Proceedings Pac NW Stream Hab Management Workshop (1984)
Ed Thomas J. Hassler
Publisher Arcada CA Humboldt State U.
1985 California Coop Fish Unit
222-245

Evaluating Fish Response to Woody Debris

James R. Sedell[1]
Frederick J. Swanson[1]
Stanley V. Gregory[2]

[1] U.S. Department of Agriculture, Forest Service
Pacific Northwest Forest and Range Experiment Station
Forestry Sciences Laboratory
Corvallis, Oregon 97331

[2] Department of Fisheries and Wildlife
Oregon State University
Corvallis, Oregon 97331

SEE PAGE 237 for INFO ON NUMBER OF PIECES OF WOODY DEBRIS IN STREAMS.

Abstract

Fish respond favorably to debris in streams. Pristine streams contain vast amounts of large wood in their channels and along their edges. For decades the principal tool for fish habitat management has been debris jam removal. We examine the evidence for evaluating the role coarse woody debris plays in the geomorphology of streams, specifically: longitudinal profiles, channel patterns and position, channel geometry, sediment and organic matter storage, and channel dynamics. From this physical template we examine the fisheries implications of coarse woody debris (CWD): blockage to migration, water quality, and summer and winter rearing habitat. The issue of current management practices for providing wood inputs to stream is discussed in terms of the question how much wood is enough.

Introduction

Our understanding of the importance of large woody debris in western streams has changed in the last 40 years. The pendulum is swinging from taking all woody debris out of the stream to putting it all back. Uncertainty still exists as to how to quantitatively describe the role wood plays for fish: determining how much wood is enough, how much to take out and where to take it out. One thing is certain; streams and rivers need what the timber industry calls "merchantable trees" in order to sustain a diversity of habitats and diversity and abundance of most salmonids throughout a year.

We will evaluate the importance of woody debris by providing a brief account of debris in pristine streams, management effects on coarse woody debris (CWD), and how CWD affects fish and stream geomorphology. Having examined these issues, we will address the question: how much CWD is enough?

Historical perspective of CWD conditions and management in streams

Pristine streams and rivers in North America contained large quantities of downed trees (Froehlich, 1972; Swanson et al., 1976; Sedell et al., 1982; Sedell and Luchessa, 1982; Sedell and Froggatt, 1984; Triska, in press; Harmon et al., in press). The record consistently indicates that wood from downed trees was a dominent feature of streams regardless of their location in North America. Volume of wood in over 80 streams reported by Harmon et al. (in press) ranged from about 150-3500 m^3 ha^{-1}. Sedell and Swanson (in press) characterize streams in present old-growth forest as being structurally dominated by large ~~tree-sized~~ woody debris.

Streams throughout North America have been systematically cleaned of downed trees and woody debris for over 150 years (Sedell et al., 1982; Sedell and Luchessa, 1982). For example, from the middle of 1800's to about 1920, large and intermediate-sized rivers in North America were cleaned of drift jams and downed trees so steamboats and rafts could navigate the rivers. From the 1880's to around 1915, small rivers and streams were cleaned of debris so logs could be transported out of the woods to the mills. Many streams had several splash dams to augment the flow in order to drive logs (Sedell and Luchessa, 1982).

Stream clean-up of debris jams to benefit fisheries was initiated on a major scale in the late 1940's and early 1950's in Oregon and Washington. In the late 1950's and early 1960's, the California Department of Fish and Game conducted a program to remove old log jams on nearly every major coastal river that supported anadromous fish (Hall and Baker, 1982).

During this period, log and debris jams and loose aggregations of debris with the potential to form jams were removed. This was a period when large volumes of unstable slash accumulated in streams. The result of the programs for debris jam removal, however, was to put fishery biologists into the position of being river engineers, a role they were not equipped to carry out. In general, debris in streams was viewed negatively as: restricting fish passage, supplying material for construction of yet larger jams, and causing channel scour during floods. In the extreme cases during the 1940's and 50's, all of the above fears were well founded (McKernan et al., 1950; Gharrett and Hodges, 1950).

From the 1970's to the present, the important influence of large woody debris on stream geomorphology and in creating and maintaining spawning and rearing habitat has been recognized and documented by managers and researchers.

Geomorphic Functions of Woody Debris in Streams

Recent interest in CWD in streams and rivers has been stimulated by the desire to control aquatic habitat and the movement of sediment and water. Controversy has often fueled this interest. For example, CWD can be a hazard to life or property -- damaging or destroying structures and impeding flood flows. This potential hazard and the desire to clear CWD from rivers and streams for navigation and fish passage have resulted in the long history of debris removal. This runs counter to the increasingly common practice of introducing and retaining CWD in streams for fish habitat improvement or channel stabilization. Such conflicts in management objectives have triggered intensive research on the behavior and functions of CWD in streams and rivers.

Channel Morphology

Coarse woody debris influences channel morphology on a variety of scales. At the broadest level, it affects the longitudinal profile of a river. Locally, accumulations of CWD influences channel position and the formation of channel features such as pools and riffles. At the finest scale are features formed by a single piece of CWD. Fish rearing and spawning habitats are very dependent on these stream channel characteristics.

(a) Longitudinal profile

The influence of CWD on the longitudinal profile of channels can be considered for entire profiles and for restricted reaches. Steps in the channel profile are created where large single logs or accumulations of CWD form a dam which traps a wedge of sediment (Heede, 1972a; Keller and Swanson, 1979; Pearce and Watson, 1983). The tread of such a step is primarily composed of the stored sediment; the debris accumulation forms the riser.

Steps created by CWD reportedly vary widely in their importance to the channel profile. Marston (1982) evaluated effects of CWD in 13 watersheds of up to fifth-order in the Oregon Coast Range. Steps created by CWD controlled 6% of total fall in the channels. At this large basin scale, geologic factors, not CWD, controlled the shape of the longitudinal profile. Stream reaches in other areas have much greater proportions of the channel fall occurring over CWD: 50-100% in the Rocky Mountains of Colorado and White Mountains of Arizona (Heede, 1972a, 1972b); 30-60% in watersheds <5 km^2 in area and <20% in larger basins in Redwood Creek, California (Keller and Tally, 1979); 10-52% in the White Mountains, New Hampshire (Bilby, 1981); and 30-80% in the western Cascades, Oregon (Keller and Swanson, 1979; Swanson et al., 1976). Bob Rainville, Idaho Panhandle National Forest, Coeur D'Alene Idaho, (personnal communication) determined that 80% of the pools found in small streams < 6% gradients were created by CWD.

These differences in the degree to which CWD controls stream profiles are related to abundance and size of CWD and the opportunities for channels to bypass obstructions. Several factors combine to produce a downstream decrease in the importance of CWD in altering longitudinal channel profiles. Bilby (1981), for example, observed that the percent of channel drop formed by CWD decreased from 52 to 42 to 10% from first- to third-order channels, respectively, in the Hubbard Brook Experimental Forest, New Hampshire. The decreases were a result of wider channels, more stream power and short tree boles and branches.

(b) Channel pattern and position

CWD triggers abrupt and persistent changes in channel pattern and position by blocking flow in a main channel. More chronic change in channel position and pattern results from the effect of CWD deflecting stream flow against banks, accelerating lateral migration of channels. Entire sections of major rivers can be changed drastically, as was the case of the Red River in northern Louisiana, where an accumulation of CWD grew to a length of more than 300 km over ~ 200 years (Lobeck, 1939). Floodplain forests undercut by the river in upstream areas washed downstream and accumulated in this jam, which blocked the main stem and mouths of tributary streams, forming lakes and swampy areas. Less-dramatic changes are more typical, such as when CWD accumulations trigger cutoff of meander bends, forming an abandoned channel (Keller and Swanson, 1979).

The effect of CWD on rates of lateral migration of channels is undocumented but the phenomenon has been observed locally (Keller and Tally, 1979). The presence of standing live trees of great age along stream banks in Redwood Creek, northern California, suggest steam position is very stable on steep lands (Keller and Swanson, 1979; Keller *et al.*, in press). In contrast, streams on gentle lowlands with mobile bed and bank material can experience rapid lateral channel migration and entrainment of CWD as a result of bank erosion (Everitt, 1968). In both high gradient and low gradient rivers in the Pacific Northwest, meander cutoffs and debris-plugged secondary channels result in a plus for winter and summer habitat rearing (Sedell and Luchessa, 1982; Sedell *et al.*, in press).

The combined effects of CWD on channel position and geometry can lead to alteration of the channel pattern. Murgatroyd and Ternan (1983), for example, observed decreased sinuosity in a forested reach relative to an upstream sod-lined channel. They attribute this contrast to channel widening in response to establishment of the forest.

CWD may indirectly influence channel position by aiding establishment of vegetation in the floodway (Swanson and Lienkaemper, 1982).

(c) Channel geometry

Effects of CWD on channel geometry have been quantified over stream reaches and at sites of individual CWD accumulations. CWD partially or completely crossing a channel commonly deflects streamflow laterally or causes it to diverge. Associated deposition of sediment upstream from the CWD, as well as downstream in the case of low-gradient channels, widen and decrease the depth of the channel (Keller and Swanson, 1979). Zimmerman *et al.* (1967) contrasted channel geometry, particularly channel width, between sod and forested stream banks in the Sleepers River basin, New Hampshire. Average channel width and variation in width was greater along forested reaches in channels draining watersheds <~6 km^2. This was attributed to CWD in the channel and tree root mats in the stream banks. The influence of CWD on variation in width of larger channels was minimal.

In another comparison of geometry between channels with sod and forested banks, Murgatroyd and Ternan (1983) observed channels shallower and up to three times wider in the forested reach. The thick turf and root mat were the primary cause of the narrower channel through sod-lined reaches. Bank erosion in the 50-year-old forest contributed to differences as a result of stream flow through and around accumulations of CWD, rootthrow along the channel margins, and aggradation caused by accelerated sediment input from the bank erosion. The tendency of sod to constrain channel width accentuates the apparent influence of forest vegetation on channel width in these comparisons.

Channels at accumulations of CWD along five streams flowing through coastal redwood forests, northern California, were 27-124% wider than overall average channel widths on stream reaches draining 1.1-19.8 km^2 (Keller and Tally, 1979). Hogan (in press) observed a similar, though less pronounced, pattern in seven larger stream reaches in British Columbia. At both the California and the Sleep-ers River New Hampshire sites, maximum variability in stream width occurred at a drainage area of ~6 km^2.

Associated changes in channel depth are much more difficult to quantify because of extreme channel irregularity imposed by the CWD. It is not uncommon to find water flowing simultaneously at several heights and in several directions through a CWD accumulation.

CWD can have a dominant control on the abundance and geometry of pools and riffles, which has important implications for fish habitat. Pools are formed, or their geometry is modified, by scour and deposition associated with stream flowing over, under, and around CWD. In meandering streams lacking CWD, pools typically form at the outside of meander bends with an along-stream spacing of five to seven bankfull-channel widths (Leopold et al., 1964). Pools may be absent or very small in steep channels controlled by boulders or bedrock and lacking CWD.

Coarse woody debris can increase pool frequency and variability in pool depths. Lisle and Kelsey (1982) hypothesized that CWD can increase pool frequency and that the location of the thalweg (deepest portion of the channel) is related to large roughness elements in the channel, such as CWD. Scour at these roughness elements forms pools. In studies of Jacoby Creek, a 30 km^2 basin in northern California, they observed a pool spacing of 4.6 widths and 86 percent of the pools were associated with large roughness elements, of which CWD made up a substantial proportion. In a comparison of stream reaches with high and low CWD levels in British Columbia, Hogan (in press) documented greater variability in pool depths resulting from formation of scour pools associated with CWD.

Keller et al. (in press) examined 10 stream segments with drainage areas up to 27.2 km^2 in the Redwood Creek basin, northern California, and observed pool spacing of 4 or fewer channel widths in six of them. CWD significantly influenced the morphology of 50 to 100% of the pools in these study reaches. In six reaches (drainage areas 1.6 to 9.8 km^2) disturbed by logging they observed pools spacing of 1.3 to 4.1 channel widths and 43 and 100% of the pools influenced by CWD.

In another comparison of geometry between channels with sod and forested banks, Murgatroyd and Ternan (1983) observed channels shallower and up to three times wider in the forested reach. The thick turf and root mat were the primary cause of the narrower channel through sod-lined reaches. Bank erosion in the 50-year-old forest contributed to differences as a result of stream flow through and around accumulations of CWD, rootthrow along the channel margins, and aggradation caused by accelerated sediment input from the bank erosion. The tendency of sod to constrain channel width accentuates the apparent influence of forest vegetation on channel width in these comparisons.

Channels at accumulations of CWD along five streams flowing through coastal redwood forests, northern California, were 27-124% wider than overall average channel widths on stream reaches draining 1.1-19.8 km^2 (Keller and Tally, 1979). Hogan (in press) observed a similar, though less pronounced, pattern in seven larger stream reaches in British Columbia. At both the California and the Sleep-ers River New Hampshire sites, maximum variability in stream width occurred at a drainage area of ~6 km^2.

Associated changes in channel depth are much more difficult to quantify because of extreme channel irregularity imposed by the CWD. It is not uncommon to find water flowing simultaneously at several heights and in several directions through a CWD accumulation.

CWD can have a dominant control on the abundance and geometry of pools and riffles, which has important implications for fish habitat. Pools are formed, or their geometry is modified, by scour and deposition associated with stream flowing over, under, and around CWD. In meandering streams lacking CWD, pools typically form at the outside of meander bends with an along-stream spacing of five to seven bankfull-channel widths (Leopold et al., 1964). Pools may be absent or very small in steep channels controlled by boulders or bedrock and lacking CWD.

Coarse woody debris can increase pool frequency and variability in pool depths. Lisle and Kelsey (1982) hypothesized that CWD can increase pool frequency and that the location of the thalweg (deepest portion of the channel) is related to large roughness elements in the channel, such as CWD. Scour at these roughness elements forms pools. In studies of Jacoby Creek, a 30 km^2 basin in northern California, they observed a pool spacing of 4.6 widths and 86 percent of the pools were associated with large roughness elements, of which CWD made up a substantial proportion. In a comparison of stream reaches with high and low CWD levels in British Columbia, Hogan (in press) documented greater variability in pool depths resulting from formation of scour pools associated with CWD.

Keller et al. (in press) examined 10 stream segments with drainage areas up to 27.2 km^2 in the Redwood Creek basin, northern California, and observed pool spacing of 4 or fewer channel widths in six of them. CWD significantly influenced the morphology of 50 to 100% of the pools in these study reaches. In six reaches (drainage areas 1.6 to 9.8 km^2) disturbed by logging they observed pools spacing of 1.3 to 4.1 channel widths and 43 and 100% of the pools influenced by CWD.

Several experiments document changes in pool abundance before and after CWD removal. MacDonald and Keller (1983) observed that pools increased from 5 to 8 in a 100 m reach in the first year after removal. Pool spacing decreased from 2.5 to 1.6 channel widths. After debris removal from a stream in Mt. St. Helen's blast zone, pool frequency increased several fold. However, the pools were small and very shallow with a net loss of 30% in water volume (Sedell, unpublished data). Bilby (1984) reported reduction in number and area of pools after cleanup of CWD in a 11.5-m-wide segment of Salmon Creek, Coast Range, Washington. Even after cleanup operations, however, CWD exposed by erosion of sediment influenced several of the pools.

The physical dynamics of CWD must also be taken into account in considering its effects on channel geometry. The introduction of CWD to channels and its movement and accumulation downstream trigger abrupt and prolonged changes in channel configuration. When a new piece of CWD enters a channel, it may move immediately or remain in place at least temporarily. If it remains in the channel, a long period of adjustment begins as scour of the stream bed and deposition of sediment and other CWD alter the hydraulic conditions and morphology of the site. Such changes have never been systematically documented.

The entrainment of live vegetation and transport of CWD in floods and mass-movement events can dramatically change channel geometry. Changes are probably greatest in systems where channel form is dominated by CWD, notably small, steep, forested stream. A debris torrent down such a stream converts a complex channel with numerous pools into a smooth, bedrock- or cobble-lined chute, commonly terminating at a massive pile of CWD and sediment at the downstream end (Keller and Swanson, 1979; Swanson and Lienkaemper, 1978; Benda, in press). The role of CWD in channel modification during floods is difficult to distinguish from effects of the flood waters alone, and nothing more than anecdotal observations have addressed this issue in the literature.

Accumulations of CWD emplaced by mass movements and floods affect channel location, pattern, and geometry. Subsequent streamflow typically bypasses such obstructions if the valley floor is wide enough to accommodate changes in channel position (Hack and Goodlett, 1960). Steps in the longitudinal profile of the channel form where debris accumulations collect in narrow valleys (Pearce and Watson, 1983; and others). Sedell and Dahm (1984) found these areas to be very productive biologically, often providing excellent spawning and rearing situations. However, torrents clump fish habitat instead of leaving it spread throughout a stream channel.

(d) Sediment and organic-matter storage

The large size and relative stability of CWD result in storage of inorganic sediment and organic matter in stream channels. The CWD is itself in temporary storage and it forms structures that store additional material. Research by geomorphologists has emphasized storage of inorganic material, principally potential bedload, while ecologists have concentrated on CWD as stored organic material and as structures for storing other organic materials.

It is difficult to clearly separate these roles, because organic and inorganic materials are commonly thoroughly mixed and they work together to enhance the overall stability of a structure. CWD provides the main structural elements of an accumulation, and the finer, more equidimensional inorganic particles of higher bulk density fill interstitial areas and weight down the organic material. The entire size distribution of organic and inorganic materials, from massive boles to silt and clay, thus form accumulations of distinctive architecture. Furthermore, the relative importance of organic and inorganic features in stabilizing sediment deposits depends on their relative sizes. Large boulders and bedrock outcrops trap and stabilize CWD, which in turn forms a site for deposition of finer sediment. In small, steep channels that transport gravel and finer sediment, the structural stability of CWD pieces is a more dominant factor in determining the stability of sediment storage sites than in low gradient (<2%) streams.

Three approaches to quantifying volumes of sediment in storage sites involve measuring (1) volumes of sediment stored in sites related to CWD, (2) changes in sediment export from a channel after removal of CWD, and (3) changes in volume of stored sediment after removal of CWD. Past studies have considered sediment storage by individual, massive accumulations of CWD and by scattered, smaller accumulations.

Two studies of stored-sediment volume associated with CWD have been conducted in northwestern North America. Megahan and Nowlin (1976) and Megahan (1982) found that CWD accounted for 35% of the obstructions and 49% of the stored-sediment volume in seven watersheds in Idaho ranging in area from 0.26-2.02 km^2. The CWD was principally pieces of tree boles and had greater longevity and amounts of stored sediment than rocks, roots, and finer organic debris, which were the other types of obstructions sampled. Total sediment stored in these watersheds was ~15 times the average annual sediment yield, which amounted to 0.23 m^3 of stored sediment per meter of channel length for all types of obstructions. Clearcut logging of one basin and selective cutting of another resulted in decreased sediment storage because of damage to natural obstructions during tree felling and efforts to remove logging slash from the channels.

In an old-growth Douglas-fir forest in western Oregon, which had a much greater abundance of CWD than the Idaho sites, Swanson and Lienkaemper (1978) measured 1.92 m^3 m^{-1} of sediment stored by CWD in a 120-m-long segment of a third-order stream.

Bilby (1981) compared sediment yields from a 175-m section of stream in a second-order watershed before and after removal of CWD at the Hubbard Brook Experimental Forest, New Hampshire. He also compared post-treatment sediment yields with a nearby control basin forested with 65-year-old northern hardwood vegetation. In the first year after removal, export of fine and coarse particulate matter increased 500% over the value expected for the untreated condition. This pulse of exported sediment was material previously stored in the channel and released from storage by the treatment, and material that entered the channel since treatment.

It is difficult to clearly separate these roles, because organic and inorganic materials are commonly thoroughly mixed and they work together to enhance the overall stability of a structure. CWD provides the main structural elements of an accumulation, and the finer, more equidimensional inorganic particles of higher bulk density fill interstitial areas and weight down the organic material. The entire size distribution of organic and inorganic materials, from massive boles to silt and clay, thus form accumulations of distinctive architecture. Furthermore, the relative importance of organic and inorganic features in stabilizing sediment deposits depends on their relative sizes. Large boulders and bedrock outcrops trap and stabilize CWD, which in turn forms a site for deposition of finer sediment. In small, steep channels that transport gravel and finer sediment, the structural stability of CWD pieces is a more dominant factor in determining the stability of sediment storage sites than in low gradient (<2%) streams.

Three approaches to quantifying volumes of sediment in storage sites involve measuring (1) volumes of sediment stored in sites related to CWD, (2) changes in sediment export from a channel after removal of CWD, and (3) changes in volume of stored sediment after removal of CWD. Past studies have considered sediment storage by individual, massive accumulations of CWD and by scattered, smaller accumulations.

Two studies of stored-sediment volume associated with CWD have been conducted in northwestern North America. Megahan and Nowlin (1976) and Megahan (1982) found that CWD accounted for 35% of the obstructions and 49% of the stored-sediment volume in seven watersheds in Idaho ranging in area from 0.26–2.02 km^2. The CWD was principally pieces of tree boles and had greater longevity and amounts of stored sediment than rocks, roots, and finer organic debris, which were the other types of obstructions sampled. Total sediment stored in these watersheds was ~15 times the average annual sediment yield, which amounted to 0.23 m^3 of stored sediment per meter of channel length for all types of obstructions. Clearcut logging of one basin and selective cutting of another resulted in decreased sediment storage because of damage to natural obstructions during tree felling and efforts to remove logging slash from the channels.

In an old-growth Douglas-fir forest in western Oregon, which had a much greater abundance of CWD than the Idaho sites, Swanson and Lienkaemper (1978) measured 1.92 m^3 m^{-1} of sediment stored by CWD in a 120-m-long segment of a third-order stream.

Bilby (1981) compared sediment yields from a 175-m section of stream in a second-order watershed before and after removal of CWD at the Hubbard Brook Experimental Forest, New Hampshire. He also compared post-treatment sediment yields with a nearby control basin forested with 65-year-old northern hardwood vegetation. In the first year after removal, export of fine and coarse particulate matter increased 500% over the value expected for the untreated condition. This pulse of exported sediment was material previously stored in the channel and released from storage by the treatment, and material that entered the channel since treatment.

Effects of CWD removal on stored sediment have also been evaluated by repeated surveys of channel cross-sections before and after treatment. Using this technique, Beschta (1979) observed that removal of several large CWD jams released 5250 m^3 of stored sediment from a 250-m section of a third-order stream in the Coast Ranges of Oregon.

Baker (1979) examined the effects of removal of major accumulations of CWD on sediment storage and fish populations in seven streams in the Cascade and Coast Ranges of Oregon. Quantities of stored sediment ranged from 800-4500 m^3 and lengths of accumulations and associated sediment from ~40-100 m. Three of the accumulations were completely removed, releasing 29-97% of the stored sediment within 2 years. A single channel was opened through the other four jams and only 8-20% of stored sediment left these sites during the same period.

MacDonald and Keller (1983) observed that 60% of the 90 m^3 of CWD-stored sediment left a 100-m segment of Larry Damm Creek in north Coastal California in the first winter following removal of 60 m^3 of CWD.

Obviously, CWD has major effects on storage of stream sediments and can be manipulated so as to alter both total amounts and transit times for inorganic and organic particulates.

(e) Dynamics - physical

The dynamics of CWD in channels involve periodic input and redistribution. Stand structure and composition, physical and biological processes leading to the input of CWD, and the geometry of the site where CWD comes to rest all influence the size distribution and stability of CWD when it first enters a channel. Once in a channel or floodway, pieces of CWD may move downstream. The potential for downstream movement is controlled by a variety of factors determining the stability of CWD pieces: size of piece relative to size of stream; degree of burial; degree of stabilization by rooting into substrate by the piece itself or by other trees extending roots through the CWD; stage of decay, which influences potential for fragmentation; and position and orientation, including considerations such as proportion of mass supported outside the flooded area and tendency of stream flow to force CWD pieces against stable features.

The dynamics of CWD in streams has been observed by dendrochronologic analysis of the residence time of CWD pieces (Swanson et al., 1976), repeated mapping of CWD (Bryant, 1982; Lienkaemper and Swanson, 1980; Megahan, 1982), and repeatedly relocating tagged pieces of CWD (Bilby, 1984). The studies in the Oregon Cascades revealed that pieces much longer than bankfull width remained in place for many decades. Pieces of debris with shorter than bankfull width were susceptible to movement during floods.

Influence of Woody Debris on Fish Populations

Channel morphology, particularly as influenced by CWD, along with streamside vegetation, determines characteristics. Before 1970, wood generally was not recognized as an important component of stream channels, but rather a hinderance to fish migration and a cause of oxygen depletion in streams. In contrast, recent investigations have identified the many roles CWD plays in the formation and stabilization of fish habitat. Here we consider fisheries implications of CWD in terms of fish passage, water quality, and habitat.

(a) Blockage to migration

Wood debris accumulates in stream channels naturally, but timber harvest can increase input of wood to streams, causing massive log jams, as well as large quantities of slash. Debris accumulations in river basins containing anadromous salmonids commonly have been viewed as potential blocks to upstream migration of adult salmon (Elliot, 1978; Meehan et al., 1969; Narver, 1971). After 1936, fishery-management agencies in the Pacific Northwest developed large-scale programs for removing log jams from streams and rivers to increase access to spawning and nursery areas (Hall and Baker, 1982; Sedell and Luchessa, 1982). Debris removal operations have continued for many years with little or no evaluation of their success or impacts on other aspects of fish habitat than migration. Narver (1971) felt that complete blockages to fish passage were relatively rare and that most jams hindered migration only at certain flows.

Although log jams block fish passage in some streams, they rarely remove a major fraction of available spawning or rearing habitat in a drainage basin. Sedell and Luchessa (1982) estimated log jams prevented fish migration to 12% and 20% of the length of potential fish-producing streams in the Coquille and Tillamook River basins respectively in Oregon in the 1940's and early 1950's. Sedell and Luchessa (1982) also estimated only 5.5% of the length of potential fish-bearing streams in the Siuslaw National Forest in western Oregon were blocked by log jams in the late 1970's, and nearly all of the blocked area was in small streams at gradients between 5 and 10 percent. In coastal Oregon and Washington, very little rearing and spawning occurs in such high-gradient systems.

Removal of log jams as barriers to fish migration was also supported by the view that wood debris accelerated bank cutting and streambed instability by de-flecting currents into streambanks (International Pacific Salmon Fisheries Commission, 1966). The resulting siltation and shifting sediments were believed to smother and scour salmonid eggs and reduce the abundance of invertebrates (Gammon, 1970). This view is also reflected in a sediment-stability rating system of the U.S. Forest Service that reduces channel stability ratings if CWD is abundant (Pfankuch, 1975).

Removal of log jams may actually increase the adverse effects of siltation and sediment instability. Abundance of sea-run Dolly Varden trout decreased immediately after removal of debris dams in an Alaskan stream (Elliott, 1978). Two years after removal of jams, numbers of trout were only 20% of the original, pre-removal populations, and the abundance and composition of aquatic macroinvertebrates were altered. Removal of wood accumulations generally releases large volumes of sediment. Baker (1979) investigated the effects of logjam removal in seven stream reaches in Oregon and found that release of stored sediments and destruction of existing habitats were the principal effects of CWD removal practices. Fish populations did not decline in these streams after removal of the jams when sufficnet wood and sediments remained in place.

(b) Water quality

CWD contains organic compounds that potentially inhibit microbial decay and deter consumption by insects, but such problems are rare. In sufficient quantities, these chemicals are lethal to aquatic organisms. Sitka spruce and western hemlock bark were found to be toxic to pink salmon fry (Buchanan et al., 1976). Salmon fry were more sensitive to extracts of hemlock bark than spruce bark extracts; 50% of the fry were killed in 96 hours at a concentration of 56 mg liter^{-1} of hemlock bark extract and 100-120 mg liter^{-1} of spruce bark extract (96-hour LC50). These concentrations are sufficiently high that toxic effects would be limited to situations of abnormally high loadings of fresh-wood debris, such as log-holding facilities or recent clearcut with heavy accumulations of slash. Leachates of Douglas-fir needles, western hemlock needles, and red alder leaves were toxic to guppies and steelhead trout (Ponce, 1974). Leachates of whole hemlock logs, with and without bark, were not toxic to fry of rainbow trout and chinook salmon in 96-hours of exposure (Atkinson, 1971). However, Ponce (1974) concluded that concentrations of leachates required to cause mortality were so high that oxygen depletion would become a threat long before toxic effects would be a serious factor. This research was restricted to foliage, but a later study by Peters et al. (1976) investigated the toxic effects of specific leachates of wood and foliage of western red cedar on coho salmon and aquatic insects. Foliage terpenes and heartwood tropolenes were more toxic than bark extracts and heartwood lignins. In separate tests aquatic insects were more tolerant of leachates than salmon, and fry were the most sensitive developmental stage in the salmon. The authors analyzed stream water from several natural streams and streams influenced by logging practices and concluded that adverse effects of cedar debris would be restricted to freshly logged areas with large amounts of slash in the streams or swampy areas with naturally high accumulation of fresh wood debris.

Note

Depletion of dissolved oxygen concentrations by microbial respiration and chemical oxidation associated with wood affect fish populations adversely. Concentrations of dissolved oxygen in stream water and interstitial water in a coastal stream in Oregon decreased to potentially lethal levels after logging (Hall and Lantz, 1969). Dissolved oxygen concentrations increased after debris removal, but were still significantly lower than prelogging concentrations. The extremely low concentrations (as low as 0.6 mg liter^{-1}) of oxygen observed in this study were associated with localized, concentrations of logging slash that ponded stream waters. Egg-to-fry mortality of sockeye salmon was increased significantly by intrusion of bark debris into spawning gravels (Servizi et al., 1970). At concentrations greater than 4% (volume/volume), mortality increased as a result of oxygen depletion by the decomposition of bark, and emergence was retarded at concentrations exceeding 1%. Ponce (1974) found that chemical oxygen demand of Douglas-fir wood exceeded the biological oxygen demand by an order of magnitude. Mortality and exclusion of fish from stream reaches as a result of oxygen consumption associated with wood debris are likely to occur only under conditions of unusually large accumulations of fresh CWD. Aeration in moderate- to high-gradient streams is likely to be sufficient to prevent major reductions in oxygen concentrations (Ice, 1977). The potential adverse effect of wood on oxygen supply for fish and invertebrates is not a major concern under natural conditions and present logging standards.

(c) Habitat

CWD plays a major role in the geomorphology of stream channels; therefore, the habitat of fish populations in streams is intricately linked to the dynamics of CWD. CWD potentially provides cover for fish, creates important hydrologic features such as pools and backwaters, and stores inorganic sediment. The importance of CWD to fish populations has been recognized in a number of recent review articles (Meehan et al, 1977; Franklin et al., 1981; Sedell et al., 1982; Bryant, 1983; Maser et al., 1984; Bisson and Sedell, in press).

Early investigations of fish habitat in streams identified wood debris as a major source of cover (Tarzwell, 1936; Boussu, 1954; Hunt, 1971). Hartman (1965) observed that coho salmon and steelhead trout were associated with debris dams and that abundance of these salmonids decreased in winter in areas where log cover was absent. Subsequent investigations have documented the use of wood habitats by fish in streams (Lister and Genoe, 1979; Everest and Meehan, 1981; June, 1981; Osborn, 1981).

In the Pacific Northwest, most of the annual precipitation occurs from October through March; therefore, winter is a period of high flow, low stream temperature, and low light intensity. Stable winter habitat and refuges during high flow are critical for the survival of fish in streams. Chapman and Bjornn (1969) and Bjornn (1971) observed that salmonids hide in cracks and crevices in stream bottoms at temperatures less than 5°C and cited winter cover as a major factor in salmonid populations dynamics. Wilzbach (1985) observed similar winter hiding behavior in cutthroat trout in a forested reach but found that trout in a open clearcut reach with much less CWD did not hide in the substrates. She experimentally demonstrated that trout did not exhibit the hiding behavior when prey items in the drift were abundant and that fish in the forested reach would abandon their hiding behavior when insect drift was artifically increased. Nevertheless, stable winter cover is important to stream fish (Tschaplinski and Hartmann, 1983), and CWD is an important source of cover.

Bustard and Narver (1975b) observed that coho salmon fry, juvenile (age 1+) coho salmon, and juvenile steelhead (age 1+) used logs and upturned tree roots as their major source of winter cover in several streams on Vancouver Island, British Columbia. At very low stream temperatures (~2.5°C), juvenile trout and salmon were observed hiding under logs and roots. Forest practices may alter the stability of winter cover provided by CWD by removing or disturbing large pieces. Toews and Moore (1982) found that streambanks eroded more and debris cover was removed more readily in streams in logged areas compared to unlogged reaches. Juvenile coho salmon in Carnation Creek, British Columbia, inhabited deep pools, log jams, and undercut banks with tree roots and debris in winter (Tschaplinski and Hartman, 1983). During winter, stream reaches with these habitat types retained higher populations of juvenile salmon than reaches with-out these habitats, and fewer fish were lost after freshets in reaches with abundant CWD. Several streambanks in clearcut reaches collapsed during winter flows and salmon populations decreased in these areas. However, logging did not result in a change in numbers of salmon that migrated out of Carnation Creek in the autumn or into the stream in the spring.

In addition to large, stable accumulations of CWD, habitats outside the main axis of the channel (e.g. backwaters, sloughs, side channels) are critical refuges for fish during high discharge events and rearing areas for young fish. CWD, boulders, and living trees are the major structural features responsible for the creation and maintenance of backwaters and side channels in third-order streams in the Cascade Mountains (Kelly Moore, Oregon State University, Corvallis OR, unpublished data). A major component of off-channel habitats in rivers of the Olympic Peninsula is wood debris accumulating at the upstream end of side channels and protecting the habitat from scour at high flows (Sedell et al., in press). Bustard and Narver (1975a) observed that juvenile coho salmon moved into sidepools and small tributaries during winter floods. In a manipulation of sidepool structure and cover, they observed a strong preference for river edge habitats as opposed to the main channel (Bustard and Narver, 1975a), preferring sidepools with overhanging bank cover and silt-free substrates to the greatest extent. Off-channel ponds in rivers of the Olympic Peninsula supported the majority of salmonid production in the drainage (Petersen, 1980; 1982). Side channels and terrace tributaries contained the highest standing crops of juvenile coho salmon in the Hoh River of the Olympic Peninsula (Sedell et al., 1982). Sedell et al. (in press) observed that side channels with major accumulations of CWD supported coho salmon densities 8 times that of side channels without CWD.

In a survey of habitat utilization in 19 stream reaches in Washington, Bisson et al. (1982) found coho salmon fry predominantly in backwater pools. In reaches above anadromous zones, backwater pools were the preferred habitat of cutthroat trout. Fry of cutthroat trout in streams in the Cascade Mountains of Oregon occupied backwater habitats and were not found in the main channel until early fall, and even then they remained in main channel habitats close to backwaters (Moore, unpublished data). Moore also experimentally altered the abundance of stream margin habitats, and the resulting populations of trout fry in the reaches were directly proportional to the area of backwater habitats.

The abundance of fish in streams and rivers is strongly related to the abundance of CWD. Densities of brown trout in a Danish stream declined after removal of small wood debris (Mortensen, 1977). Lestelle (1978) observed that numbers and biomass of resident cutthroat trout declined in winter after a removal of 85% of the wood volume in a stream in Washington. Reentry of wood into the channel returned the volume of CWD to levels equivalent to wood volumes in a control stream after 1 year; numbers and biomass of trout were equal in the treatment and control streams after recovery of wood volumes. Reduction in debris resulted in a reduction of pool volume as well. Yearling steelhead and yearling and older cutthroat trout preferred habitats with abundant wood debris in streams in Washington (Bisson et al., 1982). In a comparison of fish populations in reaches of an Oregon stream that flowed through a major conifer forest and a 20-year-old alder stand, House and Boehne (in press) observed greater abundance and biomass of coho salmon, steelhead, and cutthroat in the reach in the mature forest. This response was attributed to the abundance of debris in the mature stand and the lack of debris in the young alder-dominated reach. Numbers of juvenile coho salmon were positively correlated with presence of CWD. Pool volumes and available area of spawning gravel were much greater in the reach with greater amounts of CWD. Murphy and Hall (1981) found that volumes of wood in streams in clearcuts (5-17 years after logging) and second-growth timber (12-35 years after logging) were significantly lower than volumes in streams in old-growth forests.

Densities of juvenile coho salmon declined after removal of wood debris in two Alaskan streams (Bryant, 1982). Murphy et al. (in press) found that CWD was a major determinant in winter survival of coho salmon, steelhead, and Dolly Varden trout populations in streams in southeast Alaska. Streams in clearcut reaches supported higher standing crops of young-of-the-year salmonids than streams with buffer strips or old-growth forests. However, streams with buffer strips contained significantly more yearling salmonids than streams flowing through clearcuts or old-growth forests; populations of yearling fish were lowest in streams in clearcuts. Populations of yearling salmonids were positively correlated with volumes of CWD. The blowdown of trees in the buffer strips provided an important source of debris that increased overwintering survival. Though summer growth was greatest in open reaches, winter habitat was a major limitation on survival to the next year class.

Clearcut streams may be more productive but over winter habitat is limiting

Influences of CWD on fish populations are not restricted to sheer volumes of debris. The architecture and position of wood accumulations control the functions of wood in stream ecosystems. Beschta (personal communication, Oregon State University, Corvallis, Oregon) examined pool formation by simulated logs in an artificial channel under various flow conditions. The position of the log in the water column had profound effects on the size of pool formed; a log located at the water surface at maximum discharge caused the formation of the largest pool, and logs resting on the streambed created the smallest pools.

Spatial distribution of wood is an important factor that influences the quality of fish habitat. Fish occupy three-dimensional space in the water column, and therefore the architectural arrangement of wood accumulations affects the potential use of that habitat. Little research has been completed on this aspect of fish habitat, but a recent study in streams in British Columbia found that fish abundance around wood debris increased as complexity of the accumulation increased (Forward, 1984). Intricate networks of logs, branches, roots, and small wood debris create a more complex, diverse array of cover and hydrologic features for fish populations.

Warmwater fishes are also positively related to CWD. Hachman (1975) sampled fish populations in five reaches of a small Missouri river, two of which had no snags and the rest with snags. Fish populations were 25% less, and fish of catchable size 51% less in the snagless sections. Some species such as catfish use crevices in logs as spawning sites, so cleaning and snaging of streams may also influence reproductive success (Marzolf, 1978; Funk and Robinson, 1974). Angermeier and Karr (1984) manipulated the abundance of woody debris in a small Illinois stream to determine its importance to fish. When a stream reach was divided along midchannel, and debris was added to one side, but removed from the other, fish and benthic invertebrates were usually more abundant on the side with woody debris than on the cleared side. Most large fish (age 2+) avoided reaches without debris, whereas some smaller fish (such as Johnny darter) preferred them. They felt that extensive removal of woody debris may disrupt structure and function of fish communities in small low-gradient streams.

Management of CWD Inputs to streams

As road building associated with logging operations extends even farther into steep country, the probability of channel-scouring debris torrents increases. Debris torrents, initiated by small landslides, move catastrophically down stream channels, severely eroding the streambed. These torrents routinely cause an abrupt release of stored sediment and organic debris, which eventually clumps into one spot, often scouring the upstream channel to bedrock. In one watershed in the Coast Ranges in Oregon, 30% of the first-order streams have been scoured to bedrock; and 60% of the second-order streams and 40% of the third-order streams have experienced debris torrents (Swanson and Lienkaemper, 1978). These torrents have scoured the channels and left large deposits of organic material and inorganic sediment where the gradient flattened to about 4% or the tributary entered a larger stream at an angle greater than 40°. More than 80% of these debris torrents were caused by logging activity or road failures (Swanson and Lienkaemper, 1978). Debris torrents can travel a kilometer or more and affect several stream orders, severely reducing the capability of the stream for dispersed retention of organic material. As a result, the most active zones of microbial and biological processing become clumped through-out the river basin instead of being more uniformly distributed throughout the drainage network. Streams in old-growth forests without recent torrents maintain a stair-step profile throughout the length of the stream. Streams experiencing debris torrents either have clumped depositional areas and a few large steps or have been sluiced out to the point that steps are provided only by bedrock outcrops (Sedell and Dahm, 1984).

Other common forestry practices reduce debris loading and storage relative to the undisturbed stream ecosystem. Thinning and harvest rotations of 60 to 100 years remove the future source of large debris, cutting off resupply. Growing demand for wood fiber also encourages the leaving of less forest residue and the exploitation of additional tree species (Triska and Cromack, 1980).

When putting wood back into streams, three aspects need to be considered: (1) what kind of woody structure is desirable, (2) where should it be placed in the basin; and (3) how much wood is enough.

There is no question that the complexity of wood accumulations in streams is important to wood associated fish populations. Accumulations of large and small pieces along with roots or root wads provide the most complex habitats and a several-fold increase in utilization over a single log (Forward, 1984). Donald Siedelman of Alaska Department of Fish and Wildlife, Ketchikan Alaska (personal communication) collected juvenile salmon from different habitat types in a large river. Coho and chinook salmon juveniles were 2-3 times more abundant in log jams composed of 2 or more downed trees than in a habitat formed by a single downed tree with attached root wad. Habitats formed by stumps were utilized by about 1/2 the juvenile salmonids found in habitats formed by single downed trees. Small accumulations of various sized pieces of wood provide the most complex and best utilized habitats in all sizes of rivers and streams.

may favor clumping of leave trees

Where would additions of debris in streams and rivers be most beneficial? In pristine intermediate to large streams and rivers, CWD accumulates in predictable places below tributary junctions, where the valley floor widens, at channel bends, and at geologic constrictions such as fault lines, canyons, or earth flows. Large streams or rivers redistribute CWD with each major freshet. The source area of trees for large rivers is primarily the flood plain forest which the river cuts into annually by lateral migration, from terraces where the river may cut through a forest stand during a high flood, and from large downed trees perched on gravel bars or along the edges of point bars or islands. Unlike the source areas of living trees which need a major flood to provide significant inputs, downed trees and stumps can change annually with smaller discharge events. Once downed trees form jams on bends or outer margins of the floodplain, the likelihood of transport back to the main channel is greatly diminished unless the river changes course. As mentioned earlier, such wood dominated edge habitat is very important for coho salmon and steelhead trout juveniles.

On smaller streams the source area of woody debris is all along the stream. Downed trees and parts of trees are more randomly distributed because small streams lack the power to bunch the wood. Even in 3rd to 4th order streams geologic constrictions and tributary junctions tend to be the major areas where wood and sediments accumulate. Rather than placing single pieces of wood, or cutting a tree for the stream anywhere a source tree is available, stream reaches in widened valley floors and areas below tributary junctions can be better enhanced by introduction of multiple trees in different configurations. Downed trees in bed rock areas may be an important device for storing needed spawning gravels. The important point is that reaches of streams which have wider than average channel and valley widths generally are often areas in pristine streams with the most diverse spawning and rearing habitats for the most fish species and age classes within a species.

A third consideration in using woody debris, or rather not removing it, is how much is enough? We should be able to find streams which are overloaded to the extent that fish populations are greatly diminished. For salmonids we have not yet found the end point. Numbers of large pieces of woody debris per 100 m of stream length vary for old growth or mature forests, second growth forests, and blow down buffer strips (Table 1). In

Table 1. Frequency of large pieces of woody debris per 100 m stream length in streams with drainage areas < 10 km^2 and in different forest conditions.

		Wood Debris Pieces per 100 m stream reach
Old growth or mature forest		
Mack Cr.	Oregon Cascades	22-28
Lookout Cr.	Oregon cascades	18-20
Lobster Cr.	Oregon Coast	18
Sheehan Cr.	Southeast Alaska	33-45
Cummins Cr.	Oregon Coast	20-23
S. Fork Hoh River tributaries	Olympic Penninsula Washington	18-20
Second Growth		
Knowles Cr.	Oregon Coast	1-3
Lobster Cr.	Oregon Coast	1-2
Fish Cr. (repeatedly salvaged)	Oregon Cascades	4-5
Blowndown Buffer Strip		
Sheehan Cr.	Southeast Alaska	135

Note

Sheehan Creek, Murphy *et al.* (in press) and Koski *et al.* (in this volume) found the best winter habitat for juvenile salmonids was found in a blowdown reach. This study is one of the very few which correlates woody debris with salmonid densities. Murphy *et al.* (in press) recommend designing buffer strips to provide debris to streams which have 30 to 150 trees (> 30 cm diameter) every 100 m along a stream. House and Boehne (in press) also found a direct relationship between summertime numbers of juvinel coho salmon and frequency of CWD in Tobe Cr. in the Oregon Coast range. Tschaplinski and Hartman (1983) found a direct correlation between volume of wood and juvenile coho wintering in Carnation Cr. At present we have not found out how much CWD is enough for maximum fish production. From Table 1 it is safe to say that streams flowing through second growth forests and recently harvested areas contain between 1/5 and 1/20 the number of large woody pieces found in streams in mature forests. This translates to a drastic reduction in salmonid habitat. From the few studies avilable, it appears that salmonid production could be enhanced several fold with a 5 to 20 fold increase in wood.

≤12"

The low end is ≅ 100% retention for our streams

We have a unique opportunity with current low stumpage prices for timber, and National Forests submitting 10 year management plans to incorporate plans to maintain wood inputs to streams that approximate natural levels present in mature forests. Such plans would halt habitat loss resulting from debris impoverishment.

Acknowledgements

Our sincere thanks to Judy Bufford for editing, bibliographic help, and ramroding the final edition. Marcy Liljberg maintained her efficiency and humor during the manuscript typing. Thanks to James D. Hall and Fred Everest for reviewing the manuscript. This is a contribution from NSF Riparian Grant No. DEB-8112455.

Literature Cited

Angermeier, P.L. and J.R. Karr. 1984. Relationships between woody debris and fish habitat in a small warmwater stream. Transactions of the American Fisheries Society 113(6):716-726.

Atkinson, S.W. 1971. BOD and toxicity of log leachates. M.S. Thesis, Oregon State Univ., Corvallis, Oregon. 58 pp.

Baker, C.P. 1979. The impacts of logjam removal on fish populations and stream habitat in western Oregon. Ph.D. Thesis, Oregon State Univ., Corvallis, Oregon. 86 pp.

Benda, L.E. In press. Behavior and effect of debris flows on streams in the Oregon coast range. Submitted to a symposium "Delineation of landslide, flash flood and debris flow hazards in Utah", June 14-15, 1984, Utah State Univ., Logan, Utah.

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

Bilby, R.E. 1981. Role of organic debris dams in regulating the export of dissolved and particulate matter from a forested watershed. Ecology 62(5):1234-1243.

Bilby, R.E. 1984. Post-logging removal of woody debris affects stream channel stability. J. For. 82(10):609-613.

Bisson, P.A. and J.R. Sedell. In press. Salmonid populations in logged an unlogged stream sections of western Washington. In: W.R. Meehan, T. Hanley and T.R. Merrill, editors. Proceedings of a Symposium on fish and wildlife relationships in old-growth forests, 1982 April 12-13, Juneau, Alaska. Am. Inst. Fish. Res. Biologists.

Bisson, P.A., J.L. Nielsen, R.A. Palmson, 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 editor. Proceedings of a symposium on, Acquisition and utilization of aquatic habitat inventory information. Portland, Oregon, October 28-30, 1981. Hagen Publishing, Billings. Montana.

Bjornn, T.C. 1971. Trout and salmon movements in two Idaho streams as related to temperature, food, streamflow, cover and population denisty. Trans. Am. Fish. Soc. 100:423-438.

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

Bryant, M.D. 1982. Organic debris in salmonid habitat in southeast Alaska: measurement and effects. Pages 259-265 in: N.B. Armantrout editor. Proceedings, Acquisition and utilization of aquatic habitat inventory information, October 28-30, 1981. Portland, Oregon.

Bryant, M.D. 1983. The role and management of woody debris in west coast Salmonid nursery streams. North Am. J. of Fish. Manag. 3:322-330.

Buchanan, D.V., P.S. Tate, and J.R. Moring. 1976. Acute toxicities of spruce and hemlock bark extracts to some estuarine organisms in southeastern Alaska. J. Fish. Res. Bd. Canada 33:1188-1192.

Bustard, D.R. and D.W. Narver. 1975a. Preferences of juvenile coho salmon (Oncorhynchus kisutch) and cutthroat trout (Salmo clarki) relative to simulated alteration of winter habitat. J. Fish. Res. Bd. Canada 32:681-687.

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

Chapman, D.W. and T.C. Bjornn. 1969. Distribution of salmonids in streams with special reference to food and feeding. Pages 153-176 in T.G. Northcote editor. Proceedings, Salmon and Trout in Streams, February 22-24. Univ. of British Columbia, Vancouver, B.C.

Elliot, S. 1978. Ecology of rearing fish. Alaska Dept. Fish and Game, Fed. Aid in Fish Rest., Juneau, Alaska, Ann. Rep., Proj. F-9-10, 19(D-I), 39-52.

Everest, F.H. and W.R. Meehan. 1981. Forest management and anadromous fish habitat productivity. Trans. North Am. Wildl. and Nat. Resourc. Conf. 46:521-530.

Everitt, B.L. 1968. Use of the cottonwood in an investigation of the recent history of a flood plain. Amer. J. Sci. 266:417-439.

Forward, C.D. 1984. Organic debris complexity and its effect on small scale distribution and abundance of coho (Oncorhynchus kisutch) fry populatins in Carnation Creek, British Columbia.. B.S.F. Thesis, Univ. of British Columbia, Vancouver, B.C. 48 pp. + appendices.

Hickman, G.D. 1975. Value of Instream Cover to the Fish Populations of Middle Fabius River, Missouri. Aquatic Series, No 14, Missouri Department of Conservation, Jefferson City, Missouri.

Hogan, D. In press. The influence of large organic debris on channel morphology in Queen Charlotte Island streams. In: Proceedings of the Western Division American Fisheries society, July 16-20, 1984. Victoria, B.C.

House, R. and P.L. Boehne. In press. The effects of instream structure on salmonid habitat and populations in Tobe Creek, Oregon. N. Amer. J. of Fisheries Management. 26 pp.

Hunt, R.L. 1971. Responses of a brook trout populations to habitat development in Lawrence Creek. Wisc. Dept. Nat. Resour. Tech. Bull. No 48. 35 pp.

Ice, G.G. 1978. Reaeration in a turbulent stream system. Ph.D. Thesis, Oregon State University, Corvallis, Oregon. 174 pp.

International Pacific Salmon Fisheries Commission. 1966. Effects of log driving on the salmon and trout populations in the Stellako River, Vancouver, British Columbia. Prog. Rep. 14, 88 pp.

June, J.A. 1981. Life history and habitat utilizatoin of cutthroat trout (Salmo clarki) in a headwater steram on the Olympic Peninsula, Washington. MS. Thesis, University of Washington, Seattle, Washington.

Keller, E.A. and F.J. Swanson. 1979. Effects of large organic material on channel form and fluvial processes. Earth Surf. 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. Pages 169-197 in D.D. Rhodes and G.P. Williams editors. Adjustments of the Fluvial System. 1979 Proceedings of the Tenth Annual Geomorphology Symposium. State Univ. N.Y., Binghamton, New York.

Keller, E.A., A. MacDonald, T. Tally and N.J. Merritt. In press. Effects of large organic debris on channel morphology and sediment storage in selected tributaries of Redwood Creek. In: Geomorphic Processes and Aquatic Habitat in the Redwood Creek Drainage Basin. U.S.G.S. Prof. Pap. Washington, D.C.

Leopold, L.B., M.G. Wolman and J.P. Miller. 1964. Fluvial Processes in Geomorphology, 522 pp. Freeman, San Francisco, Calif.

Lestelle, L.C. 1978. The effects of forest debris removal on a populations of resident cutthroat trout in a small headwater stream. M.S. Thesis, Univ. Washington, Seattle.

Lienkaemper, G.W. and F. Swanson. 1980. Changes in large organic debris in forested streams, western Oregon. Abstr. 76th Annu. Meet. Geol. Sci. Am. 12(3):116.

Lisle, T.E. and H.M. Kelsey. 1982. Effects of large roughness elements on the thalweg course and pool spacing. Pages 134-135 in L.B. Leopold editor. American Geomorphological Field Group Field Trip Guidebook. 1982 Conference, Pinedale, Wyo. Luna B. Leoplold, Berkeley, Calif.

Lister, D.B. and H.S. Genoe. 1979. Stream habitat utilization by cohabiting underyearlings of chinook (Oncorhynchus tshawytscha) and coho salmon (O. kisutch) in the Big Qualicum River, British Columbia. J. Fish. Res. Bd. Can. 27:1215-1224.

Lobeck, A.K. 1939. Geomorphology, 428 pp. McGraw-Hill Book Co., N.Y.

MacDonald, A. and E. Keller. 1983. Large organic debris and anadromous fish habitat in the Coastal Redwood Enviornment: the hydrologic system. Tech. Completion Rep., 48 pp. OWRT Project B-213-CAL, Water Resour. Cent., Univ. Calif., Davis. California.

McKernan, D.L., D.R. Johnson, and J.I. Hodges. 1950. Some factors influencing the trends of salmon populations in Oregon. Transactions of the 15th North American Wildlife Conference 1950:427-449.

Marston, R.A. 1982. The geomorphic significance of log steps in forest streams. Annu. Assoc. Am. Geogr. 72:99-108.

Marzolf, G.R. 1978. The potential effects of clearing and snagging on stream ecosystems. Report No. FWS/OBS-78/14, Office of Biological Service, Fish and Widlife Service, U.S. Department of the Interior, Washington, D.C.

Maser, C. and J.M. Trappe, tech. eds. 1984. The seen and unseen world of the fallen tree. U.S.D.A. For. Serv. Gen Tech. Rep. PNW-164, 56 pp. Pac. Northwest For. and Range Exp. Stn., Portland, Oregon.

Meehan, W.R., W.A. Farr, D.M. Bishop, and J.H. Patric. 1969. Some effects of clearcutting on salmon habitat on two southeastern Alaska streams. U.S.D.A. For. Serv., For. and Range Exp. Stn. Gen. Tech. Rep. PNW-82, 45 pp. Portland, Oregon.

Meehan, W.R., F.J. Swanson, and J.R. Sedell. 1977. Influences of riparian vegetation on aquatic ecosystems with particular references to salmonid fishes and their food supply. In: Importance, preservation and management of riparian habitat, a symposium. U.S.D.A. For. Serv., Gen. Tech. Rep. RM-43, 217 pp., Rocky Mt. For. and Range Exp. Stn., Fort Collins, Colorado.

Megahan, W.F. 1982. Channel sediment storage behind obstructions in forested drainage basins draining the granitic bedrock of the Idaho Batholith, pp. 114-121. In: F.J. Swanson, R.J. Janda, T. Dunne and D.N. Swanston (eds.). Sediment Budget and Routing in Forested Drainage Basins. U.S.D.A. For. Serv. Res. Pap. PNW-141. Pac. Northwest For. and Range Exp. Stn., Portland, Oregon.

Megahan, W.F. and R.A. Nowlin. 1976. Sediment storage in channels draining small forested watersheds in the mountains of central Idaho, pp. 4/115-4/126. In: Proceedings of the 3rd Federal Interagency Sedimentation Conference. Denver, Colo. Sedimentation Committee of Water Resources Council, Washington, D.C.

Murgatroyd, A.L. and J.L. Ternan. 1983. The impact of afforestation on stream bank erosion and channel form. Earth Surf. Processes and Landforms 8:357-369.

Mortensen, E. 1977. Density-dependent mortality of trout fry (Salmo trutta L.) and its relationship to the management of small streams. J. Fish. Biol. 11:613-617.

Murphy, M.L. and J.D. Hall. 1981. Varied effects of clear-cut logging on predators and their habitat in small streams of the Cascade Mountains, Oregon. Can. J. Fish. Aquat. Sci. 38:137-145.

Murphy, M.L., V.K. Koski, J. Heifetz, S.W. Johnson, D. Kirchhofer, and J.F. Thedinga. In press. Role of large organic debris as winter habitat for juvenile salmonids in Alaska streams. In proccedings of western division, Amer. Fish. Soc. July 16-20, 1984, Victoria, B.C.

Narver, D.W. 1971. Effects of logging debris on fish production. Pages 100-111 in J.T. Krygier and J.D. Hall editors. Proceedings, Forest Land Uses and Stream Environment, October 19-21, 1970, Oregon State Univ., Corvallis, Oregon.

Osborn, J.G. 1981. The effects of logging on cutthroat trout (Salmo clarki) in small headwater streams. Univ. Wash., Fish. Res. Inst. FRI-VW-8113, Seattle, Washington. 89 pp.

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

Peters, G.B., H.J. Dawson, B.F. Hrutfiord, R.R. Whitney. 1976. Aqueous leachate from western red cedar: effects on some aquatic organisms. J. Fish. Res. Bd. Can. 33:2073-2079.

Peterson, N.P. 1980. The role of spring ponds in the winter ecology and natural production of coho salmon (Oncorhynchus kisutch) on the Olympic Peninsula, Washington. M.S. Thesis, Univ. of Washington, Seattle, Washington. 96 pp.

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

Pfankuch, D.J. 1975. Stream reach inventory and channel stability evaluation. U.S.D.A. For. Serv., Northern Region (RI-75-002) 26 pp.

Ponce, S.L. 1974. The biochemical oxygen demand of finely divided logging debris in stream water. Water Resour. Res. 10:983-988.

Sedell, J.R. and C.N. Dahm. 1984. Catastrophic disturbances to stream ecosystems: volcanism and clear-cut logging. Pages 531-539 in M.J. Klug and C.A. Reddy editors. Current perspectives in microbial ecology. American Society for Microbiology, Washington, D.C.

Sedell, J.R., and J.L. Froggatt. In Press. Importance of streamside forests to large rivers: the isolation of the Willamette River, Oregon, U.S.A. from its floodplain. Verh. Int. Ver. Limnol. 22:

Sedell, J.R. and K.J. Luchessa. 1982. Using the historical record as an aid to salmonid habitat enhancement. Pages 210-223 in N.B. Armantrout editor. Proceedings, Acquisition and utilization of aquatic habitat inventory information. October 28-30, 1981, Portland, Oregon, West. Div. Am. Fish. Soc., Bethesda, Maryland.

Sedell, J.R. and F. Swanson. In press. Ecological characteristics of streams in old-growth forests of the Pacific Northwest. In W.R. Meehan, T. Hanley, and T.R. Merrill editors. Proceedings, Fish and Wildlife relationships on old-gorwth forests, 1982, April 12-13, Juneau, Alaska. Am. Inst. Fish Res. Biologists.

Sedell, J.R., F.H. Everest and F.J. Swanson. 1982. Fish habitat and streamside management: past and present. Pages 244-255 in Proceedings, Society of American Foresters, Annual Meeting, September 27-30, 1981, Soc. Am. For., Bethesda, Maryland.

Sedell, J.R., J.E. Yuska and R.W. Speaker. In press. Habitats and salmonid distribution in pristine sediment-rich river valley systems: S. Fork Hoh and Queets Rivers, Olympic National Park. In: W.R. Meehan, T. Hanley and T.R. Merrill editors. Proceedings, Fish and Wildlife relationships in old-growth forests, 1982 April 12-13, Juneau, Alaska, Am. Inst. Fish. Res. Biologists.

Servizi, J.A., D.W. Martens and R.W. Gordon. 1970. Effects of decaying bark on incubating salmon eggs. Int. Pac. Salmon Fish. Comm. Prog. Rep. 24, 28 pp.

Swanson, F.J. and G.W. Lienkaemper. 1978. Physical consequences of large organic debris in Pacific Northwest streams. U.S.D.A. For. Serv. Gen. Tech. Rep. PNW-69, 12 pp. Pac. Northwest For. and Range Exp. Stn., Portland, Oreg.

Swanson, F.J. and G.W. Lienkaemper. 1982. Interactions among fluvial processes, forest vegetation, and aquatic ecosystems, South Fork Hoh River, Olympic National Park, pp. 30-34. In: J.F. Franklin, E.E. Starkey and J.W. Matthews (eds.). Ecological Research in National Parks of the Pacific Northwest. Oreg. State Univ., For. Res. Lab., Corvallis.

Swanson, F.J., G.W. Lienkaemper and J.R. Sedell. 1976. History, physical effects, and management implications of large organic debris in western Oregon streams. U.S.D.A. For. Serv. Gen. Tech. Rep. PNW-56, 15 pp. Pac. Northwest For. and Range Exp. Stn., Portland, Oregon.

Tarzewell, C.M. 1936. Experimental evidence on the value of trout stream improvement in Michigan. Trans. Am. Fish. Soc. 66:177-187.

Toews, D.A.A. and M.K. Moore. 1982. The effects of streamside logging on large organic debris in Carnation Creek. Land Manage. Rep. 11: 29 pp. Prov. B.C., Min. For., Vancouver, B.C.

Triska, F.J. In Press. Role of wood debris in modifying channel geomorphology and riparian habitats of a large lowland river under pristine conditions: a historical case study. Verh. Int. Ver. Limnol. 22:

Triska, F.J. and K. Cromack, Jr. 1980. The role of wood debris in forests and streams. Pages 171-190 in R.H. Waring editor. Forests: fresh perspectives from ecosystem analysis. Proceedings 40th Biology Colloquium. Oregon State University Press, Corvallis, Oregon.

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 of overwinter survival. Can. J. Fish. Aquat. Sci. 40:452-461.

Wilzbach, Margaret. 1985. Prey abundance overrides cover in determining abundance of cutthroat trout in an Oregon Cascade stream. Unpublished Ph.D. Thesis, Oregeon State University, Corvallis, Oregon.

Zimmerman, R.C., J.R. Goodlett and G.H. Comer. 1967. The influence of vegetation on channel form of small streams. Pages 255-275 in Symposium on River Morphology. Int. Assoc. Sci. Hydrol. Publ. 75.