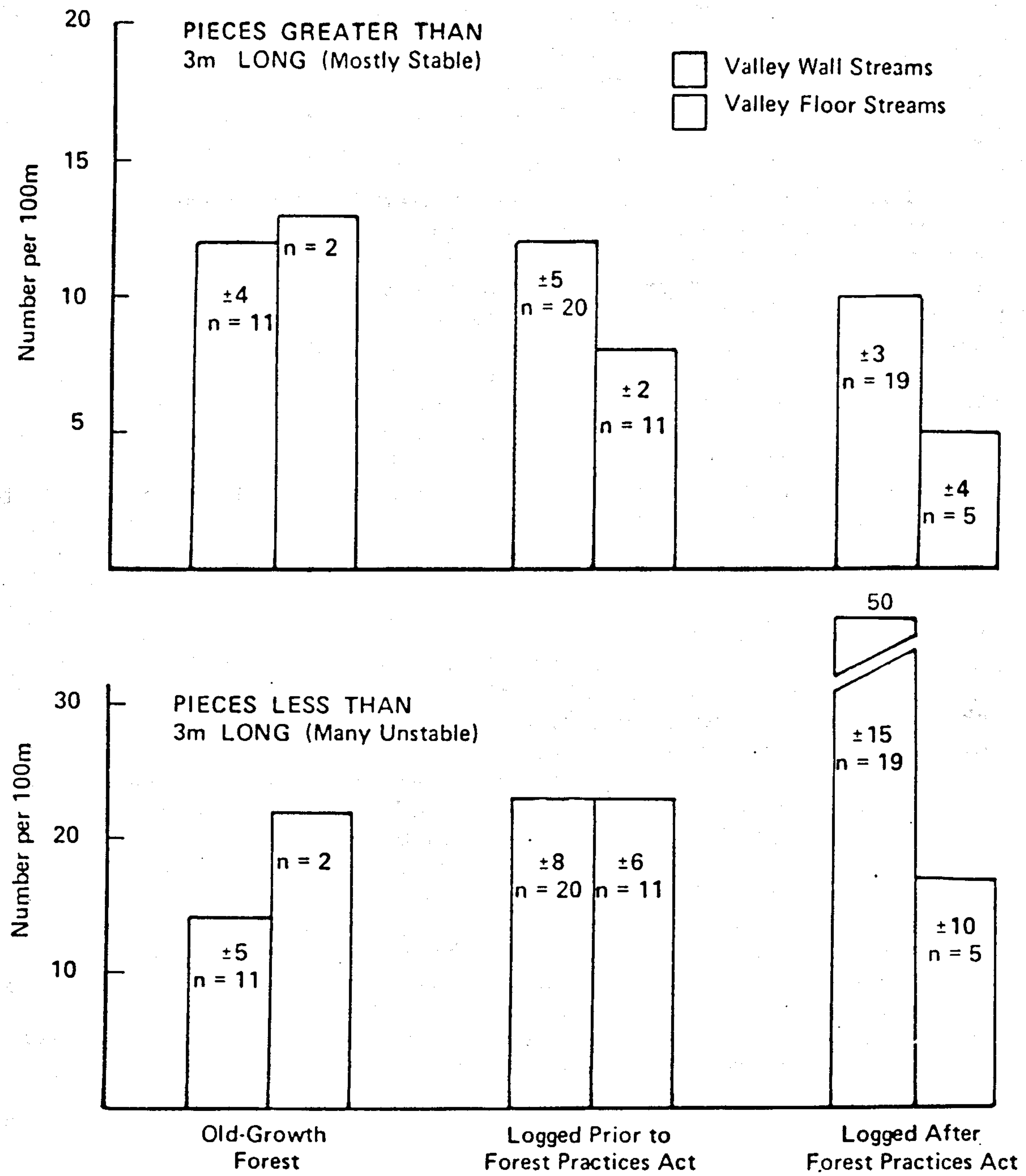


Figure 12. Effects of stream cleaning following implementation of the Washington Forest Practices Act on the relative abundance of stable and unstable debris in steep valley wall streams and low gradient valley floor streams in southwestern Washington (from Bisson and Sedell 1984).

Fewer studies have examined the impact of logjam removal for fish passage. Baker (1979) noted reductions in fish population abundance in the vicinity of logjams immediately after complete debris removal, but was unable to detect significant declines in abundance where part of the jam was allowed to remain. Baker (1979) also observed damage to downstream spawning and rearing areas caused by releases of large quantities of sediment that had been stored upstream from the logjams that were completely removed, causing him to conclude that partial removal was usually preferable to complete removal, in addition to being less expensive.

Loss of productive fish habitat caused by debris removal has led to the formulation of stream cleaning guidelines designed to reduce the adverse effects of logging slash, promote the upstream passage of spawning adults, and protect the habitat of important rearing areas (Toews and Moore 1982, Bryant 1983, Bilby 1984a, Vanderhayden 1984). The guidelines contain minor differences, but all share the goals of (1) conserving existing large, stable debris that was in the channel prior to logging, (2) removing only small, unstable material such as branches and tops that could contribute to the formation of an impassable logjam or potentially threaten life and property downstream, (3) removing slash to a sufficient distance from the channel that it will not likely be re-entrained during subsequent storms, and (4) removing only a portion of logjams in such a way that the chance of complete washout of the jam is kept to a minimum. Because these guidelines are relatively new, their effectiveness has not been fully evaluated over a range of stream sizes and types.

Small, ephemeral headwater streams (first- and second-order channels without fish populations) do not receive the same protection during logging as do larger fish-bearing streams into which they drain. These streams are usually located in steep channels, and they often fill with slash when surrounding timber is felled, bucked, and yarded. The question whether stream cleaning should be carried out in small headwater channels has stimulated considerable debate. Arguments in favor of cleaning include removal of debris that could become part of a debris torrent or contribute to water quality degradation, and removal of debris that could block culverts or otherwise obstruct road drainage and potentially cause a mass slope failure, Arguments in opposition to cleaning include maintaining debris to slow the routing of water and sediment, providing organic matter storage and processing sites that will gradually release detrital food materials to the downstream community, and leaving debris accumulations to trap fine sediment from road surface erosion. No criteria based on protection of downstream fish habitat have yet been proposed for determining where and when debris should be removed from ephemeral headwater streams: development and testing of removal guidelines constitute an important current need. Until such criteria are established, we suggest that a conservative approach to debris removal from headwater channels is warranted, and that woody debris (including some logging slash) be left undisturbed in most areas.

Alternative Riparian Management Procedures

Treatment of riparian zones to ensure protection of existing debris, as well as a continued supply of future debris, has included proposals that range from leaving large buffer strips of unmanaged forest along both sides of the stream to intensive streamside management involving harvest of merchantable trees and subsequent introductions of debris substitutes into the channel. It seems unlikely, given the various factors that influence management decisions, that identical practices will be followed on public and private timberland, on different sizes and types of streams, and in different geographic areas and geomorphic terrains (Brown and Beschta 1985). What, then, are some of the choices in providing for a stream's debris needs, and what do we know about the relative effectiveness of these management alternatives?

Buffer Strips and Streamside Management Zones. The term "buffer strip," as used here, means a strip of vegetation next to the stream where part or all of the trees are left during timber harvest. Although buffer strips are sometimes considered to be unmanaged areas containing mature conifers and other vegetation associated with old-growth forests, most logging regulations permit the selective harvest of some merchantable timber within the "streamside management zone" (SMZ) either during logging of the mature stand or during commercial thinnings. As a result, many buffer strips along Pacific Northwest streams do not possess an abundance of old-growth trees, but are a mixture of a few large conifers, smaller nonmerchantable conifers, deciduous trees, and herbaceous vegetation. Current regulations generally specify a fixed width SMZ, with the width being determined by the particular stream class or type. Stream types are themselves determined by stream size, discharge, navigability, recreational use, and the presence or absence of anadromous fishes.

Are the SMZs that are being left along stream corridors sufficient to provide the quantity and quality of debris necessary to maintain productive fish habitat? In most cases it is difficult to answer this question because the regulations took effect little more than a decade ago, and many studies of debris recruitment were conducted in watersheds that were logged to the edge of the exposed channel before forest practices were standardized. Furthermore, most streams in managed watersheds still contain residual debris from the preharvest stand (Swanson and Lienkaemper 1978, Crette 1985), and the recruitment rate of debris from SMZs left under the new regulations has yet to be determined over a range of stream sizes and buffer strip widths, and within the context of modern timber utilization standards.

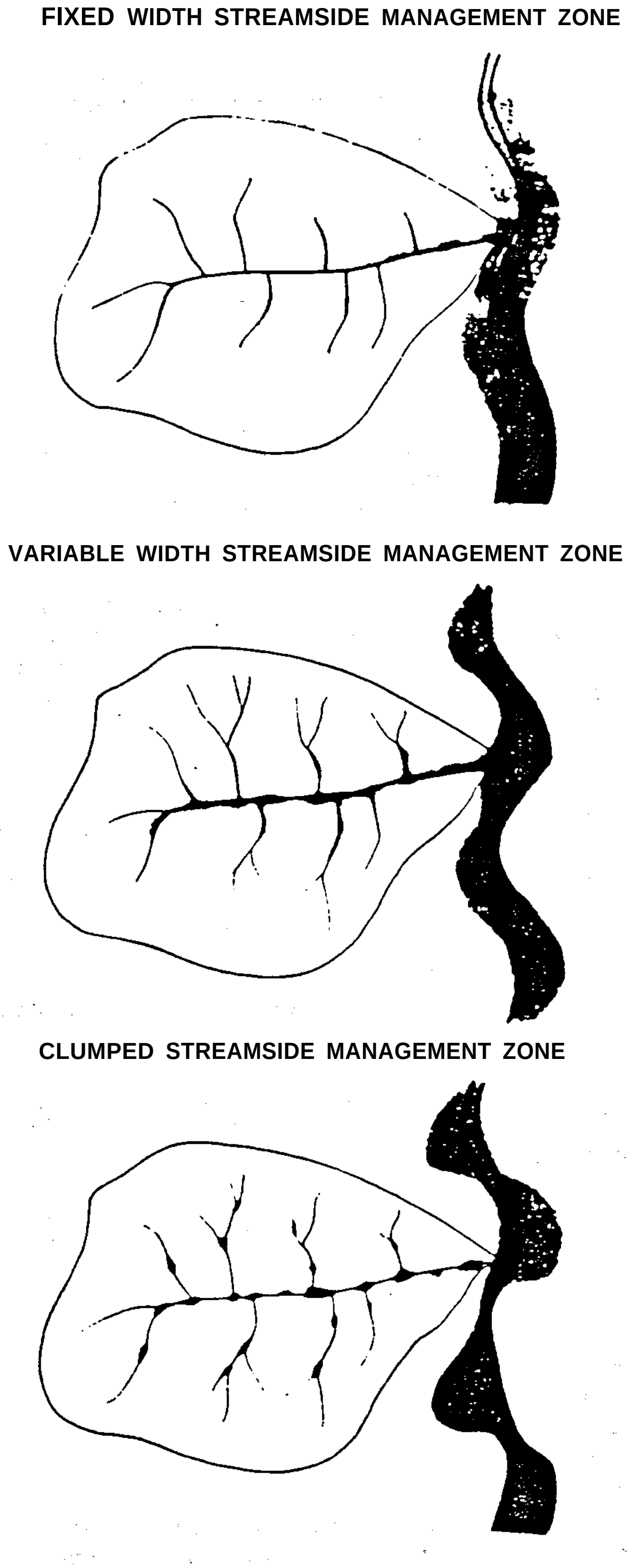
But although our knowledge of debris abundance in streams in managed second-growth watersheds is incomplete, there is evidence that past forest practices have resulted in long-term decline in debris and debris-related fish habitat in small to medium size streams, particularly those that have undergone extensive channel cleaning. While there may be a short-term increase in the debris load caused by the entry of slash during harvesting and yarding, this small, unstable material is often transported downstream within a few years, as noted earlier in this paper. In the absence of delivery of new debris to second-growth forested streams from episodic inputs such as massive blow down or a debris avalanche, the second-growth riparian zone becomes the only significant debris source. In young forest stands the input of new debris large enough to be stable in third-order and greater channels remains low through the first forty to sixty years of the rotation (Figure 9). Sedell et al. (1985) compared the frequency of large debris pieces in second-growth streams with those in old-growth streams as well as streams that had experienced buffer strip blow down. They found that, on average, the second-growth sites possessed a much lower debris frequency than either the old-growth sites or the buffer strip blow down sites (also see Figure 6). Grette (1985) reached a similar conclusion for the second-growth forested streams he studied in western Washington: the debris load in second-growth coastal streams was significantly lower than in old-growth sites. In many of these study areas, some effort had been made to protect the streambank and streamside vegetation during logging, yet the streams became progressively debris-impoverished when the second-growth riparian stands (in many cases dominated by deciduous tree species) did not provide enough new woody material within the rotation period of the timber plantation to replace debris lost during channel cleaning and gradual decay of debris from the preharvest forest.

The available evidence therefore suggests that removing nearly all the large trees from riparian zones during timber harvest, as has been practiced along many streams of the Pacific Northwest, has resulted in debris recruitment rates in second-growth forests that are lower than recruitment rates in old-growth forested streams. The majority, but not all, of the studies further indicate that reduced debris abundance may cause a decline in the quantity and quality of pools and cover, resulting in habitat that is less suitable for certain species or age classes of salmon and trout. Until current forest practices are fully evaluated, we will not be able to judge their adequacy in protecting future debris sources. However, because the primary intent of streamside management regulation has been to protect streams from temperature increases and to control erosion rather than to provide for future debris, there is reason to believe that current practices may not, in some cases, ensure a continued supply of the proper kinds and sizes of debris to maintain productive fish habitat, particularly in those streams in which large pieces are necessary for stability.

If present approaches to streamside management are causing reductions in debris inputs to streams in managed forests, what can be done to improve the way streamside zones are managed for debris recruitment? Several options have been suggested. One method is to leave an undisturbed buffer strip of old-growth timber along the channel, This practice will ensure a supply of long, large-diameter logs, but it will probably be the most costly in terms of timber value forgone, and in some cases may lead to the debris being delivered to the channel during a single event such as massive blow down or bank undercutting during a large flood (H. A. Froehlich, pers. comm.). A second approach is to leave a predetermined fraction of the timber that is deemed adequate to satisfy the stream's habitat needs, and allow the wood to enter the channel through natural processes. A third approach is to remove timber from the streamside management zone on a double rotation basis, where trees are harvested every other rotation (i.e., 100 to 150 years) rather than on a 50 to 80 year cycle. This approach would allow riparian trees to reach a larger size and have a significantly greater chance of entering the channel through chronic delivery processes. A fourth method is to design and engineer streamside vegetation stand structure and composition using silvicultural techniques aimed at (1) maintaining a relatively even delivery of large woody debris to the channel and (2) providing a mix of riparian tree species. This approach could include deliberate introductions of unmerchantable trees and debris (cull logs, stumps with root wads, or large branches and tops) during harvest or midrotation activities such as thinning (Figure 7). A final approach is to put substitute structures, such as large boulders and rock-filled gabions, into the channel in place of debris. All of these techniques have certain benefits and drawbacks, but none have been tested over the full range of stream sizes.

Fixed Width versus Variable Width Management Zones. The possibility of replacing the traditional fixed width management zone with a variable width zone (Figure 13) offers a chance to tailor streamside management practices to the specific conditions of the stream and its valley. Fixed width buffer strips or management zones are relatively easy to administer, and they require no prior knowledge of existing stream habitat, but they may call for leaving trees that have very little chance of entering the stream, or they may fail to provide enough protection to important debris source areas. Determination of variable width management zones requires prior knowledge of valley morphology and stream habitat so that recognition is given to source areas (e.g., meandering reaches with numerous undercut banks) and also to off-channel areas along floodplains that may be utilized for winter rearing. On some streams it may be preferable to leave clumps of trees (Figure 13) rather than narrow strips. Clumps might lessen the possibility of catastrophic blow down and provide added benefits to certain wildlife species in terms of increased riparian patch size. However, size and spacing of clumps would need to be carefully planned in order to avoid leaving long stream reaches without an adequate debris supply or sufficient shading and cover,

Selective Logging Within the SMZ. As our knowledge of the types and sizes of debris required for habitat formation and stability in the stream channels expands, our ability to decide what trees may be safely taken during timber harvest without negative consequences for the stream will increase accordingly. Because debris stability is strongly influenced by channel width as well as the size of the piece, we should be able to predict what size log will function effectively in maintaining good fish habitat if we know something about stream size, gradient, and valley form. It seems possible, for example, that relatively small deciduous trees could perform all the necessary roles required of debris in small channels, while longer trees will be necessary for wider channels. Large conifers are usually necessary for stability and to anchor accumulations of smaller debris in streams with channels greater than 15 to 25 meters wide (Lienkaemper and Swanson 1987, in press) while smaller deciduous species of the proper length can be stable in narrower channels (Bilby, unpublished data). Furthermore, the natural abundance of debris is now becoming known from streams throughout the Pacific Northwest (Table 1), and this information will provide useful baseline levels against which to evaluate debris recruitment from SMZs in which different amounts of timber have been removed. Additional research on the functioning of various tree species and debris sizes in channels of different width, gradient, and valley form will aid management decisions regarding where, what kind, and how many trees can be selectively removed from streamside management zones during timber



FIXED WIDTH STREAMSIDE MANAGEMENT ZONE

VARIABLE WIDTH STREAMSIDE MANAGEMENT ZONE

CLUMPED STREAMSIDE MANAGEMENT ZONE

Figure 13. Schematic representation of alternative riparian management for streamside protection.

harvest and thinning without interfering with fish habitat considerations and other important riparian functions.

Substitutes for Debris. Structures that have been used to fulfill the roles of large woody debris in maintaining fish habitat include individually placed boulders, rock filled gabions, flow deflectors (usually built of various combinations of concrete, rocks, and wood), and floating log covers. Many of these structures have been intended to provide additional cover in streams where cover is scarce, but gabions have been used to trap spawning gravel in sediment-poor channels and to cause scouring of the streambed to create rearing pools. Some of the design concepts for debris substitutes have originated from stream enhancement projects in the midwestern United States (White and Brynildson 1967, Hunt 1977), and have only recently been applied to Pacific Northwest streams,

While structural substitutes for debris are now being incorporated into stream enhancement programs in several western states and provinces, evaluation of the success of these substitutes has, in many cases, been lacking. Two areas of the Pacific coast where structural enhancements of natural streams have been evaluated are the Keogh River of eastern Vancouver Island, British Columbia, and some coastal streams on U.S. Department of Interior, Bureau of Land Management, commercial forest land in southwestern Oregon. The Keogh River enhancement project has included boulder placement, installation of rock and gabion wing deflectors, V-notch wiers, half-log floating covers, and clusters of logs cabled to the streambank (Ward and Slaney 1979). Many of the techniques used on the Keogh River have been featured in the Stream Enhancement Guide (Anonymous 1980) published jointly by the Canadian government and the province of British Columbia. The Keogh River study is the only project in the Pacific Northwest where salmonid enhancement has been assessed on a whole, watershed scale. As such, it provides an excellent opportunity to examine the costs and benefits of a variety of stream enhancements, although not all enhancement procedures were meant to duplicate the functions of woody debris. The Bureau of Land Mangernent (BLM) enhancement projects along the Oregon coast have been slightly less comprehensive in scope than the Keogh River project (not as many different techniques have been tried) but have focused instead on enhancing streams where previous logging practices have resulted in significantly reduced levels of debris in the channels (Anderson 1982, House and Boehne 1985, 1986). The BLM projects have relied extensively on the use of gabions and log sills to trap spawning gravel and to create plunge pools for rearing habitat.

Both the Keogh River and BLM enhancement projects have succeeded in improving either the spawning or rearing habitat for which they were intended, resulting in an increase in salmonid production. However, both projects have illustrated that substitution of other structures for large woody debris can be very expensive. For example, the cost (in 1977 Canadian dollars) of placing individual boulders in the Keogh River was $22 to $24 per boulder, depending on whether the boulders were placed with heavy equipment or flown to the stream by helicopter (Ward and Slaney 1979). House and Boehne (1985) note that planning estimates of costs for boulder placement in western Oregon streams should average U.S. $35 per boulder. Anderson (1982) reported that the 1981 installation of gabions for spawning gravel retention in tributaries of the Coos River, Oregon, cost a total of U.S. $225,000, with the cost per individual gabion ranging from $300 in a fourth-order stream to $1,700 in a sixth-order stream. House and Boehne (1985) suggest an average figure of $1,200 per gabion. These cost determinations were for materials and labor, and did not include engineering design or road access costs. Clearly, such projects can be very expensive, and project managers will need to weigh the cost of replacing debris after it is gone from the stream against the cost of providing for debris with woody material from the riparian zone. In many instances, substitution at a later time may be more costly than permitting debris to be recruited to the channel naturally. Even where enhancement of channel structure is warranted, the use of native materials such as logs to achieve the hydraulic diversity necessary for productive fish habitat may provide the most cost-effective means of treating extensive stream reaches (Lisle 1982).

How Much Is Too Little? How Much Is Too Much? Both forest and fishery managers are concerned with the questions of how much debris in streams is too little, how much is "optimum," and how much is too much. There are no simple answers to these questions, for the habitat requirements of various salmonid species, as well as juvenile and adult stages, often differ (see Everest et al., this volume). The problem is further compounded by a lack of information on changes in fish production resulting from experimental manipulations of debris abundance in natural streams. Until such manipulations are carried out, exact prescriptions for optimum debris loadings will remain conjectural. Nevertheless, some generalizations regarding situations where debris is too scarce or too abundant are possible, based on our current knowledge.

How do we recognize when debris is too scarce? Some of the criteria include (1) insufficient numbers and quality of pools, (2) lack of storage sites for sediment and organic matter, (3) loss of hydraulic complexity, (4) lack of hiding places from predators, and (5) loss of winter cover. Actual estimates of the quantities of debris needed for adequate fish habitat maintenance are best obtained from pre- and postlogging measurements, based on the assumption that restoration of preharvest conditions will yield satisfactory habitat conditions (an assumption that may not always be valid), However, resource limitations almost always preclude before-and-after studies of every potentially affected site: however, knowledge of debris loadings typical of streams of similar size in the same geographical area will help to provide references against which changes caused by management activities can be evaluated.

Under what conditions can debris levels become excessive? Some. of the criteria for judging when too much debris is present include (1) the presence of debris dams that completely block upstream spawning migrations, (2) a substantial impairment of water quality, (3) the presence of numerous floatable debris pieces that have a high probability of being moved during storms and which pose a significant threat to life, property, or aquatic habitat downstream, and (4) where debris accumulations strongly interfere with important recreational uses such as angling, swimming, and boating. It is clear that migration blocks result from too much unstable debris that accumulates in large logjams, thus preventing access to spawning grounds, but the question whether there can be too much debris for good rearing habitat is unresolved, Sedell et al. (1985), based on comparisons of sites that had experienced massive inputs of large debris from buffer strip blow down, have stated that we have yet to find streams "which are overloaded to the extent that fish populations are greatly diminished." There is also evidence that salmonid population densities may increase in proportion to the hydraulic complexity created by a debris matrix (Forward 1984). These studies, while suggestive of the idea that "more is better," are primarily based on comparisons of fish populations among streams with different debris loads: however, other environmental factors differed among the sites as well. To determine if there is a point at which debris becomes excessive for good rearing habitat, it will be necessary to vary the amount of debris in streams while keeping other environmental factors relatively constant. Such experiments have not yet been completed.

Is there such a thing as an optimum debris load for a stream? In the absence of data from controlled field experiments, we cannot answer with certainty. However, salmonid populations in the Pacific Northwest have evolved in debris-rich environments characteristic of unmanaged coniferous forest streams, and the species have developed adaptations that enable them to maximize production in hydraulically complex channels where debris is abundant. These adptations include seasonal migrations to productive summer and winter rearing areas (Northcote 1978) and preferences for different habitats within the stream (Chapman 1966), many of which are associated with large woody debris. Natural debris levels in small streams are becoming known (Table 1), but debris loadings in larger rivers are less well quantified, partly because pristine river systems are rare along the Pacific coast. Future experimentation should establish whether debris levels in streams in old-growth forests yield optimum habitat, and whether debris loads can be deliberately adjusted to some optimum level in order to enhance salmonid production.

A Need for Testing

Throughout this paper we have stressed the need for controlled field experiments and long-term testing. That large woody debris is essential for the maintenance of productive salmonid habitat is now well established, and there is strong evidence for a general pattern of declining debris abundance in streams in second-growth forests. Additional information on the role of debris in streams will be sought by biologists, hydrologists, and geomorphologists endeavoring to understand basic stream processes. However, studies of the linkages between specific streamside management practices and instream process'es are essential to a better understanding of the long-term consequences of forest management for fish habitat. These studies will need to go beyond postlogging surveys of habitat change and examine preplanned manipulations of debris loads and recruitment rates during actual management operations, This approach will involve both aquatic scientists and forest engineers. In many cases, answers to the questions posed above will not come quickly, and long-term site-specific monitoring will be necessary. Because it is important to evaluate management impacts on fish production on a whole basin scale, the coordinated efforts of landowners, public agencies, and universities will often be required,

This paper has summarized the available evidence for the role of large woody debris in creating habitat for salmon and trout in the Pacific Northwest, as well as the evidence for the progressive depletion of debris from streams as a result of channel cleaning, and the failure of managed riparian zones to provide enough large woody material within the context of short-term timber crop rotations. We have shown that many alternatives have been suggested for streamside management in order to maintain a continued supply of stable debris in the future, but that scientific testing of these options has not been completed. Without the benefit of rigorously designed and controlled field studies, our ability to make intelligent decisions regarding streamside management for large woody debris will be significantly delayed.

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