THE GEOMORPHIC AND ECOLOGICAL INFLUENCE OF LARGE WOODY DEBRIS IN STREAMS AND RIVERS

by

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Abstract. Large pieces of wood, such as logs, stumps, and large branches are an important ecological component of streams flowing through coast redwood (*Sequoia sempervirens*) forests of Northern California. The distribution and abundance, geomorphic role, and ecological role of large woody debris (LWD) vary through the channel network. This review summarizes pertinent literature and describes how the physical and ecological characteristics of wood change from small to large streams. Streamside and in-channel management practices influence LWD recruitment and transport processes, and significantly alter its functions. Management decisions can be better defined through a process-based classification that describes the influence of wood through the channel network.

Introduction

Logs, stumps, and branches that enter and are transported by rivers and streams are important influences on channel morphology and aquatic ecology. Large woody debris (LWD), generally defined as wood ≥ 10 cm diameter and ≥ 1 m length, obstructs streamflow, stores and distributes sediment, and creates channel features, such as pools, riffles, and waterfalls. Wood intercepts organic matter traveling downstream, allowing this material to be processed by instream organisms. Macroinvertebrates and fish occupy and use pools and riffles as habitat, and sediment deposition provides sites for riparian forest regeneration.

The ecological importance of wood is not limited to the instream environment. On the forest floor, woody debris is both a nutrient source and a habitat element for plants, insects, and vertebrates. In estuaries and near shore ocean environments, LWD provides nursery habitat, protection, and a nutrient source for various organisms. Reviews by Harmon et al. (1986), Sedell et al. (1988), and Triska and Cromack (1980) thoroughly treat these topics.

This review focuses on the instream geomorphic and ecological roles of LWD, highlighting effects occurring at the reach level and basin-wide along the channel network from headwaters to large rivers. When possible, the examples are drawn from redwood (*Sequoia sempervirens*) ecosystems. However, since such examples do not exist for every situation, studies from other systems are used to demonstrate basic concepts, while recognizing possible local differences.

This literature survey is divided into six general subject areas: 1) characteristics, distribution, and transport of LWD, 2) LWD and channel morphology; 3) LWD and stream ecology; 4) management impacts on LWD; 5) synthesis and a proposal for stream classification and; 6) management recommendations. The first section examines regional LWD loading, general trends of log size through the stream network, and the influences and mechanisms of LWD transport. Section two discusses the influence of LWD on sediment storage, channel dimension and stability, and basin-wide effects of wood on pool formation. Section three explores how wood affects nutrient retention, the distribution of macroinvertebrates and salmonids, and the presence of riparian forest patches. The fourth section looks at how timber harvest, flood control, and road maintenance affect the distribution and abundance of instream LWD. The fifth section includes a synthesis of the morphological and ecological effects occurring throughout the channel network. This synthesis results in a proposed designation of LWD influence zones based on channel size and gradient. The last section provides a discussion on how timber harvest and road maintenance may be modified to accommodate LWD input and transport.

In the course of preparing this review, all available literature concerning LWD in stream systems, regardless of geographic location, was consulted. A listing and summary of interesting results from all studies is contained in the appendix (Tables A-1 through A-13).

Characteristics, Distribution, and Transport of LWD

LWD loading and distribution. Large woody debris loading refers to the weight or volume of wood per square meter of stream channel (kg/m^2 or m^3/m^2). Along the Pacific Coast, streams flowing through the redwood forests of Northern California exhibit the highest levels of instream wood loading (Table 1, Harmon et al. 1986, Bilby and Bisson 1998). Massive redwood logs contribute huge amounts of biomass to stream channels, and in some reaches loading is dominated by a single piece of woody debris (Tally 1980). LWD loading generally decreases as one moves to more northern forests, with southeastern Alaska streams that flow through sitka spruce forests (*Picea sitchensis*) displaying the lowest abundance of instream wood (Table 1, Bilby and Bisson 1998). When compared with other regions across North America, forests of the Pacific Coast have the greatest levels of terrestrial and aquatic woody debris (Harmon et al. 1986).

Table 1. Loading of LWD (m^3/m^2) in streams flowing through unmanaged forests along the Pacific Coast from Northern California to Southeastern Alaska. Loading is greatest in coast redwood (*Sequoia sempervirens*) systems of Northern California and generally decreases as one moves to more northern forests.

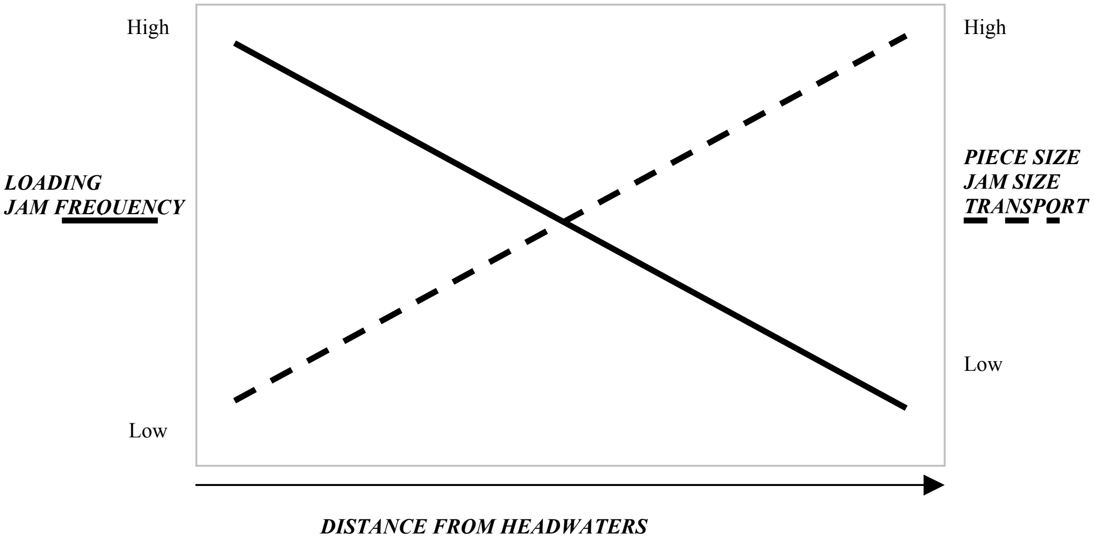
LOCATION	FOREST TYPE	LOADING	REFERENCE
Alaska	• Sitka spruce (*Picea sitchensis*), western hemlock (*Tsuga heterophylla*),	• 0.019 m^3/m^2	Harmon et al. 1986
Alaska	• Sitka spruce (*Picea sitchensis*), western hemlock (*Tsuga heterophylla*), red alder (*Alnus rubra*)	• 0.061 m^3/m^2	Robison and Beschta 1990
British Columbia, Canada	• Sitka spruce (*Picea sitchensis*), western hemlock (*Tsuga heterophylla*)	• 0.068 m^3/m^2	Harmon et al. 1986
Oregon	• Douglas fir (*Pseudotsuga menziesii*)	• 0.057 m^3/m^2	Harmon et al. 1986
Northern California	• Douglas fir (*Pseudotsuga menziesii*)	• 0.028 m^3/m^2	Harmon et al. 1986
Northern California	• Coast Redwood (*Sequoia sempervirens*)	• 0.155 m^3/m^2	Harmon et al. 1986
Northern California	• Coast redwood (*Sequoia sempervirens*)	• 0.181 m^3/m^2	Keller and MacDonald 1983

Within a stream network, the abundance and distribution of LWD is strongly influenced by channel size and dominant input mechanism (Bilby and Ward 1989, Beechie and Sibley 1997). Debris loading is greatest in low order streams (smallest) and generally decreases in the downstream direction (Figure 1, Keller and Swanson 1979, Keller et al. 1985, Lienkaemper and Swanson 1987, Robison and Beschta 1990, Montgomery et al. 1995). Narrow, low order channels lack the streamflow necessary to transport and redistribute most fallen logs (Swanson and Lienkaemper 1978). Wood enters through windthrow, bank erosion, and mass wasting, and unless transported by debris torrents or flood flows, remains randomly distributed in the channel (Table 2, Swanson et al. 1976, Keller and Swanson 1979). Logs may remain stationary for long periods of time (greater than 200 years in some cases), but will eventually leave through transport, or decay from decomposition and physical abrasion (Tally 1980, Harmon et al. 1986, Murphy and Koski 1989).

Table 2. The distribution and mechanisms of LWD input and transport from low to high order streams. Jams range from randomly oriented single pieces to large, clumped accumulations within the stream and on bars and floodplains. In small streams, wood enters and moves along the stream primarily during heavy storms, which trigger landslides and provide adequate flow to transport logs. In larger streams and rivers, LWD mobility increases, leaving wood in distinct jams in the water or on bars.

	LOW ORDERS	INTERMEDIATE ORDERS	HIGH ORDERS
DISTRIBUTION	• Random • Single piece	• Clumped in jams within streams	• Clumped in jams on bars and floodplains
INPUT MECHANISMS	• Windthrow • Bank erosion • Mass Wasting	• Windthrow • Bank erosion • Fluvial transport	• Bank erosion • Fluvial transport
TRANSPORT MECHANISMS	• Debris flows • Flood flows	• Flotation	• Flotation

Figure 1. Schematic representation of the general trend of LWD characteristics along the channel network. Debris loading and jam frequency is highest in small, low order streams and generally decreases in higher orders. The piece size, jam size, and transport tend to increase along the same gradient. The relationship shows that small channels contain more wood per channel area than large channels, but larger channels have a greater capacity to transport and redistribute LWD pieces.



Intermediate order channels are wide and deep enough to move and redistribute in-channel wood (Swanson and Lienkaemper 1978, Bilby and Ward 1989). The main input mechanisms are windthrow, bank erosion, and fluvial transport from upstream reaches (Table 2, Keller and Swanson 1979). Wood accumulates within the channel or on meander bends in irregularly spaced but distinct jams that have profound influence on stream morphology and ecology (Fetherston et al. 1995, Abbe and Montgomery 1996, Hogan et al. 1998). Jam frequency (number of jams per meter) decreases as channels become larger and are more able to transport wood, while at the same time the size of LWD jams increases (Keller and Tally 1979, Bisson et al. 1987). The trend of increasing LWD jam size down the channel network runs counter to the trend of decreasing LWD loading, however, both are a consequence of the increasing capacity of streams to transport wood (Figure 1).

In high order streams, most wood enters through bank undercutting and fluvial transport. The wood deposits on gravel bars or terraces along the river margin (Table 2, Keller and

Swanson 1979, Bisson et al. 1987). Wood collecting on bars or islands is frequently out of contact with the low flow channel and may have a limited effect on channel morphology (Keller and Swanson 1979). Fluvially deposited LWD still provides important ecological services for salmonids, such as escape cover, and for riparian forest development (Harmon et al. 1986, Fetherston et al. 1995). In low gradient rivers and streams, channel width and sinuosity are main factors controlling the abundance and distribution of LWD accumulations (Nakamura and Swanson 1994). Wide, unconstrained reaches bordered by floodplains and terraces possess abundant storage and depositional sites for transported logs. Reaches flowing through wide valleys develop secondary channels at the base of terraces and along valley walls that trap wood mobilized during large floods. The mouths of secondary channels may be significant LWD storage sites (Swanson and Lienkaemper 1979, Nakamura and Swanson 1994). Constrained reaches have less extensive floodplain and valley regions and are thus less able to accumulate LWD. Another factor contributing to greater abundance of LWD in sinuous channels is riparian forest development. Riparian forests develop on floodplains and terraces, providing a direct source of wood to stream channels (Lienkaemper and Swanson 1979, Nakamura and Swanson 1994). Confined channels also have a greater capacity to transport wood downstream during high flows (Keller and Swanson 1979).

LWD size and volume. As LWD loading decreases down the channel network, the average size (length and diameter) and volume of instream wood increases (Figure 1, Bilby and Ward 1989, 1991). Channel width is a dominant influence on measures of LWD loading, as it is directly related to channel area (Beechie and Sibley 1997). Low order streams have small channel area and a low capacity to transport in-channel wood, leading to high debris loads. Channel width also controls the average size of wood in streams (Bilby and Ward 1989, 1991, Robison and Beschta 1990). Stable pieces of wood remain stationary during normal to high flows. As channels become wider and deeper, the average size of a stable piece of wood increases. Pieces shorter than bankfull width and with a diameter less than bankfull depth are more likely to be transported out of a reach by streamflow (Bilby 1984, Braudrick et al. 1997). In progressively larger channels, a larger proportion of small pieces is removed, leading to a greater average size of in-channel LWD (Bisson et al. 1987, Bilby and Ward 1989).

Influences on LWD transport. The stability of LWD depends on the physical characteristics of the piece and piece orientation within the channel. Log length and diameter are major controls on the movement of wood in rivers and streams (Swanson et al. 1976, Bilby 1984, Nakamura and Swanson 1994). Most transported pieces are shorter than bankfull width, indicating that length may be a rough estimate of wood susceptibility to transport (Bilby 1984, Lienkaemper and Swanson 1987, Nakamura and Swanson 1994). Shorter pieces move more easily than longer pieces, as they encounter fewer instream obstructions and have less contact with bank regions, leaving fewer opportunities for pieces to deposit and accumulate (Bilby 1984). In low to intermediate order streams (3 m to 25 m bankfull width), Lienkaemper and Swanson (1987) found that all transported pieces travelling more than 10 m were shorter than bankfull width. Nakamura and Swanson (1994) also observed that most transported pieces were shorter than bankfull width, while 20% of un-transported pieces were longer than bankfull width. Rootwads increase the stability of logs by increasing the surface area available for snagging on instream obstructions and potentially increasing log diameter to greater than the average bankfull depth (Sedell et al. 1988).

Log position influences the degree to which a piece is exposed to streamflow and potentially transported. Important positional factors contributing to the stability of in-channel wood are the percent of the piece anchored to the bank, the proportion of the piece in the water, and the angle of orientation to flow (Bryant 1983). Burial of one end in the streambed or along the banks reduces piece exposure to streamflow and significantly increases LWD stability. Pieces buried at both ends are extremely stable and may remain in place for decades (Bilby 1984). Increased stability also results when LWD only partially resides in the stream, with one end either buried or simply resting above the bankfull channel.

Within the channel, pieces oriented increasingly perpendicular to flow are transported more easily than pieces oriented in a downstream direction (Bryant 1983). Bryant (1983) observed a southeastern Alaska stream and developed criteria that identified the most stable pieces of wood as those with 70% of their mass anchored to the stream bank, 15% of their mass touching the water, both ends buried, and oriented 30 degrees to flow. However, precise relationships between physical characteristics, piece orientation, and wood transport are yet to be established. Braudrick and Grant (2000) performed flume experiments with pieces shorter than bankfull width and found that orientation to flow, presence of a rootwad, log density, and log diameter were the most influential factors in LWD transport. Braudrick et al. (1997) simulated wood movement through a system, using flume experiments, and observed three distinct transport regimes based on the degree of piece congestion. The transport regime depended on the rate of log input compared to stream discharge. The results showed that low order channels with high rates of wood input and relatively low discharge have a congested transport regime, while high order channels with low wood input rates and greater discharge are uncongested.

LWD transport mechanisms. The mechanisms of wood transport vary down the stream network with respect to channel size (Table 2, Keller and Swanson 1979). Small, steep, low order tributaries primarily move wood through debris torrents triggered during heavy rainfall and flood flows (Swanson et al. 1976, Keller and Swanson 1979, Nakamura and Swanson 1993). Debris flows usually originate in 1st and 2nd order channels with bank slopes that exceed 50%; torrents are rare in intermediate order streams with moderately sloping banks (Swanson et al. 1976, Swanson and Lienkaemper 1978). Torrents bring material from hillslopes into stream channels, transporting logs and sediment short distances to form large accumulations, or transport wood and sediment over longer distances to be deposited in lower gradient reaches (Keller and Swanson 1979). In some cases, debris flows scour existing in-channel debris and sediment, leaving a bedrock channel that is devoid of complexity (Swanson et al. 1976, Swanson and Lienkaemper 1978). In intermediate to high order channels, flotation is the main transport mechanism. Flotation of logs occurs infrequently in small channels, mainly during unusually high flows that also trigger debris torrents (Swanson et al. 1976, Singer and Swanson 1983). The transport of wood during elevated flows is most common in larger streams, and is an important LWD recruitment mechanism in reaches that have relatively low input of trees from the adjacent riparian forest (Keller and Swanson 1979).

LWD and Channel Morphology

Sediment storage. Logs and stumps deflect streamflow, creating low energy environments that encourage the deposition of sediment upstream of the obstruction (Lisle 1986b). Anchored or attached pieces can protect and strengthen streambanks, which serves to reduce rates of bank erosion and sediment delivery into the channel (Keller and Swanson 1979). LWD obstructions create sediment storage sites that buffer the movement of bedload sediment through a system. In low order streams, in-channel LWD produces open storage sites that collect and store sediment during high flows (Keller et al. 1985). The storage capacity of these LWD-created sites can be quite large. Tally (1980) estimated that wood stored 200 years worth of bedload in undisturbed reaches flowing through Redwood National Park, with space for another 100 years worth of sediment yield. In the Oregon Coast Ranges, Swanson et al. (1976) estimated that the sediment yield of forested streams was less than 10% of the material in storage, and found that in one 100 m section of stream, wood trapped and stored 230m^3 of sediment. The storage capacity of LWD has also been observed in Idaho batholith streams, where logs accounted for 34% of channel obstructions and 50% of sediment storage (Megahan 1982).

The displacement or removal of log steps significantly increases sediment transport out of low order stream reaches. Removal of wood from streams reduces the amount of available storage sites and decreases streambed roughness, leading to higher rates of sediment transport. Winter high flows transported 5000m^3 of sediment out of a 250 m stream reach in western Washington after Beschta (1979) experimentally removed all pieces of in-channel wood. Bilby (1981) removed wood from a New Hampshire stream and saw a 500% increase in sediment export over the next year. In steep mountain reaches, log steps are a natural influence on hydraulic geometry and play an important role in channel slope adjustment (Swanson et al. 1976, Keller and Swanson 1979, Tally 1980, Heede 1985a, b). Log steps removed from an Arizona stream were eventually replaced by gravel bars, which assumed control over the drop in elevation (Heede 1985a,b). Increased bedload movement of coarse sediment was required to offset the removal of naturally occurring log steps.

The relative contribution of LWD obstructions to sediment storage decreases down the stream network (Figure 2, Table 3). In channels <7 m wide, Bilby and Ward (1989) found that 40% of debris pieces were associated with sediment accumulations. An examination of progressively wider streams (with decreasing gradient) revealed that <30% of debris pieces in channels between 7 m to 10 m, and <20% of debris pieces in channels >10 m were associated with sediment accumulations. Thus, in high gradient reaches, LWD obstructions have a greater role in bedload storage and in controlling the release of sediment (Nakamura and Swanson 1993). Logs are the primary structural component in the formation of step pools that dissipate stream energy, forming low energy depositional sites just upstream of the created waterfall and on the margins of the resulting plunge pool (Heede 1972, Bilby and Bisson 1998).

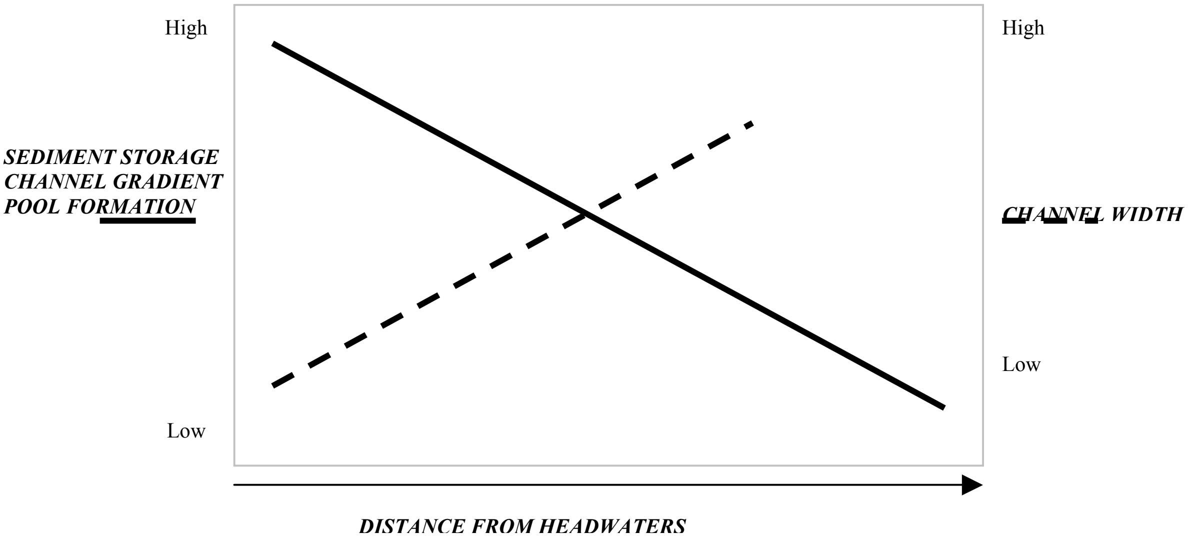
Table 3. The predominant storage sites and pool types associated with LWD from low to high order streams. Step pools form in small channels and accumulate sediment just upstream of the obstruction. In wider streams, accumulations obstruct flow and create low energy depositional environments downstream. Large rivers accumulate sediment in hydraulically formed floodplains and gravel bars.

	LOW ORDERS	INTERMEDIATE ORDERS	HIGH ORDERS
STORAGE SITES	• Upstream of log steps	• Downstream of single pieces and log steps	• Floodplains and gravel bars
POOL TYPES	• Step pools	• LWD formed lateral scour	• Hydraulically formed lateral scour

Narrow, low order streams often lack significant floodplains and gravel bars, which are important sediment storage sites for intermediate to high orders. In wider streams and large rivers, obstructions create zones of locally high shear stress and a low energy depositional site just downstream (Table 3, Lisle 1986b, Fetherston et al. 1995, Abbe and Montgomery 1996). These channel margin gravel bars and mid-channel islands accumulate additional LWD and sediment, allowing surfaces to build in elevation. The surfaces are sites for riparian regeneration and forest development, further stabilizing the accumulated sediment (Fetherston et al. 1995, Abbe and Montgomery 1996).

In low gradient reaches, wood has a limited effect over sediment accumulation and transport, mainly providing temporary storage (Figure 2, Table 3, Nakamura and Swanson 1993). Large woody debris may actually limit sediment storage by influencing and retarding floodplain and bar development (Smith et al. 1993b). LWD deflects the channel thalweg, resulting in irregular wood controlled lateral scour and increased local sediment export (Smith et al. 1993b, Nakamura and Swanson 1993). After removing log obstructions from a southeastern Alaska stream, Smith et al. (1993b) observed that streamflow initially mobilized sediment causing an increase in net sediment yield. After the channel re-adjusted, the loss of turbulence and increased resistance associated with bar formation resulted in a more regular sequence of bars that stored greater amounts of sediment.

Figure 2. Schematic representation of the general trend of the effects of LWD on channel morphology along the stream network. The sediment storage capacity, influence on channel gradient, and influence on pool formation is greatest in small streams and decreases in higher orders. The influence of LWD on channel width increases along the same gradient, but has a limited effect on the width of large rivers.



Channel dimension. The presence of LWD influences local channel gradient and channel width. In low orders, logs form steps that create waterfalls where the stream abruptly drops in elevation. The presence of steps and waterfalls dissipates stream energy, making the stream less able to transport sediment (Heede 1985a, b). Step forming LWD accounts for 30% to 80% of the elevation drop in moderate to steep gradient streams along the coasts of Northern California and Oregon (Swanson et al. 1976, Keller and Swanson 1979, Keller and Tally 1979). As channel gradient decreases, and channels widen, fewer pieces of wood are able to span the channel and form steps, decreasing the occurrence of waterfalls and lessening the control LWD has on elevation (Figure 2, Keller et al. 1985, Bilby and Ward 1989). In very steep reaches, however, wood may rest on top of large boulders and have a limited effect on sediment storage, waterfall formation, and gradient control (Keller and Tally 1979).

LWD increases local channel width in streams not confined by bedrock (Figure 2, Swanson et al. 1976, Bryant 1980, 1983). Sediment deposits upstream of wood accumulations, or downstream of wood accumulations in low gradient reaches, widen and decrease channel depth (Keller and Swanson 1979). Partially spanning fallen trees deflect the thalweg laterally, causing the stream current to diverge and widen the stream channel (Bisson et al. 1987). In moderate to low gradient streams along the Pacific Coast, studies show that the scour around single pieces of wood and large jams widens the channel by 50% to 200% over average bankfull width (Keller et al. 1985, Keller and Swanson 1979, Bryant 1980, 1983, Nakamura and Swanson 1993). In low gradient southeastern Alaska streams, Robison and Beschta (1990) found that the difference in average bankfull width between streams was best explained by the volume of LWD per 100 m of channel in study reaches. Streams with the greatest volume of wood along their length were the widest.

In low to intermediate orders, large jams of wood have the greatest overall influence on channel morphology, while individual pieces influence the bed between jams (Hogan et al. 1998). LWD jams are initiated by the presence of key pieces that are of sufficient length and width to trap transported logs. Jams persist for many years, and as they age, channel morphology increases in complexity (Hogan et al. 1998). After formation, sediment accumulates upstream of the jam, initially resulting in a less complex, sediment laden channel. As wood ages and decays, the porosity of the jam increases, creating differential scour and diverse channel forms that become more complex as the jam further deteriorates. Old growth forests have relatively low rates of jam formation, thus jams of varying age, and a complex channel morphology. Harvested or disturbed basins have accelerated rates of jam formation, thus jam age is less varied, leading to a less complex channel morphology (Hogan et al. 1998). Local stream gradients upstream of reaches controlled by key-LWD or LWD jams are lower than channel averages, contributing to a stepped profile, and local channel widths upstream of key-LWD of LWD jams can be significantly greater (Nakamura and Swanson 1993).

Influence on channel stability. LWD stabilizes channels by dissipating stream energy, armoring stream banks, and creating sites of local scour and fill (Keller and Swanson 1979). In low order streams, log steps create cascades, which reduce available energy by increasing channel roughness and leave less energy to erode and scour bed and banks (Heede 1985a, b). Steps are a major control on bank stability, and removal or reduction in size and abundance of these features through management or timber harvest can destabilize channels (Beschta 1979, Adenlof and Wohl 1994). After removing log steps from reaches in low to intermediate sized streams, Beschta (1979) and Bilby (1984) observed severe erosion that completely modified the stream channel through scour and fill. In low gradient alluvial reaches, wood and boulder obstructions act to stabilize the location of pools and bars during high flow (Lisle 1986b). The obstructions create backwater eddies, which are low energy depositional sites that reduce local shear stress and stabilize bed material (Smith et al. 1993a, b).

LWD also contributes to channel instability. Logs divert streamflow and force lateral cutting in streams with minimal bedrock influence (Keller and Swanson 1979, Swanson and Lienkaemper 1979). Lateral stream erosion leads to bank undercutting and eventual slumping into the channel. In streams impacted by debris flows, wood and sediment accumulations divert flow against adjacent steep banks and can initiate failure of the affected hillslope (Swanson et al. 1976). Wood carried by flood flows reduces bank cohesion by battering low banks and severely abrading streamside vegetation (Swanson and Lienkaemper 1979). In high orders, large jams commonly induce channel migration and cause major changes in streambed topography (Hickin 1984, Nakamura and Swanson 1993).

Influence on pool formation. In step-pool and plane bedded (steep to moderate gradient) stream reaches, wood obstructions are the primary element in pool formation (Figure 2, Montgomery et al. 1995, Abbe and Montgomery 1996, Beechie and Sibley 1997, Montgomery and Buffington 1997). Step-pool and plane bedded reaches are found in steep to moderate gradients, and studies along the Pacific Coast show that 20% to 80% of pools are formed in association with LWD (Lisle 1986b, Andrus et al. 1988, Carlson et al. 1990, Robison and Beschta 1990, Nakamura and Swanson 1994, Montgomery et al. 1995, Wood-Smith and Buffington 1996, Montgomery and Buffington 1997).

In narrow, steep gradient streams, a large proportion of fallen logs fully span the channel and obstruct streamflow to form cascades and plunge pools (Table 3, Bilby and Ward 1989, 1991, Robison and Beschta 1990, Richmond and Fausch 1995). Other instream obstructions, such as boulders, are active in the formation of cascades and plunge pools, but wood exerts the greatest control over pool creation (Keller and Swanson 1979).

In wider, low gradient streams, fewer logs are able to span the channel, so most pieces extend partway across and are oriented diagonal to flow (Gregory et al. 1993, Richmond and Fausch 1995). Scour pools form adjacent to partially spanning pieces, as streamflow is forced under and around obstructions. Dominant pool types shift from step-pools to scour pools down the channel network from step-pool to plane bedded reaches (Table 3, Bilby and Ward 1989, 1991, Robison and Beschta 1990, Richmond and Fausch 1995). Bilby and Ward (1989) surveyed western Washington streams and found that plunge pools were the most common (40%) pool type in streams <7 m bankfull width, while scour pools were the most common (60%) pool types in stream >10 m bankfull width. Bilby and Ward (1991) witnessed the same general shift in pool types among both logged and undisturbed basins.

Further down the channel network, in pool-riffle reaches, the interaction between streamflow and sediment transport is the most important element in pool formation (Leopold et al. 1964, Montgomery and Buffington 1997). The presence of wood has a lesser effect on pool formation and the frequency of LWD associated pools generally decreases with increasing channel width (Bilby and Ward 1991). In stream gradients ranging from 0.01 to 0.05, Montgomery et al. (1995) and Beechie and Sibley (1997) found a strong relationship between the number of pools and LWD loading, while in stream gradients <0.01 to <0.02 the relationship was significantly weaker. Smith et al. (1993a, b) removed wood from a low gradient southeastern Alaska stream and found that pool spacing was similar before and after. The results indicate that in low gradient rivers and streams, hydraulic factors rather than channel obstructions exert a greater control over the formation of pools (Swanson and Lienkaemper 1978, Montgomery et al. 1995, Beechie and Sibley 1997). In very large rivers, most wood deposits in the active channel on bars, islands, or in secondary channels, out of contact with the low flow water surface (Piegay et al. 1999). In these cases, pool formation in the main channel may be independent of LWD presence, but wood along shallow channel margins or in small secondary channels does create pools that are important refuge for salmonids (Bisson et al. 1987).

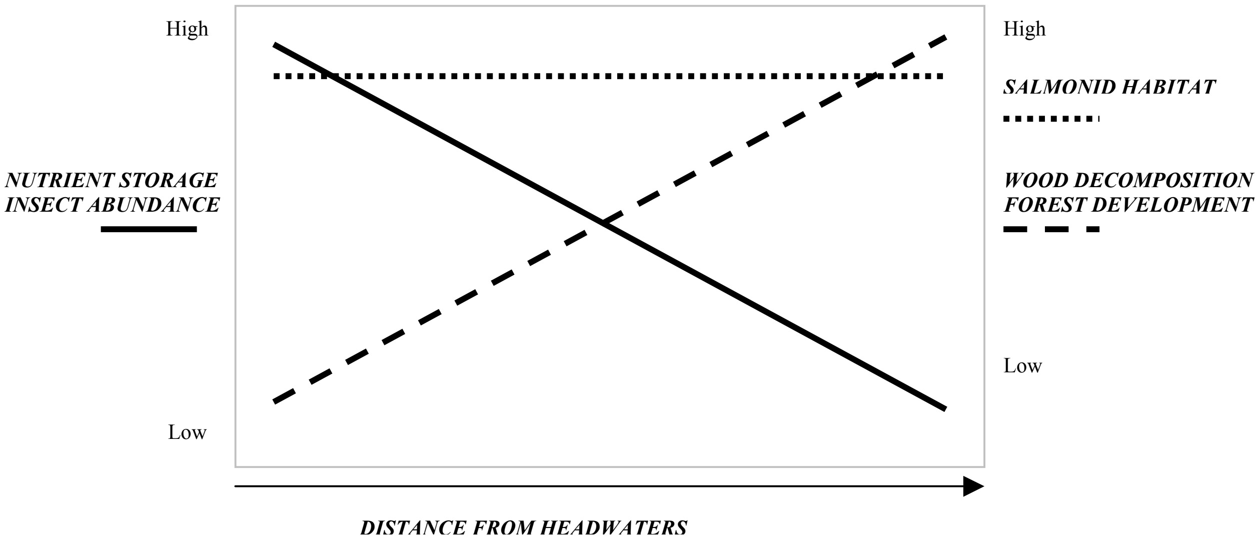
LWD and Stream Ecology

Nutrient dynamics. Allochthonous material from the riparian forest is a primary energy source for undisturbed rivers and streams (Gregory et al. 1991). Wood obstructions potentially store large amounts of externally derived organic matter (Figure 3). In Rocky Mountain streams of various successional stages, Trotter (1990) found that reaches with LWD stored twice as much organic matter as reaches where wood was experimentally removed. Bilby and Likens (1980) removed LWD from a low order stream in New

Hampshire and observed significant increases in the export of dissolved organic carbon (18% increase), fine particulate organic matter (<1mm; 638% increase), and coarse particulate organic matter (>1mm; 138% increase). During high discharges, the same reaches showed a 500% increase in the export of fine particulate organic matter and coarse particulate organic matter (Bilby 1981).

Salmon carcasses are an important source of organic matter for stream systems (Cederholm and Petersen 1985, Cederholm et al. 1989). In western Washington streams, twenty-two species of mammals and birds were found to consume coho salmon (*Oncorhynchus kisutch*) carcasses (Cederholm et al. 1989). Woody debris plays an important role in making nutrients from dead fish available by preventing the rapid transport of carcasses downstream. Cederholm and Petersen (1985) found a positive relationship between LWD loading and the number of retained coho salmon carcasses. Branches and logs physically obstruct the movement of dead fish, and the distance a carcass drifted downstream in a controlled release experiment was inversely related to the amount of LWD. In a separate experiment, pools were the most common carcass deposition sites and most pools that retained dead fish were formed by LWD (Cederholm et al. 1989).

Figure 3. Schematic representation of the general trend of the effects of LWD on stream ecology down channel network. Wood-associated nutrient storage and insect abundance is highest in small, low order streams and generally decreases in higher orders. The importance of LWD for salmonid habitat is equally important throughout the basin, although the role of wood varies. Wood decomposes more quickly in the terrestrial environment, and hence more quickly in higher orders where LWD frequently resides partway or completely out of the channel. The influence of LWD on riparian forest development decreases with increasing channel confinement that reduces active floodplain area.



Accumulations of organic matter behind log debris dams are sites for the uptake of nutrients. The sediment associated with LWD is high in organic matter content and maintains locally elevated respiration rates. Hedin (1990) found that community respiration was three times higher in sediment behind log debris dams than elsewhere on the streambed. As an attachment substrate for microorganisms that uptake nutrients, wood debris is active in nitrogen and phosphorous removal (Aumen et al. 1990).

Wood is a potential nutrient source for stream ecosystems. Logs contribute fine particulate organic matter through macroinvertebrate processing and physical abrasion. In streams with high debris loads, logs are a greater source of fine particulate organic matter than leaves or pine needles (Ward and Aumen 1986). The physical production of fine particulate organic matter is greatest in winter, when logs are shattered by high flow and through collisions with mobilized substrate.

The decomposition of wood into basic nutrient forms occurs very slowly in water (Sedell et al. 1988). Fungi and macroinvertebrate decomposers require an aerobic environment, but waterlogging prevents the deep penetration of oxygen into the wood interior. Pieces partly submerged beneath the water surface show variable rates of decomposition, with sections exposed to air breaking down more rapidly. In small streams that are shallow and narrow, wood is partly or completely submerged only during the high flows of winter and spring. Wood decomposition rates may be much more rapid in the summer, when pieces are exposed to air (Sedell et al. 1988). Intermediate stream orders are wide and deep enough to submerge logs during high and low flow periods, and may have relatively slow wood decomposition rates. In large rivers, wood is deposited on banks and islands frequently out of contact with the water surface, possibly encouraging rapid rates of LWD break down (Figure 3).

Physical abrasion and macroinvertebrate grazing gradually expose more wood surface area and increase oxygen penetration. As logs decompose, the concentration of essential nutrients, such as nitrogen, increases partly through nitrogen fixation (Sedell et al. 1988). The nitrogen fixation occurring on fallen wood may account for 5% to 10% of the annual nitrogen supplied to streams (Sedell et al. 1988).

Macroinvertebrates. The macroinvertebrate fauna associated with LWD ranges from obligate restriction to purely opportunistic use (Dudley and Anderson 1982). In coastal and Cascades Oregon streams, Dudley and Anderson (1982) found 45 taxa closely associated with wood and over 80 taxa facultatively associated. Obligate groups are mostly xylophagous and rely on wood as a direct nutrient source. Obligates are mainly comprised of borers and gougers, which remove and process log particles. Most obligate groups are found on soft, rotten wood or grooved, textured wood with a large surface area. Major xylophagous species are the wood gouging caddisfly *Heteroplectron californicum* and elmid beetle *Lara avara.* Anderson et al. (1978) found caddisflies to be the most conspicuous and diverse wood associated insects, however, the density and abundance of *L. avara* was more strongly associated with the amount of wood available, irrespective of stream size. Higher densities of xylophagous insects occur on hardwoods than on conifers (Anderson et al. 1978). Hardwoods have a higher nutritional value due to greater microbial activity and nitrogen content (Sedell et al. 1988). Two possible mechanisms for wood exploitation by macroinvertebrates are consumption to obtain digestible carbon and nitrogen from microbial flora to meet energy and nutrient requirements, and cultivation and retention of a gut flora to provide nutrients and aid in digestion of wood fiber (Anderson et al. 1978).

Facultative groups use wood as an attachment substrate for filter feeding and grazing, as refugia during high flows and protection from predators, and as an oviposition site. Wood acts as a stable feeding platform for net spinning caddisflies and may channel flow along surface features to maximize filter-feeding efficiency (Dudley and Anderson 1982, Harmon et al. 1986). Wood is also used in case construction, particularly by *Limnephilidae* caddisflies (Merritt and Cummins 1996). Smooth, firm wood is a suitable attachment site for filter feeders and macroinvertebrates grazing on biofilm (Dudley and Anderson 1982). In New York, Hax and Golladay (1993) found macroinvertebrate densities on wood substrates to be higher than densities on leaves and other detritus. Densities were correlated with the amount of biofilm, which was highest on logs. Biofilm is a food source for grazing aquatic insects. Collector/gatherers occurred in higher proportions on leaves, while collector/filterers preferred wood attachment sites.

The primary basis of association for most facultative taxa is cover from predators and refuge from abiotic stress (Dudley and Anderson 1982). Grooves and cracks support high densities of macroinvertebrates presumably seeking escape cover, as many times predators dominate the total biomass within these microhabitats. Most groups are found on grooved or textured surfaces (Dudley and Anderson 1982). In Australia, O'Connor (1991) compared different wood surfaces and found that grooved snags supported higher densities of aquatic insects. The results supported a habitat complexity hypothesis predicting an increase in species richness with increasing habitat complexity. Physically complex substrates provide more habitat opportunities for algae, microbes, and macroinvertebrates. Depositional sites upstream of log obstructions may support locally high macroinvertebrate densities as organisms gather to process organic material. Log obstructions also act as refugia during high discharge by creating areas of low water flux and low bedflow (Palmer 1996). These areas retain existing populations and encourage deposit of drifting organisms.

Caddisflies and Diptera commonly pupate in moist or saturated logs in the channel or along the stream margin (Harmon et al. 1986). Limnephilid caddisflies deposit egg masses on damp wood, while hydropsychids prefer submerged branches or overhanging wood.

The sequence of colonizers on a newly fallen piece of wood follows the stage of decay (Sedell et al. 1988). Fresh logs are primarily attachment substrates for algae and microbes, which in turn support populations in the grazer and collector/gatherer functional feeding groups. Early colonizers include chironomid midges and scraping mayflies, such as *Cinygma* spp. and *Ironodes* spp. (Merritt and Cummins 1996). As wood decays through decomposition and physical abrasion, populations of xylophagous macroinvertebrates colonize the wood surface. Gougers and borers, such as the caddisfly *H. californicum* and the elmid beetle *L. avara*, graze on the soft wood, creating a mottled surface, which increases the surface area available for algae attachment and speeds microbial decomposition. In later stages of decay, chironomid and tipulid (*Liposothrix* spp.) detrivores continue decomposition into basic nutrient elements. However, the role of aquatic macroinvertebrates in wood decomposition and processing is limited compared to terrestrial insects, with aquatic organisms consuming less than 5% of all available wood (Pereira et al. 1982, Sedell et al. 1988).

The abundance and community structure of wood associated macroinvertebrates changes in relation to stream characteristics (Table 4, Dudley and Anderson 1982). High gradient reaches with coarse substrates and exposed logs support an abundant fauna of xylophilous insects, comprised of borers, gougers, scrapers, and groups colonizing wood surfaces and crevices. In moderate gradient reaches, the accumulation of silt and fine organic matter excludes many gougers, borers, and scrapers, limiting the fauna to collectors and predators. In large rivers, physical abrasion diminishes most populations. Additionally, wood may be deposited on high banks and terraces, out of contact with the water surface and unavailable to aquatic invertebrates (Dudley and Anderson 1982, Piegay et al. 1999).

Table 4. Wood associated insect fauna and role of LWD in salmonid habitat from low to high order streams. Coarse substrates, high debris loads, and exposed logs support an abundance of aquatic insects in high order streams. The accumulation of fine silt and sediment and deposit of wood out of the channel in lower gradients excludes most wood associated insects. The role of wood in salmonid habitat varies with channel width and gradient.

	LOW ORDERS	INTERMEDIATE ORDERS	HIGH ORDERS
INSECT FAUNA	• Borers • Gougers • Scrapers • Collectors • Predators	• Collectors • Predators	• Limited, wood out of channel
ROLE IN SALMONID HABITAT	• Pool formation • Cover	• Pool formation • Cover • Spawning	• Cover

Salmonids. Along the Pacific Coast, wood is crucial in creating and maintaining the area and complexity of salmonid habitat (Figure 3, Table 4, Bisson et al. 1987). An important role of LWD in forming salmonid habitat is the creation of pools. Pools provide fish with a low energy environment to minimize energy expenditures in running water, provide maximum exposure to drifting food organisms, and are used as escape cover by individuals avoiding predators (Bisson et al. 1987, Bjornn and Reiser 1991). In moderate to high gradient streams, LWD is a primary factor controlling channel morphology, particularly pool formation (Keller and Swanson 1979, Beechie and Sibley 1997). Most pools are formed in association with LWD and wood-formed pools occupy a large proportion of the total stream surface area and total stream volume (Fausch and Northcote 1992, Crispin et al. 1993). Other instream obstructions, such as boulders, interact with flowing water to form pools. However, in addition to altering bed morphology, debris-formed pools provide other habitat values, such as cover and nutrient trapping, not offered by boulder-formed pools. Thus, streams with high volumes of wood typically support higher fish densities. In southeastern Alaska, summer periphyton biomass and the volume of instream debris best modeled the winter density of coho salmon and LWD volume alone best modeled the summer and winter density of Dolly Varden (Murphy et al. 1986).

Large woody debris obstructions also create zones of differential scour and deposit, leading to the creation of gravel bars, which are used by salmonids as spawning habitat. After adding logs to western Oregon streams, House and Boehne (1986) observed a 25-fold increase in gravel bar area. In a separate study, Crispin et al. (1993) observed a 4-fold increase in coho salmon (*Oncorhynchus kisutch*) spawning activity.

In the early to mid twentieth century, managers manipulated trout populations by installing log structures in order to increase habitat area and wood cover (Tarzwell 1937, Boussu 1954). Recent studies use manipulation to demonstrate the influence of woody debris loading on salmonid populations and fish biomass. Stream reaches with reduced levels of in-channel wood support lower salmonid populations compared to reaches with near natural LWD loading. Despite using selective techniques to remove wood from a southeastern Alaska stream and observing no significant changes in average channel width or depth, Dolloff (1986) found that the abundance of coho salmon and Dolly Varden (*Salvelinus malma*) was lower in cleared reaches. Similarly, Bryant (1985) found that the densities of coho salmon, steelhead trout (*O. mykiss*), and Dolly Varden were consistently lower in reaches with reduced LWD loading. Coho fry were particularly sensitive to the presence of wood, decreasing in density as the volume of individual LWD accumulations decreased. After removing LWD, Elliott (1986) noted a decrease in benthos abundance and an elimination of most instream overhead cover. The reduced food supply and increased susceptibility to displacement in high flows contributed to the numerical decline of Dolly Varden. Log structures installed in northern Colorado streams increased pool volume and total cover, which encouraged immigration of fish from nearby unmanipulated reaches, leading to increases in the abundance and biomass of age 2+ brook trout (*S. fontinalis*), brown trout (*S. trutta*), and rainbow trout (Gowan and Fausch 1996).

An important function of instream wood is providing high flow refuge during winter. Salmonids prefer logs, tree roots, and undercut banks as cover, and streams with abundant cover elements support high winter densities of fish (Heifetz et al. 1986, Tschaplinski and Hartman 1986, Dolloff and Reeves 1990, Bjornn and Reiser 1991). Ideal winter cover sites combine low velocity, shade, and three-dimensional complexity (McMahon and Hartman 1989). Quinn and Peterson (1996) found that overwintering survival of coho was correlated with LWD abundance and volume and habitat complexity at the end of the summer, prior to winter high flows. Cederholm et al. (1997) found little or no change in spring and fall coho populations after log additions, but saw a significant increase in winter populations. The results indicate the importance of LWD in providing winter habitat. In high flows, reaches with an abundance of complex, LWD created pools retain the greatest amount of fish (Harvey 1998).

Salmonids occupy stream positions adjacent to structures that increase habitat complexity (Murphy et al. 1986). In British Columbia, 99% of coho fry and 83% of steelhead parr occupied positions near mid-channel rootwads in drought, normal, and high flow conditions (Shirvell 1990). Coho remained near the shore, while steelhead preferred more distant wood associated sites. An artificial channel experiment showed that coho abundance increased in areas of high overhead cover complexity (McMahon and Hartman 1989). Young of the year fish prefer LWD derived lateral habitats. Moore and Gregory (1988) increased lateral habitat by 2.4-fold through the addition of woody debris and increased the number of age 0 cutthroat trout (*O. clarki*) by 2-fold. McMahon and Holtby (1992) found that complex woody debris pieces also influence the distribution and abundance of fish in streams and estuaries. Eighty percent of coho smolts occurred within 1 m of debris pieces and 95% occurred within 2 m of debris pieces. The results support the need to retain LWD for smolt production in both habitat types.

Riparian habitat. The age structure of floodplain riparian forests reflects the history of LWD deposition and fluvial disturbance. In moderate to steep gradient streams of the Pacific Northwest, LWD parallel or oblique to flow influences the development of forested floodplains (Fetherston et al. 1995). Downed logs trap alluvium and colluvium in upstream near-bank sites, providing areas for riparian seedling establishment. The logs create low velocity environments where sediment and organic material deposit, speeding soil development and providing nutrients for riparian stands. Woody debris additionally provides nutrients as nurse logs for young trees, and in this capacity also creates an elevated establishment site that minimizes competition between seedlings and other forest floor vegetation. Established forests eventually contribute LWD back to the stream during disturbance events, continuing the process of riparian forest development (Bilby and Bisson 1998).

In exposed channel bars, LWD protects downstream riparian sites by obstructing streamflow and shielding vegetation from high flows, allowing species such as alder to become established (Sedell et al. 1988). The sediment deposition, nutrient deposition, and protection afforded by LWD helps streamside vegetation quickly reach a mature stage and better withstand floods.

As channel confinement increases, the influence of LWD on riparian forest development and distribution lessens due to a general decrease in the size of wood-associated sediment deposition sites (Figure 3, Bilby and Ward 1989, Bilby and Bisson 1998). Narrow channels also lack extensive floodplain area and are more prone to debris flows that remove soil and vegetation, further limiting riparian forest development (Fetherston et al. 1995, Bilby and Bisson 1998).

In low to moderate gradient reaches, wood accumulates in large distinct jams within the channel and on the floodplain, providing abundant sites for forest establishment (Bisson et al. 1987, Abbe and Montgomery 1996). In northwest Washington, Abbe and Montgomery (1996) observed a diverse riparian forest structure dotted with anomalous old growth patches. The old growth patches were associated with LWD accumulations located in alluvial terrain characterized by frequent disturbance. The accumulations formed around key member logs, which were originally the largest streamside trees, creating distinct, stable LWD jams. Downstream of these bar area jams (BAJs), three factors facilitate the development of riparian forest: 1) local flow deceleration and decreased basal shear stress, 2) sediment deposition, 3) abundant accumulation of organic matter. Log jams create upstream arcuate gravel bars and downstream central gravel bars, which become sites for forest patch establishment and are stable as long as the wood accumulations exist. The observation of forest patches within the zone of active channel migration suggests that some LWD structures provide long-term refugia for floodplain riparian communities and remain stable despite repeated integration into the active channel.

Management Impacts on LWD

Timber harvest. Timber harvest activities in streamside forests can directly affect wood input (Table 5, Swanson and Lienkaemper 1978, Bilby and Bisson 1998). Clearcut logging, often with minimal buffer strips surrounding the stream channel, was a common management practice throughout the Pacific Northwest and Alaska until the early to late 1980s (Dominguez and Cederholm 2000). The harvesting of streamside forests may temporarily reduce or eliminate LWD recruitment to the stream (Bryant 1980). The recovery time for input to return to pre-harvest conditions may be quite long. Fifty years after logging, debris from the current stand of a western Oregon stream contributed only 14% of total LWD volume and only 7% of the wood from the current stand contributed to pool formation (Andrus et al. 1988). The results indicate that some second growth stands must grow at least 50 years before trees contribute LWD in sizes and amounts similar to old growth forests. A decay model calibrated in southeastern Alaska predicted a 70% reduction in wood 90 years after clear-cutting, and that full recovery exceeded 250 years (Murphy and Koski 1989).

Logs derived from second growth forests are smaller in diameter and have less volume than old growth LWD, contributing to lower instream loading in logged streams (Bilby and Ward 1991, Ralph et al. 1994). Second growth wood loads tend to be comprised of deciduous riparian species and small conifers that degrade more easily and have less of an effect on long-term channel morphology (Dominguez and Cederholm 2000).

A comparison between unlogged, moderately, and intensively logged catchments found that undisturbed streams contained more logs in the largest size categories (>50 cm diameter) than managed streams (Ralph et al. 1994). Intensively harvested streams displayed reduced average pool depth and area, and a significantly lower proportion of stream area occupied by pool habitat. These characteristics were related to the smaller size of in-channel wood and a modified spatial distribution where a large proportion of logs were located out of the low flow channel or did not interact with stream flow.

Table 5. The effect of certain management practices on the characteristics and abundance of LWD within stream systems. Timber harvest temporarily reduces input or changes the physical characteristics of subsequent inputs. Flood control and road maintenance activities generally result in the removal of in-channel wood.

MANAGEMENT PRACTICE	EFFECT	REFERENCES
Timber harvest	• Temporary reduction in LWD input	Bryant 1980, Andrus 1988, Murphy and Koski 1989
	• Second growth input smaller, less rot resistant with less profound effects on physical habitat	Bilby and Ward 1991, Wood-Smith and Buffington 1996, Ralph et al. 1994
	• Removal of logging residue simplifies physical habitat by failing to distinguish between naturally occurring habitat-forming logs and leftover material	Swanson et al. 1976, Swanson and Lienkaemper 1978, Beschta 1979, Bryant 1980, Keller and MacDonald 1983, Bilby 1984, Bisson et al. 1987, Bilby and Ward 1989
	• Extremely large amounts of logging material reduces intragravel flow, increases biological oxygen demand, reduces space available for invertebrates, and blocks fish migration	Hall and Lantz 1968, Narver 1970, Brown 1974
	• Destabilization of hillslopes and increase in debris avalanches	Swanson and Lienkaemper 1978
	• Narrow buffer strips (<20 m to 30 m) potentially reduce wood input	McDade et al. 1990, Van Sickle and Gregory 1990
	• Buffer strips adjacent to clearcuts have higher occurrence of windthrow and are depleted of large wood sources rapidly	Reid and Hilton 1998
Flood control and road maintenance	• Remove wood to decrease channel roughness, increase conveyance, and maintain flood capacity	Marzolf 1978, Young 1991, Gippel et al. 1996
	• Remove wood and clear jams to keep culverts and bridges free of debris and reduce structural damage during storms	Singer and Swanson 1983, Diehl 1997

Streams flowing through second growth forests have a lower frequency of LWD associated pools and fewer channel spanning logs than old growth streams, leading to a scour pool dominated system (Bilby and Ward 1991). Thus, in low to mid-order streams the percentage of LWD formed waterfalls and the control of wood on gradient is decreased by timber harvest. Old growth logs are larger and retain more bedload sediment and fine organic debris. Fine organic debris influences the physical characteristics of large jams and may contribute to an increased diversity of pool types in old growth streams (Bilby and Ward 1991). Changes in wood loading and abundance significantly alter stream morphology. Wood-Smith and Buffington (1993) showed that pool frequency, pool depth, and local shear stress were significantly different in logged versus unlogged streams.

Near-stream logging influences natural LWD input processes. Depending on the method, harvest activities destabilize hillslopes and increase the likelihood of debris avalanches (Swanson and Lienkaemper 1978). Buffer strips are a common technique to reduce logging effects on forests and streams. Most LWD inputs come from within 20 m to 30 m of the stream channel and buffers more narrow than this zone of input potentially reduce the amount of available logs (McDade et al. 1990, Van Sickle and Gregory 1990). Buffer strips adjacent to clearcuts are exposed to higher wind velocities, increasing the occurrence of windthrown logs to the stream channel (Reid and Hilton 1998). Higher rates of windthrow may lead to rapid depletion of available wood from the remaining adjacent forest, increasing short-term LWD input, but decreasing long-term input.

Woody debris clearance. During logging operations, leftover woody material accumulates on hillslopes and within streams. Historically in the Pacific Northwest, salvage logging operations removed instream wood to recover leftover material (Bisson et al. 1987). Many regulations also recommended the removal of log jams, which were perceived by fisheries biologists as impediments to anadromous fish migration. Such activities proceeded without rigorous evaluation to distinguish between natural and logging derived LWD, or between naturally occurring logjams and unnatural barriers to fish migration. Many pieces of wood were unnecessarily removed leading to the simplification of physical habitat (Bilby and Bisson 1998).

Stream cleaning reduces the abundance of large stable, habitat forming logs, leaving smaller pieces that are more easily mobilized in moderate to high flows (Swanson et al. 1976, Swanson and Lienkaemper 1978, Bryant 1980, Keller and MacDonald 1983). These small pieces collect behind remaining large logs and build massive debris dams that impede flow and increase rates of lateral stream erosion. The mobilized LWD also weakens existing stable logjams, contributing to dam failure and the initiation of debris torrents.

In moderate to high gradient streams, logs play an important role in bedload storage (Figure 2), and the removal of LWD eliminates potential storage sites (Beschta 1979, Bilby 1984, Bilby and Ward 1989). The decrease in storage capacity and subsequent release of sediment simplifies physical habitat by filling in the deepest pools, reducing pool area, and smoothing channel gradient (Sullivan et al. 1987, Dominguez and Cederholm 2000). Debris removal affects salmonid populations by decreasing the amount of available hydraulic cover available during winter high flows, and by reducing stream wetted width and perimeter (Dolloff 1986, Elliott 1986). Undisturbed reaches have more available habitat area, contain greater supplies of food, and contain more fish of all sizes than altered reaches. Smaller fish and less available hydraulic cover combine to cause an increase in the displacement of fish in high flows. Streams with reduced levels of LWD, either from instream removal or streamside harvest that decreases wood input are often modified with artificial structures designed to mimic the hydraulic and habitat forming effects of LWD (House and Boehne 1986, Riley and Fausch 1995, Wallace et al. 1995).

Alternatively, an excessive amount of logging material left in the stream may be damaging to fish populations. Fine debris lying on the gravel surface impedes interchange between intragravel flow and surface water, reducing subsurface dissolved oxygen levels (Hall and Lantz 1969, Narver 1970, Brown 1974). Reduced oxygen availability retards the development of salmonid embryos within the gravel. The decomposition of wood increases biological oxygen demand, further reducing available dissolved oxygen (Narver 1970). Tannins and lignin-like substances released by wood decomposition produce yellow and brown pigments that absorb photosynthetically active radiation, possibly reducing periphyton growth. Small pieces of wood and bark occupy interstitial pores, reducing the available living space for stream invertebrates (Narver 1970). Very large human induced accumulations of wood prevent upstream migration of anadromous salmonids (Brown 1974). Much historical management of LWD in logged streams concentrated on the removal of excess debris to allow fish passage (Bilby and Bisson 1998).

Flood control and road maintenance. In systems influenced by human infrastructure, road maintenance and flood control activities affect the abundance of large wood (Table 5). Logs and riparian vegetation increase channel roughness, reduce conveyance, and are commonly removed by managers to maintain flood capacity (Marzolf 1978, Singer and Swanson 1983, Young 1991, Gippel et al. 1996). Wood mobilized during high flows frequently becomes trapped on channel spanning bridges and culverts, leading to road overtopping and eventual structure failure. Managers clear jams to keep structures free of obstructions and reduce damage to river crossings. Such management may completely eliminate LWD or remove only the largest pieces that pose the greatest hazard, but which are most important to habitat formation.

Synthesis and a Proposal for Stream Classification

Synthesis. The geomorphic and ecological effects of LWD gradually change downstream through the channel network (Figures 2 and 3). The abundance of wood in a stream or river reflects the balance between wood entering and wood leaving a particular reach (Keller and Swanson 1979). The main controls on the geomorphic effects of LWD are piece size, channel gradient, and channel width. The ecological effect of LWD arises from log characteristics and channel morphology. Logs trap and retain nutrients, create habitat for fish and new riparian growth, and act as a direct nutrient source and attachment site for aquatic insects. This review has thus far concentrated on geomorphic and ecological effects as they occur in varying stream orders. The effects of LWD in stream systems may be better understood when integrated with existing process-based stream classification systems to create a classification based on the influence of instream wood. Such a classification system will aid in the management of instream LWD and help determine the sensitivity of stream channels to changes in LWD characteristics.

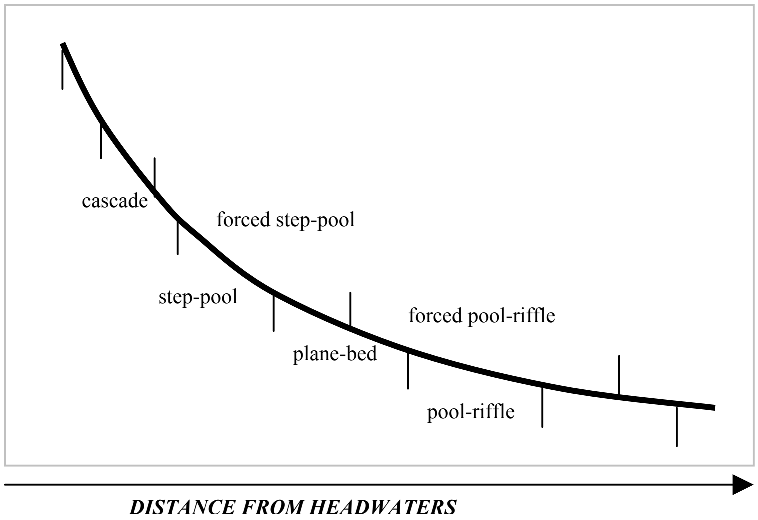
Montgomery and Buffington (1997) developed a channel classification system based on geomorphic processes. The system integrates channel processes with the spatial arrangement of specific reach morphologies. In channels composed of alluvial substrates, they identify several reach morphologies that occur in a downstream direction with reducing gradient: cascade, step-pool, plane-bed, and pool-riffle (Figure 4, Table 6). The reach morphologies reflect basin wide trends in sediment transport and storage capacity. Higher gradient reaches have a high transport capacity relative to sediment supply and function as transport zones that deliver sediment to lower gradient reaches. Reach substrate and morphology result from the balance between sediment supply and transport capacity. Other reach types arise when external influences, such as LWD, are present in stream channels and affect sediment input and output processes.

In some cases, LWD obstructions force sediment-poor bedrock channels into becoming alluvial channels, owing to the sediment storage capacity of in-channel wood. Montgomery and Buffington (1997) recognize two forced reach morphologies in alluvial channels: forced pool riffle, and forced step pool. The forced morphologies extend beyond the range of free forming analogous channel types into higher and lower gradient sections (Figure 4). Forced pool-riffle reaches span the gradient range for pool-riffle and plane-bed reaches and arise when most pools and bars form in response to LWD obstructions. Forced step-pool reaches arise when most elevation controlling steps are formed by channel spanning logs. The recognition of forced-reach morphologies as distinct types acknowledges the control LWD has on bed morphology.

Table 6. The gradient range and general characteristics of reach morphologies in alluvial channels (Data taken from Bisson and Montgomery 1996 and Montgomery and Buffington 1997).

	CASCADE	STEP-POOL	PLANE-BED	POOL RIFFLE
GRADIENT	• 0.08 to 0.30	• 0.04 to 0.08	• 0.01 to 0.04	• 0.001 to 0.02
BEDMATERIAL	• Boulder	• Cobble/boulder	• Gravel/cobble	• Gravel
CONFINEMENT	• Confined	• Confined	• Variable	• Unconfined

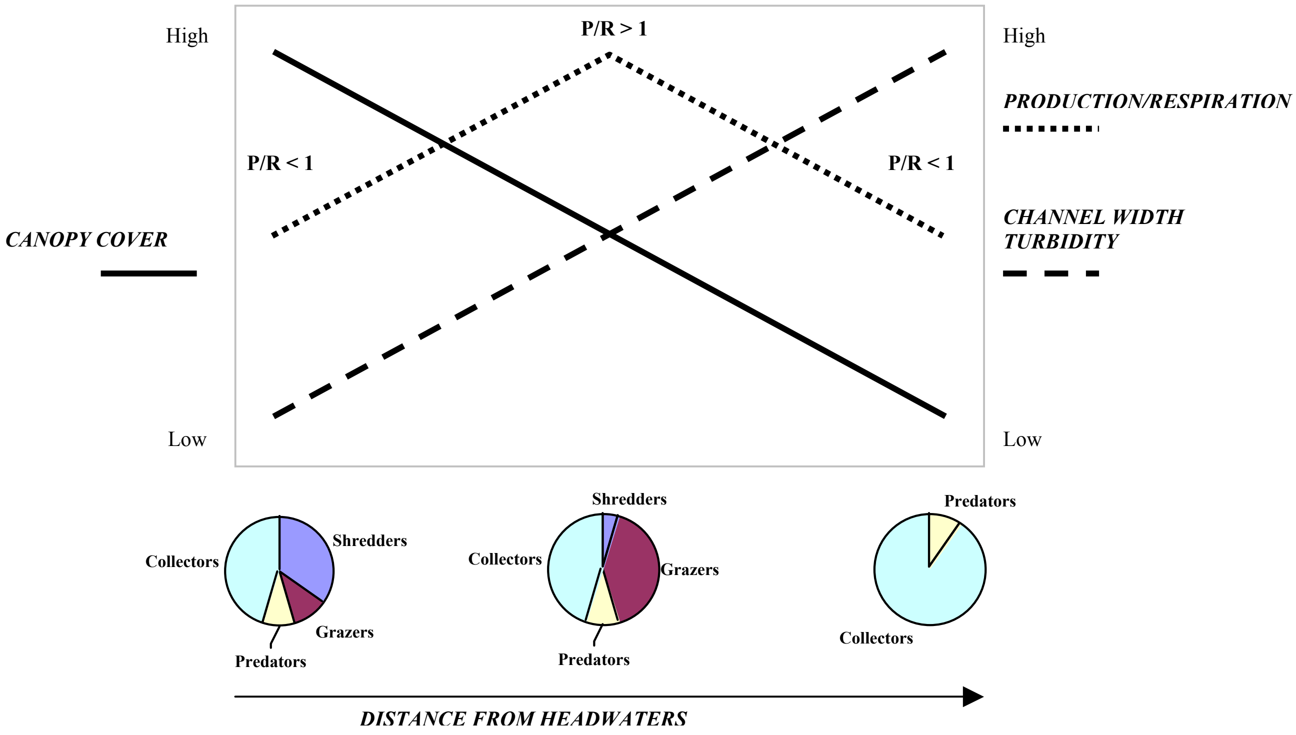
Figure 4. Generalized long profile of alluvial channels showing spatial arrangement of reach morphologies, including forced step-pool and forced pool-riffle morphologies. Forced morphologies extend beyond the gradient range of free-formed counterparts. Gradient ranges of forced morphologies depicted above are interpreted from Montgomery et al. (1995) and Beechie and Sibley (1997). The classifications are based on geomorphic processes and reflect basin wide trends in sediment transport and storage (Figure adapted from Montgomery and Buffington 1997).



The river continuum concept is an ecological framework that describes adjustments of the biological community in response to physical conditions (Figure 5, Vannote et al. 1980). Energy sources and processes change systematically from headwaters to large rivers. Low order streams tend to be narrow and shaded by streamside vegetation, resulting in low rates of instream autotrophic growth. Headwater communities rely on allochthonous inputs from leaves, pine needles, and pieces of wood as energy sources. In these reaches, the autotrophic production to heterotrophic respiration ratio (P:R) is less than one, and is reflected in algal and macroinvertebrate community structure. Algal growth is limited and the macroinvertebrate community is comprised mainly of shredder and collector functional feeding groups, which process external inputs. In intermediate order streams, channel widening reduces overhead canopy cover allowing rates of autotrophic production to exceed respiration (P:R >1). Periphyton is the dominant energy source and macroinvertebrates shift to grazers and collectors. Grazers scrape and process algae from solid surfaces, such as boulders and logs. In large rivers, shade is further reduced and channels become wider and deeper, but generally more turbid. The high turbidity and increased depth reduces light penetration and autotrophic production (P:R <1). Dissolved material and fine particles transported from upstream are the dominant energy sources and macroinvertebrate communities are comprised mainly of collectors.

The role of LWD is not explicitly addressed within the river continuum concept. However, the influence of wood on nutrient retention and macroinvertebrate communities is quite important (Bilby and Likens 1980, Wallace et al. 1995). As nutrients travel downstream, they are incorporated by stream organisms. After incorporation, processed nutrients are eventually released and again become available for uptake by stream organisms. The process by which nutrients are used and released, called spiraling, is influenced by the presence of LWD. Fallen logs delay the transport of sediment and organic matter downstream. By physically obstructing particulate and dissolved nutrients, LWD reduces the spiraling length, or distance between uptake and release (Bilby and Likens 1980, Newbold et al. 1982). Without storage behind wood accumulations, allochthonous input is transported downstream without being reduced into smaller particles by physical and biological action. Unobstructed material may be unavailable to organisms, such as macroinvertebrates, in intermediate to high order streams (Vannote et al. 1980, Bisson et al. 1987). Wood obstructions store large amounts of organic matter, the primary energy source in undisturbed streams. Thus, the presence of wood obstructions has an effect on available nutrients and biological community structure. Down the channel network the storage capacity of LWD decreases, but wood may act as growth substrate for periphyton, an attachment site for filter feeders, or as a direct food source, further influencing macroinvertebrate community structure (Dudley and Anderson 1982, Bilby and Ward 1989). In large rivers, where woody debris deposits on banks and terraces largely out of contact with the water surface, the influence on macroinvertebrate community structure and nutrient availability is limited. Unlike Montgomery and Buffington (1997) reach morphologies, the river continuum concept does not recognize ecological stream reaches that are forced by woody debris obstructions. Considering the above relations, stream ecology is most sensitive to the influence of LWD in low to intermediate stream orders.

Figure 5. The relationship between channel width, canopy, respiration, and macroinvertebrate community structure. As channels increase in width, the relative shading by riparian canopy decreases, and turbidity, caused by concentration of suspended sediment, increases. In narrow streams, the autotrophic production to heterotrophic respiration ratio is less than 1, as most production comes from allochthonous inputs. As the stream widens and shade decreases, water is clear enough to support periphyton growth and autochthonous production dominates. In large channels, turbidity and depth reduce algal growth, and production is allochthonous input transported from upstream. The relative proportion of macroinvertebrate functional feeding groups changes in response to the dominant energy source. Collectors and shredders process leafy input in small channels, grazers scrape periphyton from substrates in mid-order reaches, and collectors gather transported material in high order rivers (figure adapted from Vannote et al. 1980).



A stream classification proposal. Managers should emphasize restoring and maintaining habitat-forming processes associated with large wood (Beechie and Bolton 1999). Figures 6 and 7 describe a new classification system derived from this review of scientific literature (Figures 2 and 3) and existing process based geomorphic and ecological classifications (Figures 4 and 5). These wood influence zones, based upon position within the channel network, should not be confused with influence zones described by Robison and Beschta (1990) and O'Connor and Ziemer (1989), which are based on lateral channel position. Low to intermediate order reaches make up the single piece/debris flow zone where closely spaced, solitary logs and debris flows have the greatest effect on channel morphology and ecology. Single pieces falling across the channel accumulate sediment and allochthonous material in upstream storage sites, and in general are the major control on morphology and ecology in small streams (Montgomery and Buffington 1997). Wood moves infrequently, but usually in catastrophic bursts triggered by heavy storms. Such events may transport massive amounts of LWD downstream and cause landslides and debris flows that bring wood into the channel (Swanson et al. 1976, Singer and Swanson 1983). In very steep gradients, solitary logs may lie above the channel, resting on large boulders, having minimal effect on channel morphology (Keller and Tally 1979). However, the sediment storage capacity of log obstructions may also force high gradient bedrock channels into an alluvial reach morphology or cascade channels into a forced step-pool morphology (Montgomery et al. 1996, Montgomery and Buffington 1997).

Intermediate order streams comprise the intermediate jam zone (Figure 6). Larger channels have the capacity to redistribute wood in irregularly spaced jams. Wood generally occurs in multiple piece jams and the spacing between accumulations increases downstream. The relative confinement influences the predominant pool type and reach morphology (Figure 7). Confined channels have limited floodplain area, thus wood deposits within the channel, building jams that create a forced step-pool reach morphology. Highly confined channels have a greater capacity to transport wood downstream, and may have low wood loading, minimizing log influence on morphology and ecology (Bilby and Bisson 1998). Moderately confined to unconfined channels have floodplains and gravel bars that act as LWD storage sites. The channel margin location of LWD jams encourages the formation of lateral scour pools within a forced pool-riffle reach morphology. The intermediate jam zone then can be further classified into moderately confined and unconfined subtypes that produce different possible reach morphologies.

Higher order streams and rivers make up the large jam zone (Figure 6). Wide, deep channels transport and deposit wood on floodplains and gravel bars within the active channel, but may be out of contact with the water surface (Figure 7). Jams in this zone tend to be the largest within the channel network, but are widely spaced and have a limited effect on gradient and sediment storage. Most sediment is stored in geomorphic elements, such as floodplains and terraces. Channel margin deposits of wood encourage the formation of lateral scour pools within a forced pool-riffle morphology. Woody debris jams provide salmonids with hydraulic and escape cover during seasonal migrations. Possibly the most important role of LWD in the large jam zone is riparian forest development. Large jams provide sites for vegetation colonization, forest island growth, and forest floodplain development (Fetherston et al. 1995).

Management Recommendations

Forest management. Possibly the first step in improving the management of LWD in California stream systems is to recognize the different roles it plays in different parts of the watershed. The stream classification proposed above explicitly does that. It is equally important to understand the mechanisms by which LWD gets into streams, its potential for stability and the limitations on managers for recruiting and maintaining LWD. Timber harvest in and near streamside zones can potentially influence direct inputs of LWD to streams and can also influence indirect inputs through mechanisms such as inner gorge landslides and debris flows. However, timber harvesting in streamside zones probably has more significance on small to intermediate streams. In upper watershed areas, removal of forest from unstable upland sites that periodically contribute large quantities of LWD associated with mass wasting can also have lasting impacts. In view of these issues, the current system of regulating streamside management based on stream size, i.e., larger streams get more protection, may not achieve the desired results.

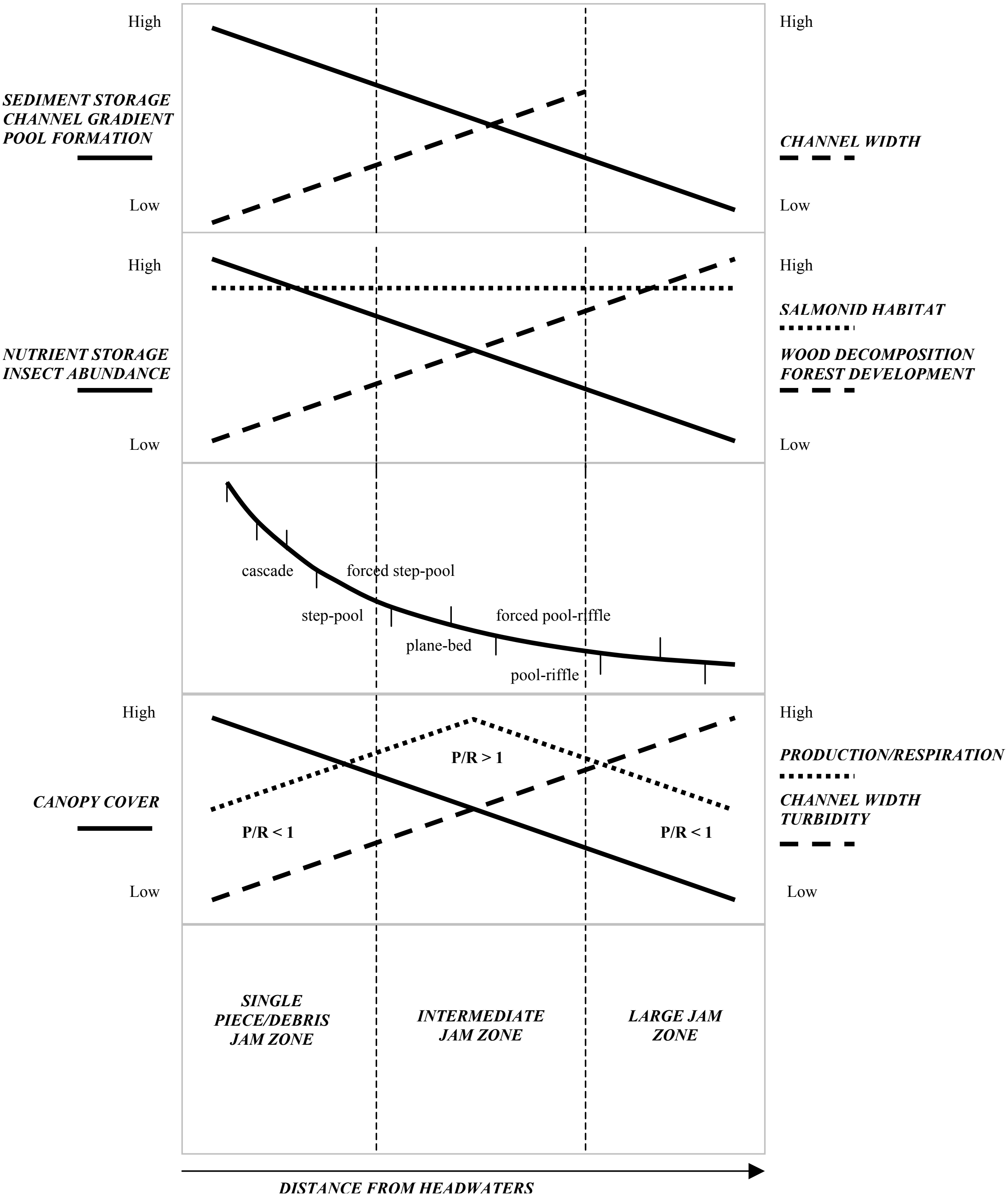
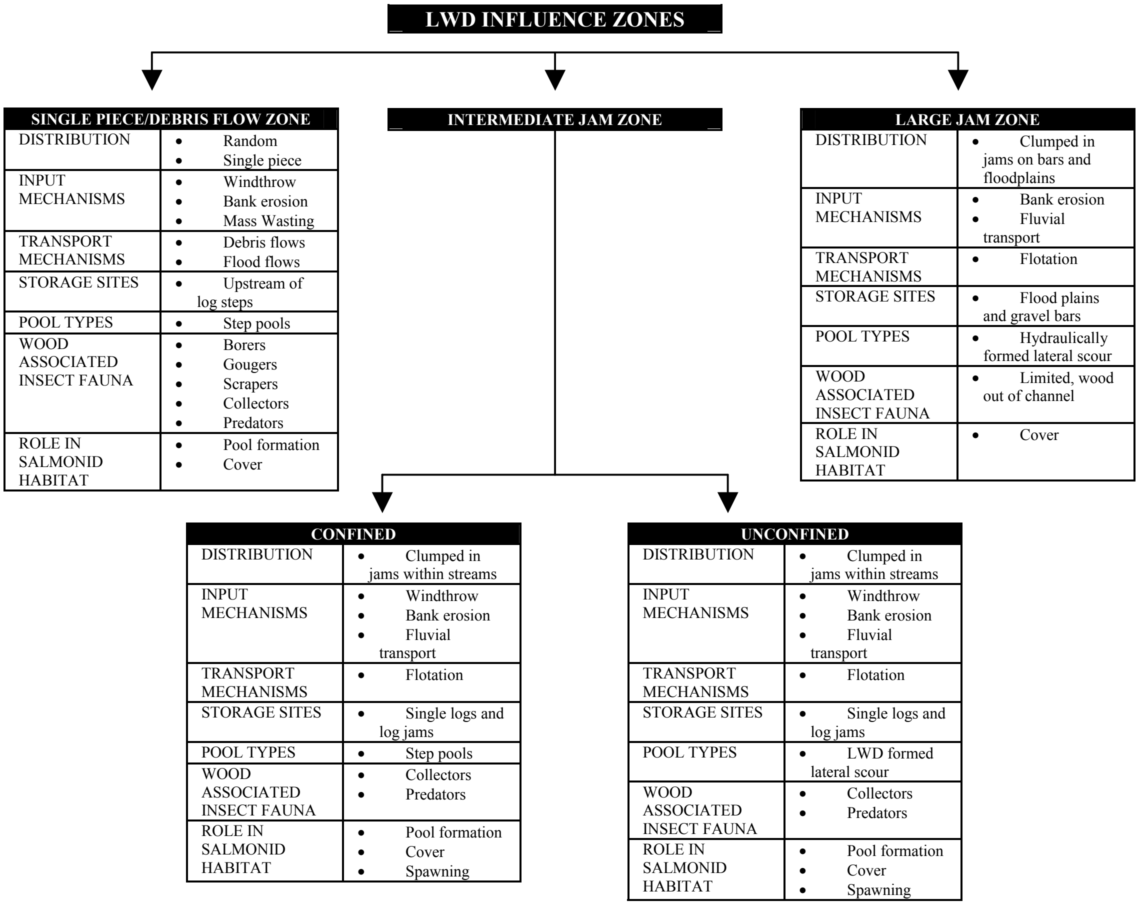


Figure 6. Location of LWD influence zones in relation to general trends occurring along the channel network and in context to geomorphic and ecological classification systems (figures adapted from Vannote et al. 1980 and Montgomery and Buffington 1997).

Figure 7. The general characteristics of LWD influence zones. Single pieces and debris flows dominate in small streams, while progressively larger jams dominate in higher orders. Intermediate jam zones can be further classified according to channel entrenchment, with confined reaches tending toward step-pool morphologies and unconfined reaches tending toward pool-riffle morphologies.



SINGLE PIECE/DEBRIS FLOW ZONE	
DISTRIBUTION	• Random • Single piece
INPUT MECHANISMS	• Windthrow • Bank erosion • Mass Wasting
TRANSPORT MECHANISMS	• Debris flows • Flood flows
STORAGE SITES	• Upstream of log steps
POOL TYPES	• Step pools
WOOD ASSOCIATED INSECT FAUNA	• Borers • Gougers • Scrapers • Collectors • Predators
ROLE IN SALMONID HABITAT	• Pool formation • Cover

LARGE JAM ZONE	
DISTRIBUTION	• Clumped in jams on bars and floodplains
INPUT MECHANISMS	• Bank erosion • Fluvial transport
TRANSPORT MECHANISMS	• Flotation
STORAGE SITES	• Flood plains and gravel bars
POOL TYPES	• Hydraulically formed lateral scour
WOOD ASSOCIATED INSECT FAUNA	• Limited, wood out of channel
ROLE IN SALMONID HABITAT	• Cover

CONFINED	
DISTRIBUTION	• Clumped in jams within streams
INPUT MECHANISMS	• Windthrow • Bank erosion • Fluvial transport
TRANSPORT MECHANISMS	• Flotation
STORAGE SITES	• Single logs and log jams
POOL TYPES	• Step pools
WOOD ASSOCIATED INSECT FAUNA	• Collectors • Predators
ROLE IN SALMONID HABITAT	• Pool formation • Cover • Spawning

UNCONFINED	
DISTRIBUTION	• Clumped in jams within streams
INPUT MECHANISMS	• Windthrow • Bank erosion • Fluvial transport
TRANSPORT MECHANISMS	• Flotation
STORAGE SITES	• Single logs and log jams
POOL TYPES	• LWD formed lateral scour
WOOD ASSOCIATED INSECT FAUNA	• Collectors • Predators
ROLE IN SALMONID HABITAT	• Pool formation • Cover • Spawning

To ensure future supplies of LWD to stream channels, buffer strips serving as reservoirs of wood supply should be wide enough to encompass the zone of LWD input, typically within 20 m to 30 m of the stream channel (Lienkaemper and Swanson 1987, McDade et al. 1990, Van Sickle and Gregory 1990). Some researchers have argued for larger buffers, based on susceptibility of buffer strips next to clear-cuts to blow-down and rapid depletion of available streamside wood (Reid and Hilton 1998). The use of a selectively logged fringe buffer adjacent to the streamside buffer may serve to reduce abnormally high rates of windthrow and preserve natural input rates. Any selective cutting within buffer strips should leave an abundant supply of the largest trees for recruitment (Murphy and Koski 1989, Abbe and Montgomery 1996). Large in this context refers to trees that can produce LWD big enough to interact with flow and influence channel morphology. To be cautious, the very largest trees should always be retained (Fetherston et al. 1995, Abbe and Montgomery 1996). There is no formula for determining the amount of wood required in a given stream so conservative judgment is warranted. Species, diameter, and wood decay rates influence the amount of wood recruitment potentially necessary (Murphy and Koski 1989).

Table 7. The possible management implications of preserving LWD input, transport, and presence within the stream channel.

MANAGEMENT PRACTICE	IMPLICATION	REFERENCES
Timber harvest	• Buffer strips should be wider than zone of LWD input	McDade et al. 1991, Van Sickle and Gregory 1990
	• Fringe buffers can protect streamside buffers from premature wood depletion	Reid and Hilton 1998
	• Selective management in buffers should consider future input required based on instream surveys	Bilby and Ward 1989, Murphy and Koski 1989
	• Selective management should leave large trees that will be stable and influence channel morphology	Fetherston et al. 1995, Abbe and Montgomery 1996
	• Active management of buffer zones can increase recruitment of certain species and sizes of wood	Beechie and Sibley 1997
	• Removal of logging debris best dealt with by selective removal	Bryant 1983, Bilby 1984, Gurnell et al. 1995
	• Knowledge of habitat conditions, and the size and abundance of LWD required to maintain conditions must be considered when removing instream wood	Bryant 1983, Bilby 1984
	• Characteristics of unmanaged streams should guide re-introduction of wood	Smith et al. 1993a, b, Montgomery et al. 1995, Abbe and Montgomery 1996, Beechie and Sibley 1997, Montgomery and Buffington 1997
Flood control and road maintenance	• Must gain quantitative understanding of effect of wood on flood heights and how moves through a system	Young 1991, Braudrick et al. 1997, Braudrick and Grant 2000
	• Design and modify bridges and culverts to allow for passage of woody debris	Diehl 1997, Flanagan et al. 1998
	• Develop management that recognizes ecological value and impact of wood on human infrastructure and public safety	Singer and Swanson 1983, Piegay and Landon 1997

Forest managers should seek to increase the recruitment of certain species, primarily conifers which produce the largest and longest lasting LWD. This may involve active management of deciduous riparian zones to promote conifer establishment and growth (Beechie and Sibley 1997). This strategy should be considered in relation to position within the channel network. Small channels (<10 m width) can form pools around smaller pieces of wood (<20 cm), such as alder logs. Large to intermediate channels require greater diameter logs to form pools (>60 cm). Data on variations in the size and amount of woody debris with changing stream size could be used to develop plans for numbers and sizes of trees to be achieved (Bilby and Ward 1989).

LWD clearance. In cases where logging debris is to be removed from a stream, it is best dealt with by selective maintenance to ensure channel stability and ecological function (Gurnell et al. 1995). An adequate amount of leftover LWD is essential to maintain wood related habitat structure (Lisle 1986a). Uncleaned streams flowing through logged or clear-cut reaches may exhibit higher levels of wood debris loading and subsequently have a greater abundance of LWD associated habitats (Lisle 1986a, Lisle and Napolitano 1998). Froehlich (1973) found that some harvest methods increased in-channel LWD abundance by >1000% over natural levels. In southeastern Alaska, Lisle (1986a) found that debris dams were more frequent in clear-cut reaches that were not cleaned after harvest than in undisturbed reaches. The clear-cut reaches showed greater residual pool depth and length, and the remaining LWD stored more bedload sediment than logs in undisturbed reaches. Leftover wood eventually deteriorates through decomposition and physical abrasion and streams eventually decrease in physical complexity if LWD is not replaced through natural inputs (Lisle and Napolitano 1998).

Indiscriminate removal of in-channel LWD for any reason can have major influence on channel processes (Beschta 1979, Bilby 1984). Knowledge of habitat conditions and the size and abundance of stable LWD required to create and maintain these conditions are considerations when removing instream wood. Bilby (1984) developed a dichotomous key based on local channel conditions and size of LWD to determine whether to remove or leave logs in the channel. Bryant (1983) used an inventory of piece length, percent of piece in the water, angle of orientation to flow, and location of anchor point to determine piece stability and suggested general removal guidelines based on the age of debris and stream gradient.

LWD placement. In streams with a paucity of LWD, re-introduction or placement of logs as instream structures provides a short-term solution to maintain wood created habitats until natural recruitment processes recover (Sullivan et al. 1987, Gurnell et al. 1995). The characteristics of unmanaged streams, such as the variability in species, size, and spacing of LWD accumulations and the goals of the project should guide the re-introduction of wood (Dominguez and Cederholm 2000). Dominguez and Cederholm (2000) developed a flow chart for determining candidate streams for rehabilitation based on fish habitat needs and characteristics of the stream and surrounding forest. Any logs added should be structured to mimic effects of natural obstructions in streams. Due to its random location, all stable logs may not be active in pool formation (Montgomery et al. 1995). Through careful placement of existing logs, managers may be able to engineer jam configurations that more efficiently enhance pool formation. The sensitivity of stream channels to wood addition varies with channel gradient. Moderate gradient reaches are highly sensitive to the presence of LWD (Sullivan et al. 1987, Montgomery et al. 1995, Abbe and Montgomery 1996, Beechie and Sibley 1997, Montgomery and Buffington 1997). Beechie and Sibley (1997) predict that increases in log abundance will lead to more rapid increase in the number of pools and pool area in moderate slope channels than in lower slope channels. The presence of pools in low gradient reaches may be independent of LWD presence (Smith et al. 1993a, b). The placement of instream structures maintains pools in the short-term, but ignores dynamic ecological and physical processes. Improved management of streamside forests offers the most promise for developing valuable and productive riparian systems (Elmore and Beschta 1989). Effective management of LWD will depend on information relating vegetative and physical characteristics of riparian areas to input of LWD (Bilby and Ward 1989).

Flood control and road maintenance. Flood control programs that encourage the removal of woody debris rarely undergo technical scrutiny, and do not always have a significant effect on flood levels (Williams and Swanson 1989, Young 1991, Dudley et al. 1998). Channel roughness depends on many factors, and the claims of reduced frequency and duration of over bank flooding, used to justify debris removal, are not unequivocally proven in the field (Gippel 1995). In Australia, Young (1991) found that the average amount of wood in lowland rivers seldom had a significant effect on flood levels, and suggested that larger pieces may be rearranged for hydraulic reasons and habitat preservation. Clearance of wood to maintain bridges and culverts is usually undertaken during low flow conditions, yet much wood enters streams and rivers during storms, through debris avalanches, bank erosion, and windthrow, reducing the effectiveness of removal programs (Singer and Swanson 1983). The use of hydraulic models may aid in the planning of debris management programs. However, in re-introducing LWD to stream channels as part of riparian restoration or instream habitat enhancement, managers must understand the geomorphic context of wood function to guide the effective placement for long-term log stability (Braudrick et al. 1997). A quantitative understanding of wood movement is needed to assess stability of re-introduced wood and to prevent unstable logs from becoming a safety hazard.

The alternative is to design bridges and culverts that allow passage of woody debris. Diehl (1997) examined drift damage to bridges across the United States and suggested adequate freeboard, wide spans, solid piers, rounded pier noses, and pier placement out of the path of drift to reduce jam accumulation. Flanagan et al. (1998) suggested methods to determine the potential of culvert crossings to impede downstream movement of logs based on the ratio of culvert width to channel width (w*), degree of upstream widening and stream approach angle to the culvert. Culverts with w* <1 are prone to clogging. Channel widening immediately upstream of culverts encourages ponding and creates eddies that orient wood perpendicular to flow and promote formation of large jams. In streams approaching crossings at a severe angle, wood cannot rotate parallel to flow and is less likely to pass through the culvert. Surveys on the size distribution of instream wood should also be included in studies assessing log passing capacity and considered before construction or modification of structures (Singer and Swanson 1983).

The management of wood in basins that are directly influenced by human infrastructure must balance ecological and safety concerns. Piegay and Landon (1997) proposed a system that recognizes the impact of LWD on public safety and human infrastructure, and the ecological value of wood. The sectored LWD maintenance plan was based on mapping of three areas: 1) woody debris supply areas, 2) areas where log jam formation is most probable, 3) areas of floodplain occupation to determine human vulnerability to flooding. The plan allowed for recruitment of LWD and the formation of jams in areas that posed little safety hazard. Intensive maintenance of instream wood occurred near flood prone areas and upstream of bridges.

Conclusion

Pieces of large wood are an important component in the ecology of streams flowing through the forests of Northern California. The physical and ecological roles of logs, stumps, and large branches vary through the channel network. In designing a management plan, one must not only consider the various roles, but also the processes by which LWD enters and is transported downstream. The LWD influence zones described in this paper could be used to define management objectives regarding forest management (LWD input), flood control and road maintenance (LWD transport), and instream rehabilitation projects (LWD loading). More specific management objectives must come from an understanding of habitat requirements and the limiting factors of sensitive species, and the characteristics of individual streams. The uncertain nature of ecological studies requires adequate monitoring, the results of which should be integrated into an adaptive management process that is designed by managers to maintain or improve ecological processes.

APPENDIX

Table A-1. The characteristics and distribution of LWD in various geographic locations and channel network locations (arranged in chronological order).

LOCATION	CHANNEL NETWORK POSITION	RESULTS	REFERENCES
Western Oregon	• 0.10 to 0.30 channel gradients	• LWD in small streams randomly distributed • LWD easily transported in larger rivers leading to size sorting and accumulations in distinct jams	Swanson et al. 1976
Western Oregon	• 0.02 to 0.50 channel gradients	• Debris loading highest in small, steep streams, decreasing downstream • In 1st and 2nd order streams LWD randomly located because streams too small to redistribute • In 3rd to 5th order streams flows large enough to redistribute debris to form distinct accumulations that directly affect channel width • In large rivers LWD thrown on islands or on banks, having little influence on channel, except during high flows	Swanson and Lienkaemper 1978
Indiana North Carolina Oregon	• 0.001 to 0.40 channel gradients	• Loading (kg/m^2) decreased with increasing channel width, watershed area, stream order, and decreasing channel gradient	Keller and Swanson 1979
Northwest California	• 0.01 to 0.40 channel gradients • 1.0 km^2 to 27 km^2 drainage areas • 2nd through 4th order streams	• Redwood debris usually dominates total loading • Loading (m^3/m^2) decreased as drainage area and width increased • Debris accumulations in lower reaches larger, more complex, and spaced further apart than in upper reaches	Keller and Tally 1979, Tally 1980, Keller and MacDonald 1983, Keller et al. 1985
New England	• 1.5 m to 7m wide channels	• Frequency of debris dams decreased from 1st order (20 to 40 dams per 100m) to 2nd order (10 to 15 dams per 100m) to 3rd order (1to 6 dams per 100m) streams	Likens and Bilby 1982
Western Oregon	• 0.03 to 0.37 channel gradients • 3.5 m to 24 m bankfull widths • 0.1 km^2 to 61 km^2 drainage areas • 1st through 5th order streams	• Amount of LWD generally decreased from small to large channels	Lienkaemper and Swanson 1987
Western Washington	• 0.13 channel gradient (<7m channel width) • 0.08 channel gradient (7m to 10m channel width) • 0.03 channel gradient (>10m channel width)	• Mean diameter, length, and volume of LWD increased with increasing channel width • Frequency of occurrence (# pieces/m) decreased with increasing channel width • Changes related to increased capacity of larger streams to move wood downstream • Higher proportion of wood input remained in the stream channel as stream size decreased	Bilby and Ward 1989
Southeast Alaska	• <0.03 channel gradients • 0.7 km^2 to 55 km^2 drainage areas • 1st through 4th order streams	• Abundance of LWD and volume per channel length (m^3/m) increased with increasing stream size • LWD loading (m^3/m^2) decreased with increasing bankfull width	Robison and Beschta 1990
Western Washington	• 3 m to 24 m bankfull channel widths	• Average LWD volume increased with increasing stream size (bankfull width) • LWD abundance (# pieces/m) decreased with increasing bankfull width	Bilby and Ward 1991
United Kingdom	• 110 km^2 drainage area	• Density of LWD jams (number of dams per 100m and number of dams per 500m) decreased downstream from headwaters and with increasing channel width • Abundance of partial spanning dams increased in downstream direction • Debris loading (kg/m^2) decreased in downstream direction	Gregory et al. 1993
Southeastern France	• 0.0012 to 0.0018 channel gradients • 3700 km^2 drainage area • 6th order river	• LWD differentially deposited on banks depending on flow and forest conditions	Piegay 1993
Western Oregon	• 0.022 average channel gradient • 23 m average channel width • 60 km^2 drainage area	• Channel width and sinuosity were main factors controlling LWD supply and distribution • Number and volume of LWD highest in wide sinuous reaches	Nakamura and Swanson 1994

Table A-1. The characteristics and distribution of LWD in various geographic locations and channel network locations (arranged in chronological order).

LOCATION	CHANNEL NETWORK POSITION	RESULTS	REFERENCES
	• 5th order channel		
Southwest Alaska **Western** Washington	• 0.002 to 0.085 channel gradients • 2.5m to 38m channel widths	• Number of LWD pieces per m^2 decreased with increasing channel width • Logs in larger channels were more readily transported • Inverse proportionality between pool spacing and LWD frequency	Montgomery et al. 1995
North Central Colorado	• 0.005 to 0.065 channel gradients • 4 m to 10 m bankfull width • 2 km^2 to 30 km^2 drainage areas • 1st through 3rd order streams	• Abundance (pieces of LWD/ m) greater in smaller streams when sorted by drainage area and width • Lower percentage of pieces spanned channel in larger streams (sorted by drainage area and width) than in smaller streams • Percentage of LWD lying perpendicular to stream channel decreased with increasing drainage area • Percentage of debris pieces in wetted channel decreased in larger streams • Percentage of LWD above wetted channels increased in smaller streams • LWD randomly distributed in streams <5.0 m width and clumped into jams in >5.0 m in width	Richmond and Fausch 1995
Northwest Washington	• 0.002 to 0.05 channel gradients • 5 m to 20 m channel widths • 2 km^2 to 120 km^2 drainage areas	• Loading and abundance decreased with increasing channel width • Channel width is dominant influence on number of pieces of LWD/m^2	Beechie and Sibley 1997
Southeastern France	• 0.0012 to 0.0018 channel gradients • 3700 km^2 drainage area • 6th order river	• LWD distribution on meander banks related to angle of bank to flow, height of flow, and presence of secondary channels	Piegay and Marston 1998
Spain	• 0.08 to 0.1575 channel gradients • 3 m to 8 m channel widths • 0.4 km^2 to 64 km^2 drainage areas • 1st through 3rd order streams	• Abundance and loading decreased in downstream direction	Elosegi et al. 1999
Southeastern France	• 0.003 to 0.008 channel gradients • 1650 km^2 drainage area	• Most LWD in active channel on high bars • LWD deposit controlled by deposit site morphology and proximity of LWD sources	Piegay et al. 1999

Table A-2. The mobility and transport mechanisms of LWD in various geographic locations and channel positions (arranged in chronological order).

LOCATION	CHANNEL NETWORK POSITION	RESULTS	REFERENCES
Western Oregon	• 0.10 to 0.30 channel gradients	• Ability of streams and rivers to move LWD depends on size of river and wood dimensions • Large rivers transport most LWD, while small streams move only small debris short distances before deposition on channel obstructions • Very large debris in small channels transported through debris torrents • Torrents rare in >2nd to 3rd order streams, as steep gradients are required to move debris	Swanson et al. 1976
Western Oregon	• 0.02 to 0.50 channel gradients	• Debris moves through flotation at high flows or through debris flows • Debris flows originate in 1st and 2nd order channels (>50% gradient, <0.2 km^2 drainage areas) • 3rd to 5th order streams (4 km^2 to 60 km^2 drainage areas) wide enough to float large debris and debris jams at high flows	Swanson and Lienkaemper 1978
Eastern Washington	• 0.015 channel gradient • 11.5 m bankfull width	• LWD movement depended on length and diameter of wood • Distance traveled by LWD inversely related to piece length • Anchored pieces more stable in high flows	Bilby 1984
Indiana North Carolina Oregon	• 0.001 to 0.40 channel gradients	• Debris torrents main transport mechanism in small, high gradient streams • Flotation main transport mechanism in large, low gradient streams	Keller and Swanson 1979
Western Oregon	• 0.03 to 0.37 channel gradients • 3.5 m to 24 m bankfull widths • 0.1 km^2 to 61 km^2 drainage areas • 1st through 5th order streams	• Wood movement occurred in larger streams during monitoring period • Distance moved depended on piece length in relation to bankfull width • All pieces moving >10 m were shorter than bankfull width	Lienkaemper and Swanson 1987
Western Oregon	• 0.03 to 0.21 channel gradients • 7 m to 25 m bankfull widths • 2nd through 5th order streams	• Debris flows redistributed LWD in steep, low- order streams • Floods redistributed LWD in medium to high order streams	Nakamura and Swanson 1993
Western Oregon	• 0.019 to 0.028 channel gradients • 9 m to 71 m channel widths • 5th order streams	• Most transported pieces shorter than bankfull width • 20% of untransported pieces longer than bankfull width • LWD length to channel width useful measure of susceptibility to transport	Nakamura and Swanson 1994
Wyoming	• 0.041 to 0.055 channel gradients • 6.4 m to 7 m low flow channel widths	• LWD less stable in burned drainage due to increased runoff and peak flows, and decreased bank stability	Young 1994
NA	• NA	• Uncongested, semi-congested, and congested wood transport based on ratio of log input (Q_{log}) to stream discharge (Q_w) • Proposed ability of channel to retain wood is function of debris roughness, which varies with channel and log dimensions	Braudrick et al. 1997
Spain	• 0.08 to 0.1575 channel gradients • 3 m to 14 m bankfull widths • 0.8 km^2 to 69 km^2 drainage areas • 1st through 3rd order streams	• Loading(m^3/m^2) decreased in downstream direction • Log mobility increased in larger streams	Elosegi et al. 1999

Table A-3. The effect of LWD on the storage and transport of bedload in various geographic locations and channel network positions (arranged in chronological order).

LOCATION	CHANNEL NETWORK POSITION	RESULTS	REFERENCES
Western Oregon	• 0.10 to 0.30 channel gradients	• LWD accumulations trapped 230 m^3 of sediment in 100 m reach	Swanson et al. 1976
Western Oregon	• 0.02 to 0.50 channel gradients	• Annual sediment yield less that 10% of material in storage • Woody material primary storage element	Swanson and Lienkaemper 1978
Northern California	• 0.01 to 0.048 channel gradients • 6.4 m to 9.6 m channel widths	• Debris stored sediment comprised 40% of channel area	Keller and Tally 1979, Tally 1980, Keller and MacDonald 1983, Keller et al. 1985
Western Washington	• 0.07 channel gradient	• Accelerated erosion of stored sediment (5000m^3) after LWD removal from 250 m reach	Beschta 1979
New Hampshire	• 0.21 average channel gradient • 3.0 m average channel width	• 500% increase in the export of stored sediment after removal of LWD	Bilby 1981
Central Idaho	• 0.21 average channel gradient • 5.0 m average channel width • 1st through 3rd order streams	• Logs accounted for 50% of total sediment stored and 34% of all channel obstructions	Megahan 1982
Eastern Washington	• 0.015 channel gradient • 11.5 m bankfull width	• Reduction in sediment storage (increased scour) after logging and stream cleaning	Bilby 1984
Arizona	• 0.07 to 0.09 channel gradients	• Removal of log steps led to increased bedload movement • Log steps eventually replaced gravel bars	Heede 1985a, 1985b
Northern California	• 0.006 to 0.014 channel gradients • 12 m average channel width	• LWD obstructions stabilize gravel channels by controlling location of pools and bars	Lisle 1986a
Alaska	• 0.01 to 0.09 channel gradients • 2 m to 6 m active channel width	• Debris acted to store sediment through the creation of low-energy depositional environments	Lisle 1986b
Western Washington	• 0.13 channel gradient (<7 m channel width) • 0.08 channel gradient (7 m to 10 m channel width) • 0.03 channel gradient (>10 m channel width)	• 40% of LWD associated with sediment accumulations in 0.13 channel gradient (<7 m channel width) • <30% of LWD associated with sediment accumulations in 0.08 channel gradient (7 m to 10 m channel width) • <20% of LWD associated with sediment accumulations in 0.03 channel gradient (>10 m channel width)	Bilby and Ward 1989
Western Washington	• 3 m to 24 m bankfull channel widths	• Sediment retention by LWD decreased with increasing stream size • Amount of sediment retained was associated with age and volume of wood	Bilby and Ward 1991
Western Oregon	• 0.03 to 0.21 channel gradients • 7 m to 25 m bankfull widths • 2nd through 5th order streams	• LWD was dominant sediment storage control in moderate to steep streams • LWD provided temporary sediment storage in low gradient reaches	Nakamura and Swanson 1993
Southeast Alaska	• 0.01 average channel gradient • 3.9 m average channel width	• Four fold increase in bedload transport and bankfull flow after LWD removal	Smith et al. 1993a
Southeast Alaska	• 0.008 to 0.010 channel gradients • 4 m average channel width	• Initial increase in bedload transport after LWD removal • Channel readjusted to form series of regularly spaced bars	Smith et al. 1993b
Colorado	• 0.11 average channel gradient • 3.5 m average channel width	• LWD major control on the storage and release of bedload	Adenlof and Wohl 1994
Western Washington	• 0.10 to 0.15 channel gradients • 3 m to 4 m channel widths	• LWD major control on sediment storage and transport	O'Connor 1994
Belgium	• 0.046 channel gradient • 0.75 m channel width • 2nd order stream	• Log jams reduced movement and transport of bed material	Assani and Petit 1995
Northeast California	• 0.02 to 0.08 channel gradients • 2 m to 12 m bankfull width	• LWD minimal effect on sediment storage	Berg et al. 1998
Northwest Washington	• 0.24 average channel gradient • 2.7 m average channel width	• LWD main component of sediment storing obstructions	Grizzel and Wolff 1998

Table A-4. The effect of LWD on channel dimension in various geographic locations and channel network positions (arranged in chronological order).

LOCATION	CHANNEL NETWORK POSITION	RESULTS	REFERENCES
Western Oregon	• 0.10 to 0.30 channel gradients	• LWD controlled 30% to 50% of drop in elevation • LWD caused pronounced local widening of streams	Swanson et al. 1976
Indiana North Carolina Oregon	• 0.001 to 0.40 channel gradients	• Scour around jams increased channel width by more than 50% • In low gradient streams LWD contributed to formation of meander cutoffs • In high gradient streams sediment storage by channel spanning wood created stepped profile • LWD controls 30% to 80% of drop in elevation	Keller and Swanson 1979
Northwest California	• 0.01 to 0.40 channel gradients • 1.0 km^2 to 27 km^2 drainage areas • 2nd through 4th order streams	• Width at debris accumulations was two or more times greater than characteristic width of channel • 60% of drop in elevation associated with LWD steps • Extensive ponded sediment upstream LWD • Wood had less effect on elevation in steeper sections where debris rests of above boulders • LWD created variety of channel depths • Effect on elevation decreased with decreasing channel gradient	Keller and Tally 1979, Tally 1980, Keller and MacDonald 1983, Keller et al. 1985
Southeast Alaska	• 42 km^2 drainage area	• LWD significant influence on channel width, and pool and bar location	Bryant 1980
Southeast Alaska	• 15 km^2 to 75 km^2 drainage areas • 4th through 5th order streams	• LWD accumulations decreased 30 years after logging • LWD influenced channel width, and pool and bar location	Bryant 1983
Arizona	• 0.07 to 0.09 channel gradients	• Log steps controlled channel gradient in steep streams • LWD part of natural hydraulic geometry of steep streams	Heede 1985a, b
Southeast Alaska	• <0.03 channel gradients • 0.7 km^2 to 55 km^2 drainage areas • 1st through 4th order streams	• Variations in local bankfull width associated with volume of instream LWD	Robison and Beschta 1990
Western Oregon	• 0.03 to 0.21 channel gradients • 7 m to 25 m bankfull widths • 2nd through 5th order streams	• Widths upstream of key LWD and LWD jams wider than channel averages in medium order channels • Gradients upstream of key LWD and LWD jams lower than channel averages in medium order channels • Channels with key LWD are 1.5 times wider than channels without key LWD	Nakamura and Swanson 1993
United Kingdom	• 11 km^2 drainage area	• LWD accumulations contributed to bank subsidence leading to widening in stream channel	Davis and Gregory 1994
Coastal British Columbia, Canada	• 0.01 to 0.07 channel gradients • 10 m to 30 m bankfull widths • 1 km^2 to 28 km^2 drainage areas	• LWD jams greatest influence on overall channel morphology • Individual pieces important to channel morphology and small scale features between jams • Channels increased in complexity as LWD jams age and deteriorate • Old growth forests had low rate of jam formation, leading to jams of various ages and complex channel forms • Disturbed forests have accelerated rates of jam formation, altering channel morphology	Hogan et al. 1998

Table A-5. The effect of LWD on pool formation and spacing in various geographic locations and channel network positions (arranged in chronological order).

LOCATION	CHANNEL NETWORK POSITION	RESULTS	REFERENCES
Western Oregon	• 0.02 to 0.50 channel gradients	• In steep streams, LWD main factor in determining character of aquatic habitat • In low gradient streams, hydraulic factors regulated aquatic habitat	Swanson and Lienkaemper 1978
Northwest California	• 0.01 to 0.048 channel gradients • 1.0 km^2 to 27 km^2 drainage areas • 2nd through 4th order streams	• Debris enhanced pools increased in abundance with increasing channel gradient • Pool spacing decreased with increasing gradient	Keller and Tally 1979, Tally 1980, Keller and MacDonald 1983, Keller et al. 1985
Southeast Alaska	• 0.001 to 0.03 channel gradient • 2nd through 4th order streams	• Most pools formed by debris • Pool volume and debris volume directly correlated	Murphy et al. 1986
Northwest California	• 0.006 to 0.014 channel gradients • 12 m average channel width • 26 km^2 drainage area	• LWD major component in pool formation and long-ter m channel stability	Lisle 1986a
Alaska	• 0.01 to 0.09 channel gradients • 2 m to 6 m active channel width • 0.5 km^2 to 2.0 km^2 drainage areas	• Debris formed 46% of pools in forested reaches • Debris formed 86% of pools in clear-cut streams due to higher debris loads	Lisle 1986b
Western Oregon	• 0.02 to 0.06 channel gradients • 5.5 m to 8 m bankfull widths • 6.5 km^2 drainage area	• 70% of all pools created primarily by woody debris	Andrus et al. 1988
Western Washington	• 0.13 channel gradient (<7 m channel width) • 0.08 channel gradient (7 m to 10 m channel width) • 0.03 channel gradient (>10 m channel width)	• Plunge pool most common (40%) of all LWD formed pools in streams <7m • Scour pools most common (60%) of all LWD formed pools in streams >10m	Bilby and Ward 1989
Eastern Oregon	• 0.02 to 0.07 channel gradients • 2 m to 6 m bankfull width • 7 km^2 to 25 km^2 drainage areas	• Debris associated with 64% of pools in all study streams	Carlson et al. 1990
Southeast Alaska	• <0.03 channel gradients • 0.7 km^2 to 55 km^2 drainage areas • 1st through 4th order streams	• LWD formed 65% to 75% of all pools • Shift in pool types from plunge to lateral scour in small to large streams	Robison and Beschta 1990
Western Washington	• 3 m to 24 m bankfull channel widths	• Frequency of LWD associated pools decreased with increasing stream size • Type of pools associated with LWD changed with stream size: scour pools increased and plunge pools decreased with increasing stream size	Bilby and Ward 1991
Western Tennessee	• 13,000 km^2 drainage area	• Physical habitat diversity strongly correlated with presence of LWD	Shields and Smith 1992
Southeast Alaska	• 0.008 to 0.01 channel gradients • 4 m average channel widths • 1.5 km^2 drainage area	• Pool spacing similar before and after LWD removal • Pools formed by non-erodible obstructions but lacked cover and hydraulic complexity of wood formed pools	Smith et al. 1993a,b
Western Oregon	• 0.022 average channel gradient • 23 m average channel width • 60 km^2 drainage area • 5th order channel	• 17% of LWD in wide sinuous channels affected pool formation, 2 to 5 times higher than other channel types	Nakamura and Swanson 1994
Southwest Alaska Western Washington	• 0.002 to 0.085 channel gradients • 2.5 to 38 m channel widths	• 73% of pools formed by LWD • 40% of wood influenced pool formation • Pool spacing inversely related to LWD loading in plane-bed, pool-riffle, and forced pool riffle channels. • Pool spacing increased with increasing channel width • >0.01 gradient channels: pool formation sensitive to LWD loading • <0.01 gradient channels: pool formation not as sensitive to LWD loading	Montgomery et al. 1995

Table A-5. The effect of LWD on pool formation and spacing in various geographic locations and channel network positions (arranged in chronological order).

LOCATION	CHANNEL NETWORK POSITION	RESULTS	REFERENCES
North Central Colorado	• 0.005 to 0.065 channel gradients • 4 m to 10 m bankfull width • 2 km^2 to 30 km^2 drainage areas • 1st through 3rd order streams	• 76% of pools formed by LWD • 4% to 20% of LWD formed pools • Higher proportion of LWD in smaller streams formed pools • LWD perpendicular to flow in small streams • LWD diagonal to flow in large streams	Richmond and Fausch 1995
Northwest Washington	• 0.005 to 0.01 channel gradients • 30 m to 80 m bankfull widths • 75 km^2 to 225 km^2 drainage areas	• 70% of all observed pools associated with LWD jams • LWD associated pools provide other habitat values (cover and nutrient trapping) not associated with pools formed other ways	Abbe and Montgomery 1996
Northwestern Nevada	• 0.02 to 0.04 channel gradients	• 10% of LWD pieces formed pools • LWD positive effects on pool formation and quality	Myers and Swanson 1996a, b
Southwest Alaska	• 0.0017 to 0.0224 channel gradients • 4 m to 25 m bankfull widths • 1 km^2 to 40 km^2 drainage areas	• LWD associated with 80% of pools in undisturbed streams • LWD associated with 55% of pools in disturbed streams	Wood-Smith and Buffington 1996
Northwest Washington	• 0.002 to 0.05 channel gradients • 5 m to 20 m channel widths • 2 km^2 to 120 km^2 drainage areas	• Pool formation in moderate to steep slope channels highly sensitive to presence of LWD • Pools in low slope channels formed by mechanisms other than LWD	Beechie and Sibley 1997
Southwest Virginia	• 0.01 to 0.06 channel gradients • 5 m average channel width	• Number of pools in low gradient reaches increased after LWD additions • Number of pools in high gradient reaches unchanged after LWD additions	Hilderbrand et al. 1997
United Kingdom	• 0.013 average channel gradient • 2 m to 5 m bankfull width	• Pools closely associated with LWD • Channels with LWD have more pools than channels without LWD	Gurnell and Sweet 1998
Southeastern France	• 0.003 to 0.008 channel gradients • 1650 km^2 drainage area	• Few pools associated with LWD • Pool size independent of LWD mass • LWD accumulations moderately influenced channel morphology	Piegay et al. 1999

Table A-6. The effect of LWD on nutrient dynamics in various geographic locations and channel network positions (arranged in chronological order).

LOCATION	CHANNEL NETWORK LOCATION	RESULTS	REFERENCES
New Hampshire	• 0.21 channel gradient • 3 m average channel width • 1st through 3rd order streams	• Increase in organic carbon transport after wood removal • 18% increase in DOC export, 632% increase in FPOC export, 138% increase in CPOM export after wood removal • Decrease in number of debris dams down the stream network: 33.5 per 100 m (1st order), 13.7 per 100m (2nd order), 2.5 per 100m (3rd order)	Bilby and Likens 1980
New Hampshire	• 0.21 channel gradient • 3m average bankfull width • 2nd order stream	• Increase in FPOM and CPOM (500%) export during high discharge after LWD removal • Twigs and FPOM are important for retention of matter, filling cracks and holes in dams to make them watertight and increase hydraulic effectiveness • Decrease in LWD control on elevation from 1st through 3rd order streams: 52% of elevation drop controlled by wood in 1st order streams, 46% of elevation drop controlled by wood in 2nd order streams, 10% of elevation drop controlled by wood in 3rd order streams	Bilby 1981
Northwest Washington	• 0.014 (0.01 to 0.02) channel gradients • 7.7 km^2 basin area	• General positive trend in LWD/m^2 and number of coho salmon (*Oncorhynchus kisutch*) carcasses retained • Carcasses important source of nutrients for aquatic and terrestrial organisms	Cederholm and Peterson 1985
Western Oregon	• 0.10 channel gradient • 6 km^2 drainage area	• Woody debris is source for approximately 90g/m/yr fine particulate organic matter (FPOM) • For systems with large accumulation of LWD and FWD, wood processing can be significant source of FPOM pool • FPOM from wood potential to be greater than that generated from leaf and needle litter processing • Production of FPOM greater in winter from physical abrasion	Ward and Aumen 1986
Pacific Northwest, USA	• N/A	• Wood decomposes more slowly in water than on land • Waterlogging prevents deep penetration of O_2 in wood • Decomposition increases as grazing or abrasion increases; allows O_2 to penetrate wood • Concentration of carbon and nitrogen increases as wood decomposes • Increase in nitrogen concentration as carbon use increases, and through nitrogen fixing microorganisms • Nitrogen fixation on wood accounts for 5% to 10% of annual nitrogen supply to stream • Slow decomposition of instream wood influences stability of LWD and maximizes role in habitat formation	Sedell et al. 1988
Northwest Washington	• Low gradient • 15 m to 24 m channel width • 3rd order streams	• Distance carcasses drifted inversely related to debris loads • Large and small organic debris most important instream retention element for carcasses • LWD formed pools were most important carcass deposition site	Cederholm et al. 1989
Northern Oregon	• N/A	• At reach scale wood not significant in Nitrogen and Phosphorous uptake • At smaller scales, woody debris active in Nitrogen and Phosphorous removal from water • Woody debris provides surface area for microorganisms that uptake nutrients	Aumen et al. 1990

Table A-6. The effect of LWD on nutrient dynamics in various geographic locations and channel network positions (arranged in chronological order).

LOCATION	CHANNEL NETWORK LOCATION	RESULTS	REFERENCES
New Hampshire	• N/A	• Organic debris dams important sites of organic matter retention and accumulation • Community respiration 3 times higher (234mg C/m^2/day) in sediment associated with organic debris dams • Organic matter content (up to 5 cm depth) significantly higher in sediment associated with debris dams (average = 1.7kg/m^2) • Results suggest debris dams are focal sites of metabolic activity in these headwater streams • Metabolic activity may be underestimated, as measured to a depth of only 5cm	Hedin 1990
New Mexico	• 0.17 to 0.19 channel gradients	• Reaches with wood stored more organic matter than reaches without wood • Decrease in average velocity and increase in stream width and depth after wood addition • Increase in average velocity and decrease in average width and depth after wood removal • Particle retention rates increased in streams with dams or wood • Dams stopped particles, deflected flow, changed water velocity, and altered width and depth of the stream • Retention may depend on channel stability; retention decreases with decreasing channel stability	Trotter 1990

Table A-7. The effect of LWD on aquatic macroinvertebrates in various geographic locations and channel network positions (arranged in chronological order).

LOCATION	CHANNEL NETWORK LOCATION	RESULTS	REFERENCES
Oregon	• 0.017 to 0.35 channel gradients	• LWD loading (kg/m^2) decreased with increasing stream order • Caddisfly were most conspicuous and diverse insects on wood • Trichoptera (*Heteroplectron californicum*) and Coleoptera (*Lara avara*) were major invertebrates associated with wood substrates • *L. avara* strongly associated with amount of wood available, irrespective of stream size • Lower insect biomass on wood compared to leaf pack • Two possible mechanisms for wood exploitation: 1) wood consumption to obtain digestible carbon and nitrogen from microbial flora, 2) cultivation and retention of gut flora	Anderson et al. 1978
Washington Oregon California	• N/A	• Continuum of faunal association on LWD ranges from obligate restriction to purely opportunistic use • Sequence of colonists parallel state of wood decay • High gradient tributaries had reasonably good fauna of borers/gougers and several other groups • Where gradient decreased, siltation and accumulation of organic fine particles excluded many gougers and scrapers; much wood buried where DO was low and fungal activity low • In main stem, abrasion diminished the role of invertebrates in wood degradation, most wood occurred in large jams, deposited on shore, and was unavailable to aquatic forms • Wood associated invertebrate community and its impact on wood was dependent on physical regime • Wood quality and texture important in determining species colonization • 66% of closely associated groups (obligate) found in soft, rotten wood, 30% on grooved, textured wood, and <10% on firm substrates • 20% of facultative groups found in soft, rotten wood, 70% on grooved, textured wood, and 10% on firm wood • Functional feeding groups associated with wood texture; smooth surfaces for attachment (filterers) and grazers, soft wood form borers • Facultative species may use wood more as refuge from predation than for attachment	Dudley and Anderson 1982
Washington Oregon California	• N/A	• Feeding is main process affecting insect mediated fragmentation • Most important insects in degradation process are borers and gougers • Compared to terrestrial situations, diversity and density of borers and gougers is low due to lack of O_2	Pereira et al. 1982
Southeast Alaska	• 1.9 m average channel width • 9 km^2 channel width • 6.5 km long	• Benthos density, # of drift invertebrates, and # of invertebrates eaten by Dolly Varden (*S. malma*) decreased after wood removal • Benthos biomass decreased by one-third during treatment phase • Invertebrate drift decreased significantly after debris removal • Debris used as substrates used by all benthic taxa, removal directly reduced abundance of benthos	Elliott 1986

Table A-7. The effect of LWD on aquatic macroinvertebrates in various geographic locations and channel network positions (arranged in chronological order).

LOCATION	CHANNEL NETWORK LOCATION	RESULTS	REFERENCES
Pacific Northwest, USA	• N/A	• Literature review • Sequence of colonists parallels stage of decay • New wood is primarily habitat for algae, microbes, grazers, an collectors • Colonization promotes decomposition and colonization by wood shredders (caddisflies, stoneflies) • Textured surface provides habitat for organisms • Fungal growth and effect of wood borers speeds decay • Detrivores and earthworms continue decomposition • Three most important wood processors consume only 2% of all available wood	Sedell et al. 1988
Arkansas	• 1st through 3rd order streams	• Trichoptera found in greater densities in benthic habitats than on LWD, but three families found in greater densities on LWD • Wood associated Trichopterans found on highly decayed wood and on LWD with rough texture, providing attachment sites for net spinning caddisflies	Phillips 1994
North Carolina	• 0.03 to 0.06 channel gradients	• Pool formation after log addition • Invertebrate abundance and biomass increased significantly after log addition • Scraper and collector/filterer abundance increased after log addition • Secondary production of scrapers and filterers decreased • Shifts in functional group abundance and biomass accentuate the importance of local abiotic factors in patch structure of invertebrate communities	Wallace et al. 1995
Victoria, Australia	• N/A	• Top of snags supported more macroinvertebrates species than other surfaces • Grooved snags supported significantly more macroinvertebrates • Results of study show importance of snag habitat in streams and rivers • Results support habitat complexity hypothesis where species richness increases with habitat complexity	O'Connor 1991
New York	• 30 m to 50 m channel width • 4th order stream	• Invertebrate densities greater on wood than on leaves • Filterers disproportionately colonized wood and collector/gatherer favored leaves • Larger percentage of scrapers on leaves than on wood • Densities correlated with biofilm development, which was greater on wood • As wood softened through physical and biological forces, wood became more physically complex, offering more microhabitats • Surface complexity and stability contributed to increased taxon density on wood	Hax and Golladay 1993
Northern Virginia	• 20 m average channel width • 4th order stream	• Debris dams stored fine sediment and leafy debris • Abundance of Chironomid and Copepod behind dams less likely to decline during floods • Other patch types showed 75% to 95% reductions in Chironomid and Copepod abundance after floods • Debris removal did not impede faunal recovery • Results suggest debris dams associated with fine sediment and leafy debris have potential to act as refugia during high flow • Patches accumulating animals were characterized by low water flux and low bedflow, likely contributing to retention or passive deposition of animals	Palmer 1996
Southwest Virginia	• 0.01 to 0.06 channel gradients • 5 m average channel width	• Benthic macroinvertebrate abundance did not increase after log additions • Net abundance of Plecoptera, Coleoptera, Trichoptera, and Oligochaeta decreased while Ephemeroptera increased with increase in pool area	Hilderbrand et al. 1997

Table A-8. The effect of LWD on fish (predominantly salmonids) habitat and populations in various geographic locations and channel network positions (arranged in chronological order).

LOCATION	CHANNEL NETWORK POSITION	RESULTS	REFERENCES
Michigan	• N/A	• Log structures increased habitat area and increased Brook trout (*Salvelinus fontinalis*) abundance	Tarzwell 1937
Montana	• 1 m channel width	• Abundance and biomass of Brook trout (*Salvelinus fontinalis*), rainbow trout (*Oncorhynchus mykiss*), brown trout (*Salmo trutta*) increased after addition of artificial wood cover • Abundance and biomass decreased after brushy cover removal	Boussu 1954
British Columbia, Columbia	• 10 km^2 drainage area	• Areas with logs, undercut banks, and deep pools filled with upturned tree roots (and other forest debris) contained coho salmon (*Oncorhynchus kisutch*)	Tschaplinski and Hartman 1983
Central Illinois	• >0.001 channel gradient • 3 m to 5 m channel width	• More species, more individuals, and larger fish captured in reaches with wood • Higher invertebrate abundance in reaches with wood • Fish preference for debris filled reaches related with food availability • Wood provided substrate for macroinvertebrates • Wood plays multidimensional role in structure and function of stream ecosystems	Angermeier and Karr 1984
Pacific Northwest	• N/A	• Literature review on historical processes and management of LWD, geomorphic functions, channel morphology, influence on fish habitat, and management of LWD inputs into streams	Sedell et al. 1988
Southeast Alaska	• 4th through 5th order streams	• Dolly Varden (*Salvelinus malma*), steelhead trout (*Oncorhynchus mykiss*), coho salmon (*Oncorhynchus kisutch*) • Where debris absent, densities of coho salmon (*Oncorhynchus kisutch*) consistently lower • Backwaters and side channels associated with LWD had higher densities of coho salmon (*Oncorhynchus kisutch*) than main channel areas with debris • Density of coho salmon (*Oncorhynchus kisutch*) fry decreased as size of accumulation decreased • Mid-channel debris, regardless of size supported lower densities of coho salmon (*Oncorhynchus kisutch*) than rootwads along the bank	Bryant 1985
Southeast Alaska	• 0.035 to 0.05 channel gradients • 2 m average channel widths	• No significant difference in average channel depth or width between cleared and uncleared reaches • In general, uncleaned stream sections contained more fish of all sizes than cleared sections • Despite used of selective techniques, numbers and production of both coho salmon (*Oncorhynchus kisutch*) and Dolly Varden (*Salvelinus malma*) were reduced by removal of LWD	Dolloff 1986
Southeast Alaska	• 1.9 m average channel width • 9 km^2 channel width • 6.5 km long	• Removal of logging debris reduced wetted width and areas from 874 m^2 and 726 m^2 • Dolly Varden (*Salvelinus malma*) population decreased from 748 to 100, two years after debris removal • Decrease in fish size after clearance • Before debris removal, fish occupied mid channel pools and tangles of debris • After removal, fish occupied backwaters and stream margins • Removal of logging debris changed morphology, briefly reduced food supply and eliminated most cover, reducing # and mean length of fish, leaving small fish susceptible to displacement • Decrease in benthos abundance, reduced amount of food eaten by Dolly Varden (*Salvelinus malma*) and may have contributed to numerical decline	Elliott 1986

Table A-8. The effect of LWD on fish (predominantly salmonids) habitat and populations in various geographic locations and channel network positions (arranged in chronological order).

LOCATION	CHANNEL NETWORK POSITION	RESULTS	REFERENCES
Southeastern Alaska	• 0.02 to 0.03 channel gradients • 2nd through 4th order streams	• Most fish, regardless of species or age, were in pools • Amounts of LWD and cobble significantly increased in occupied pool than in unoccupied pools • LWD caused 73% of all pools • Juvenile salmonids (in winter) preferred pool with cover (upturned roots, accumulation of logs, cobble substrate) • Amount of preferred winter habitat depended on amount of LWD • Clearcut reaches had less LWD and less pool area • Buffer strips protect habitat by providing LWD	Heifietz et al. 1986
Oregon	• 9.3 km^2 drainage area • 0.03 average channel gradient	• Fewer pieces of LWD in logged section (6 pieces per 100m) compared to in undisturbed section (46 pieces per 100m) • LWD most important factor controlling differences in channel morphology: LWD created stair step morphology, secondary channels, and meanders • Undisturbed sections, LWD improved pool quality and # of pools • After LWD additions, gravel abundance increased by 233%, gravel area increased 25 fold • 3 times more coho (*Oncorhynchus kisutch*) (0.88/m^2) and steelhead (*Oncorhynchus mykiss*) (0.59/m^2) in undisturbed sections • Positive correlation between fish populations (spawning and rearing habitat) and LWD	House and Boehne 1986
Alaska	• 0.01 to 0.09 channel gradients • 2 m to 6 m channel widths • 0.5 km^2 to 2 km^2 drainage area	• Debris dam frequency correlated with debris loading • Debris dams formed 86% of pools in clearcut reaches and 47% of pools in unforested reaches • Debris dams effective at maintaining depth in low flow (residual depth)	Lisle 1986a
Washington	• 280 km total stream length for basin	• Salmonid disappearance after Mount St Helens eruption • LWD related habitats made up 1% of total in new channels, 6% to 12% in old affected channels, and 12% to 16% in old unaffected channels • Streams with little amount of LWD, also had decreased amount of pool area • Debris produces cover but also reduces water velocity	Martin et al. 1986
British Columbia, Canada	• Artificial channels 4.9 m (l) by 0.9 m (w) by 0.6 m (d)	• Coho salmon (*Oncorhynchus kisutch*) abundance increased as cover complexity increased • Winter cover for coho (*Oncorhynchus kisutch*) combined low velocity, shade, and 3 dimensional complexity	McMahon and Hartman 1989
Southeastern Alaska	• 0.10 to 0.30 channel gradient • 5 m to 7 m channel width	• Winter coho salmon (*Oncorhynchus kisutch*) fry density best modeled by summer periphyton biomass and volume of instream debris • Parr abundant where debris was abundant • In both summer and winter, density of Dolly Varden (*Salvelinus malma*) parr directly related to LWD volume • Cover (LWD and undercut banks) more important for all parr in winter	Murphy et al. 1986
British Columbia, Canada	• 10 km^2 drainage area	• Reduction in volume and stability of LWD 2 years after logging • After logging, buffering of stream energy reduced, cohesion of streambanks reduced • Increase in sand led to reduced gravel quality and decreased sites available for chum (*Oncorhynchus keta*) and coho salmon (*Oncorhynchus kisutch*) spawning • Better growth by young coho salmon (*Oncorhynchus kisutch*) and cutthroat trout (*Oncorhynchus clarki*) • LWD provided overwinter cover • Decreased densities of coho (*Oncorhynchus kisutch*) led to faster growth rate, larger size, and higher winter survival	Hartman et al. 1987

Table A-8. The effect of LWD on fish (predominantly salmonids) habitat and populations in various geographic locations and channel network positions (arranged in chronological order).

LOCATION	CHANNEL NETWORK POSITION	RESULTS	REFERENCES
Oregon	• 0.10 average channel gradient • 3.2 average channel width • 5.4 km^2 drainage area • 3rd order stream	• 2.4 fold increase in lateral habitat gave 2.2 fold increase in number of age-0 cutthroat trout (*Oncorhynchus clarki*) • 86% reduction in lateral habitat gave 83% reduction in age 0 cutthroat trout (*Oncorhynchus clarki*) • Significantly higher trout production in lateral habitat of manipulated section than in control section and LWD reduced sections (95% and 24%) • Functional lateral habitat comes from LWD interaction with streambed	Moore and Gregory 1988
Southeast Alaska	• <2 m wide streams	• Logs, branches, undercut banks, dense overhead vegetation, and large boulders were primary types of cover used by coho salmon (*Oncorhynchus kisutch*) and Dolly Varden (*Salvelinus malma*) of all age classes	Dolloff and Reeves 1990
British Columbia, Canada	• 108 km^2 drainage area	• Coho salmon (*Oncorhynchus kisutch*) fry (99%) and steelhead (*Oncorhynchus mykiss*) parr (83%) occupied positions near mid-channel artificial rootwads in all flow conditions (drought, normal, and flood) • Coho preferred near shore pieces, while steelhead preferred more distant sites • Young fish preferred slow water (80%) and low light (20%) environments for protection from high currents and predators	Shirvell 1990
British Columbia, Canada	• 0.005 to 0.04 channel gradients • 2 m to 5 m average bankfull width • 1.03 to 1.37 sinuosity	• Sections with LWD removed were less sinuous, wider and shallower and had less cover for fish than unaltered sections • Pools were 9% to 25% of total volume at baseflow in removal sections, 61% to 69% of total volume in unaltered sections • Number of pieces of LWD directly influencing channel morphology was greater in unaltered sections • LWD formed 72% to 80% of pools in all sections • Depths of pools greater in unaltered sections • After surface flow ceased in summer, 96% of pool volume associated with LWD • In higher gradient reaches (0.015 to 0.04 gradient) most wood oriented perpendicular to flow • In lower gradient reaches (>0.015) much higher percentage (40%) of diagonal orientation • Standing crop of age 1+ and older salmonids was much lower in cleared sections than in unaltered sections • Biomass of age 1+ and older fish correlated with pool volume, section volume, mean depth, and length of overhead cover • Fish biomass strongly correlated with pool volume and depth • Uncleared sections had five times the current standing crop in cleared sections	Fausch and Northcote 1992
British Columbia, Canada	• Buffered, clearcut, estuarine reaches	• LWD influenced abundance of coho smolts (*Oncorhynchus kisutch*) in stream and estuary • Coho smolt (*Oncorhynchus kisutch*) distribution highly clumped around debris; 80% within 5 m of debris; 95% within 1m • Supports the need to retain LWD for smolt habitat in streams and estuaries	McMahon and Holtby 1992
Oregon	• 27 km^2 drainage area • 5th order stream	• Stream surface area and water volume increased 74% and 168% after log addition • Surface area of pool and off channel habitat increased in treated sections • Spawning activity four times higher in treated section	Crispin et al. 1993
Alberta, Canada	• 23 m channel width • 0.5 m channel depth • 571 km^2 drainage area • 4th order stream	• Fry densities higher in sections with fine woody debris (FWD) additions • FWD may have provided structurally complex habitat, used as refuge from predators and as sites from which foraging forays began	Culp et al. 1996

Table A-8. The effect of LWD on fish (predominantly salmonids) habitat and populations in various geographic locations and channel network positions (arranged in chronological order).

LOCATION	CHANNEL NETWORK POSITION	RESULTS	REFERENCES
Maryland	• Subestuarine environment	• Densities of epibenthic fish increased significantly in sites with LWD • LWD provided refuge from predation for epibenthic fish and invertebrates	Everett and Ruiz 1993
North Carolina	• 0.045 to 0.06 channel gradients • 4 m to 5 m channel width • 7 km^2 to 21 km^2 watershed area • 1st through 3rd order stream	• Higher abundance of LWD in undisturbed streams • Undisturbed reaches had 32% to 46% of habitat units associated with LWD • Brook trout (*Salvelinus fontinalis*), rainbow trout (*Oncorhynchus mykiss*), brown trout (*Salmo trutta*) had higher density and biomass in undisturbed reaches with LWD • Larger average size of LWD in undisturbed reaches • More pools and riffles of smaller size in undisturbed reaches	Flebbe and Dolloff 1995
Northern Colorado	• 0.01 to 0.024 channel gradients • 3 m to 6 m channel widths	• Pool volume increased after drop structures installed • Amount of cover increased significantly after addition of log drop structures • Treatment sections were deeper and had lower velocity than control sections • Abundance and biomass of age 2 and older increased significantly after installation of drop structures • Log drop structures increased abundance of adult brook trout (*Salvelinus fontinalis*) and possibly survival, although data not conclusive	Riley and Fausch 1995
Washington	• 2.4 m channel width (artificial channels)	• Found no evidence that summer populations were attracted to brushy debris, nor did the presence of brush influence survival or growth, comparable to free ranging coho salmon (*Oncorhynchus kisutch*) • Affinity of coho salmon (*Oncorhynchus kisutch*) for woody debris increases in winter	Spalding et al. 1995
Northern Colorado	• 0.01 to 0.03 channel gradients • 3 m to 6 m average channel width	• Pool volume and total cover increased after LWD addition • Abundance and biomass of adult of brook trout (*Salvelinus fontinalis*), brown trout (Salmo trutta), rainbow trout (*Oncorhynchus mykiss*) increased in manipulated reaches • Increased abundance and biomass resulted from immigration from surrounding reaches • Log weirs increased abundance and biomass of fish in the absence of any management limitations	Gowan and Fausch 1996
Washington	• 0.002 to 0.015 channel gradients • 38 km^2 drainage area	• Pool spacing significantly correlated with LWD abundance • Survival of coho salmon (*Oncorhynchus kisutch*) correlated with LWD abundance and volume • Positive relationship between habitat complexity (abundance of LWD and pool spacing) at the end of the summer and overwinter survival	Quinn and Peterson 1996
Wyoming	• 2 m to 5 m channel width	• 39% of pools formed by LWD, 64% of cutthroat trout (*Oncorhynchus clarki*) relocated to these pools	Young 1996
Washington	• 0.02 channel gradient • 10.0 m channel width • 3rd order stream	• Pool area increased after LWD addition • Abundance of coho salmon (*Oncorhynchus kisutch*) during spring and winter showed no response to enhancement • Winter abundance of coho (*Oncorhynchus kisutch*) increased significantly after enhancement	Cederholm et al. 1997
Northern California	• 0.022 channel gradient • 27.5 km^2 drainage area • 3rd order stream	• Pools formed by LWD scour contained more cutthroat trout (*Oncorhynchus clarki*) (0.25/m) than pools formed by boulder scour (0.16/m) • Retention of cutthroat trout (*Oncorhynchus clarki*) greatest in complex (LWD) pools during higher flows • Presence of LWD had little of no effect on trout movement or growth during low or moderate discharge, food availability was the main factor controlling movement and growth	Harvey 1998

Table A-8. The effect of LWD on fish (predominantly salmonids) habitat and populations in various geographic locations and channel network positions (arranged in chronological order).

LOCATION	CHANNEL NETWORK POSITION	RESULTS	REFERENCES
North Carolina	• 0.08 to 0.16 channel gradients • 3.5 m average channel width • 11.3 km^2 drainage area • 3^{rd} order stream	• Lower debris loading (especially of larger sizes) in disturbed reaches • High proportion of habitat units formed without LWD in disturbed reaches • Low proportion of habitat formed by 2 or more pieces of wood in disturbed reaches • 71% of pools and riffles occupied by trout in disturbed reaches versus 90% in reference reaches • Habitat units with LWD supported significantly more trout than units without	Flebbe 1999

Table A-9. The effect of LWD on riparian habitat in various geographic locations and channel network positions (arranged in chronological order).

LOCATION	CHANNEL NETWORK LOCATION	RESULTS	REFERENCES
Pacific Northwest, USA	• N/A	• LWD protects riparian sites where alder and other species become established • Fallen trees protect vegetation in exposed channel bars • Downed trees protect vegetation and create sites where sediment and organic material deposit • Deposition of sediment and organic matter boosts soil development • LWD helps stands reach mature stage and better withstand floods • Low gradient river segments have abundant LWD forming depositional areas that provide sites for future floodplains to colonize	Sedell et al. 1988
Pacific Northwest, USA	• <0.05 to >0.18 channel gradients	• Change in size, frequency, location, and longevity of depositional sites formed by LWD influences successional dynamics of riparian vegetation • Establishment of forested floodplains associated with LWD parallel or oblique to channel • LWD traps colluvium and alluvial sediment • LWD functions as nurse logs to provide nutrients and as elevated site to minimize competition between seedlings and forest floor vegetation • Nurse logs also act as refuge of young riparian species • As channel confinement increases, the influence of LWD on riparian forest distribution decreases due to decrease in area of active floodplain • Forested floodplains commonly form behind downstream of LWD on sediment deposits • Vegetation colonizes both LWD and low velocity zones • The age structure of forested floodplains reflects history of LWD deposition and fluvial disturbance • Accumulations of LWD form depositional sites where vegetation colonizes and becomes established in an otherwise unhospitable fluvial environment	Fetherston et al. 1995
Northwest Washington	• 0.005 to 0.01 channel gradients • 30 m to 80 m bankfull width • 75 km^2 to 225 km^2 drainage areas	• Riparian forests along large alluvial channels generally characterized as young and homogenous tree communities that reflect disturbance • But, observed diverse riparian forest structure and anomalous growth patches • Three factors facilitate riparian forest development downstream of LWD bar area jams: 1) local flow deceleration and decreased basal shear stress, 2) sediment deposition, 3) an abundant accumulation of organic matter on the surface • Observation of old growth riparian patches within active channel migration suggests some structures remain stable despite repeated integration into the active channel • LWD provide long-term refugia for floodplain riparian communities forming anomalous old-growth riparian forest patches in alluvial terrain characterized by frequent disturbance	Abbe and Montgomery 1996

Table A-10. The effect of timber harvest on LWD characteristics in various geographic locations and channel network positions (arranged in chronological order).

LOCATION	CHANNEL NETWORK POSITION	RESULTS	REFERENCES
Western Oregon	• 0.06 to 0.65 channel gradients • 1 m to 18 m channel widths • 0.02 km^2 to 30 km^2 drainage areas	• Logging methods near and across drainages can change the amount and condition of in-channel debris • Conventional tree falling added the most amount of logging material to the stream, followed by cable assist directional falling, and conventional falling with buffers • Attitude of logging crew played largest part in determining amount of slash remaining	Froehlich 1973
Western Oregon	• 0.10 to 0.30 channel gradients	• Clear cutting and stream cleaning may reduce abundance of large stable pieces, increase concentration of small unstable pieces through input and mobilization of instream LWD, reducing overall input	Swanson et al. 1976
Western Oregon	• 0.02 to 0.50 channel gradients	• Timber harvest may increase delivery of LWD to stream channel by increasing probability of debris avalanches • Timber harvest may alter size and distribution on debris in streams • Increased occurrence of debris torrents in clear cut areas • Removal of stable large debris may mobilize smaller logs and initiate downstream torrents • Management activities reduce LWD by thinning and harvesting, which reduces long term debris loading	Swanson and Lienkaemper 1978
Southeastern Alaska	• 42 km^2 drainage area	• Timber harvest imposed changes in stream channel related to accumulations of LWD • Natural accumulations appeared stable compared to logging debris • Absence of old growth forest along streambank eliminated LWD recruitment • As natural accumulation decays, pools may be replaced by riffles • Natural debris accumulations are affected by large floatable debris	Bryant 1980
Northern California	• 0.01 to 0.40 channel gradients • 1.0 km^2 to 27 km^2 drainage areas • 2nd through 4th order streams	• LWD introduced during harvest are smaller and more numerous than natural input • Timber harvest derived pieces are more mobile and encourage failure of downstream dams • Subsequent natural inputs are smaller than old growth species • 2nd growth trees less rot resistant than old growth redwoods • Loading in disturbed streams is lower and comprised of hemlock and tanoak • Disturbed watersheds had greater amounts of debris stored sediment, reflecting the greater extent to which storage compartments are filled in logged reaches	Keller and MacDonald 1983
Southeastern Alaska	• 0.01 to 0.09 channel gradients • 2 m to 6 m channel width • 0.5 to 2.0 km^2 drainage areas	• Debris dams more frequent in clear cut streams • Total residual pool length and depth greater in clear cut streams • LWD stored more sediment in clear cut reaches • Results suggest importance of logging debris and existing debris from clearcuts • LWD left after logging constitutes available supply of wood created structure • Removal of wood depletes LWD before riparian recruitment resumes	Lisle 1986a
Northern California	• 0.04 to 0.22 channel gradients • 1st through 2nd order streams	• Greater abundance of organic debris dams in control streams than in streams adjacent to clear cuts or harvested reaches • Increased levels of LWD loading following harvest destabilize existing debris dams or change dam characteristics through addition or mobilization of wood	O'Connor 1986
Western Oregon	• 0.02 to 0.06 channel gradients • 5.5 m to 8 m bankfull widths • 6.5 km^2 drainage area	• After logging, debris from current stand contributed 14% of total LWD volume and 7% of LWD from current stand contributed to pool formation • Results indicate that trees must grow beyond at least 50 years before stands contribute LWD in amounts similar to old growth forests	Andrus et al. 1988

Table A-10. The effect of timber harvest on LWD characteristics in various geographic locations and channel network positions (arranged in chronological order).

LOCATION	CHANNEL NETWORK POSITION	RESULTS	REFERENCES
Western Washington	• 0.13 channel gradient (<7 m channel width) • 0.08 channel gradient (7 m to 10 m channel width) • 0.03 channel gradient (>10 m channel width)	• Higher LWD abundance in old growth than 2nd growth or clear cut • Pool types changed with stand age class: scour pools more frequent in 2nd growth and clear cut, and dominant pool types in all stream sizes • Frequency of LWD associated pools significantly greater in old growth sites • Percent of LWD forming waterfalls and proportion of elevation drop controlled by LWD greatest in old growth sites • Area of LWD associated sediment greatest in old growth sites • More fine organic debris retained by old growth sites • Fine organic debris may contribute to the diversity of pool types in old growth streams • Many changes in LWD occur shortly after (<5yr) after harvest	Bilby and Ward 1989
Southeastern Alaska	• 0.04 to 0.29 channel gradients • 8.2 m to 20 m channel width	• 99% of LWD sources within 30 m of channel, 30 m buffer along both banks should maintain LWD input • Model predicted LWD reduced by 70% ninety years after clear cutting, recovery to pre-logging level exceeds 250 years • Streamside management should provide supply of LWD stable enough to provide fish habitat	Murphy and Koski 1989
Eastern Oregon Eastern Washington	• 0.02 to 0.07 channel gradients • 2 m to 6 m average channel widths	• LWD volume at logged sites 1 to 2 fold higher than unlogged sites due to logging residue and blowdown, but overall amounts were similar	Carlson et al. 1990
Oregon	• 1st through 3rd order streams	• 70% of LWD came from 20 m of channel, 11% came from 1 m of the channel • Probabilistic model based on tree height and density • Model used to interpret effect of width of buffer strips on future LWD recruitment	McDade et al. 1990
Oregon	• 0.13 channel gradient • 12 average bankfull width • 3rd order stream	• Probabilistic model predicting number and volume of LWD input • Inputs aggregated with respect to distance, tree height, and species • Demonstrates importance of considering stand composition, not just stream size in designing buffer zones	Van Sickle and Gregory 1990
Southeastern Alaska	• 0.002 to 0.02 channel gradients • 1 km^2 to 30 km^2 drainage area • 4 m to 25 m channel widths	• Channel unit distribution differs markedly between disturbed and undisturbed sites • 55% of wetted channel area in pool in undisturbed reaches and 34% in disturbed reaches • Differences in channel unit distribution attributed to difference in pool associated wood • LWD loading greater in undisturbed streams • Frequency of pool types differ between disturbed and undisturbed reaches, implying effect of land use • Pristine channel condition can be discriminated from managed channels by analyzing geomorphic variables	Wood-Smith and Buffington 1996
Western Washington	• 0.004 to 0.11 channel gradients • 0.5 km^2 to 14 km^2 drainage areas	• Unlogged streams had higher fraction of woody debris in larger size categories • Intensive timber harvesting significantly decreased fraction of stream area in pools • Intensive timber harvest reduced pool depth and pool area • Intensively harvested basins: 50% of wood outside low flow channel, 33% interacted with flow, 6% completely within channel • Moderately harvested basin: 25% of wood outside low flow channel, 50% interacted with flow, 19% fully within channel • Unlogged basins: 25% of wood outside channel, 66% interacted with channel, 32% fully in channel • Streams flowing through old growth forests retained more pieces of smaller wood • Newly recruited LWD was less stable in moderate an intensely harvested streams and less likely to contribute to contribute to habitat structure with less of a role in bedload storage	Ralph et al. 1994

Table A-10. The effect of timber harvest on LWD characteristics in various geographic locations and channel network positions (arranged in chronological order).

LOCATION	CHANNEL NETWORK POSITION	RESULTS	REFERENCES
North Carolina	• 0.01 to 0.10 channel gradients • 5 m to 11 m channel widths • 1st through 4th order streams	• LWD volume increased linearly in streams associated with late successional through old growth forests • Instream loadings build and stabilize in later stages of succession • Streams flowing through younger forests rely on LWD from stand generating disturbances; instream LWD not related to forest age • American chestnut (*Castanea dentata*) major LWD component in mid-successional streams	Hedman et al. 1996
Northern California	• 4.2 km^2 to 5 km^2 drainage areas	• LWD increased after logging due to residual trees adjacent to the stream or in buffer strips • Douglas fir provided greatest amount of LWD in second growth systems • LWD associated pools and debris jams higher in logged streams	Surfleet and Zeimer 1996
UK	• 0.013 average channel gradient • 2nd through 3rd order streams	• Number of debris dams recovered 7 to 8 years after removal • The number of hydraulically active dams did not recover as the number and size of pools was lower than before removal	Gurnell and Sweet 1998
Northern California	• 0.02 channel gradient • 7.7 m average bankfull width • 3.8 km^2 drainage area • 3rd order stream	• Logging increased input of LWD from blowdowns, leading to increased storage of bed material, increased number and total volume of pools, and temporarily increased fine sediment • Increased LWD volumes increased size and abundance on pools • Increase in LWD and LWD associated habitats may be temporary as in-channel wood decays and natural input sources recover • Reaches bordered by clearcuts and buffer strips may lose sediment storage, pool volume, and habitat complexity as LWD inputs decline	Lisle and Napolitano 1998
Western Washington	• <0.02 channel gradients • 3.0 to 12 km^2 drainage areas • 7 m to 16 m channel width	• Diameters of old growth LWD larger than 2nd growth LWD • Forestry practices: conversion of old growth coniferous to deciduous species, instream salvage, and stream cleaning have altered LWD characteristics • 60% reduction in LWD for logged old growth sites between 1982 and 1993 • Over 10 year period, number of pieces identical but LWD volume decreased as an increase in second growth LWD was insufficient to offset loss of old growth LWD • Diameter of 2nd growth LWD increased from 1982 to 1993, but still smaller than old growth LWD • Initial rapid loss of old LWD following timber harvest caused by destabilization and yarding, channel destabilization and transport, and long-term decay • Characteristics of LWD from second growth LWD much different from old growth conifers	McHenry et al. 1998
Northern California	• 0.08 channel gradient • 3 m to 20 m channel width	• LWD significantly lower in recently logged basins than in old growth redwood systems	Napolitano 1998
Northern California	• N/A	• Presence of clear cuts next to buffer strips can increase occurrence on windthrow for a distance of 150m • Results suggest use of a core buffer, greater than one tree height, flanked by a fringe buffer to protect core buffer from abnormally high rates of windthrow	Reid and Hilton 1998

Table A-11. The effect of LWD management on fish habitat in various geographic locations and channel network positions (arranged in chronological order).

LOCATION	CHANNEL NETWORK POSITION	RESULTS	REFERENCES
Central Oregon	• 0.71 km^2 to 30 km^2 drainage areas	• Burning of slash possibly increased stream temperatures, resulting in mortality of coho and cutthroat • Debris on gravel surface prevented interchange between surface and intragravel water, reducing dissolved oxygen • Decomposition of debris increased biological oxygen demand, further reducing available dissolved oxygen • To prevent reduction in dissolved oxygen, keep all debris out of channel through use of a buffer strip	Hall and Lantz 1968
Pacific Northwest, USA	• N/A	• Excess logging derived LWD may block fish passage or delay fish migration in v-shaped channels • LWD may destabilize streambed, particularly spawning gravel • Small debris (wood fiber, bark, leaves) fills interstices of gravel, reducing living space for stream invertebrates • Small debris has high BOD and COD, decreasing dissolved O2 concentration • Small debris on gravel reduces interstitial flow, and increases BOD and COD, decreased DO intragravel water, influencing depth of embryos and alevins • Tannins and lignin like substances produce yellow and brown colors that could absorb photosynthetically active radiation within a few inches of the surface	Narver 1970
Pacific Northwest, USA	• N/A	• Excess logging derived FWD may decreased dissolved O2, increase BOD, and restrict aeration of water • Excess logging derived LWD presents barriers to fish movement, can cause or contribute to "flush outs," mass movements that scour streams to bedrock and reduce complexity	Brown 1974
Western Washington	• 0.01 to 0.08 channel gradients • 1 km^2 to 30 km^2 drainage areas	• Salmonid biomass 1.5 times greater in logged sections • Logged watersheds contained higher percentages of age 0+ steelhead (*Oncorhynchus mykiss*) and age 0+ cutthroat (*Oncorhynchus clarki*) • Debris removal following timber harvest increased riffle area • Juvenile steelhead (*Oncorhynchus mykiss*) and cutthroat (*Oncorhynchus clarki*) possibly increased due to preference for riffle habitats	Bisson and Sedell 1984
Oregon	• N/A	• Structures increased diversity of streambed, trapped gravel, created gravel bars and pools • Spawning occurrence of coho and steelhead(*Oncorhynchus mykiss*) increased in modified sections • Control section supported higher densities of juvenile coho (*Oncorhynchus kisutch*), steelhead (*Oncorhynchus mykiss*), and cutthroat(*Oncorhynchus clarki*)	House and Boehne 1985
Western Washington	• N/A	• Water transportation and storage of logs severely impacts physical, chemical, and biological functioning of streams	Sedell and Duvall 1985
Southeast Alaska	• 0.035 to 0.053 channel gradient • 2 m average channel width	• Uncleaned stream section contained more fish of all size classes than cleaned sections • Numbers and production of coho (*Oncorhynchus kisutch*) and Dolly Varden (*Salvelinus malma*) reduced by LWD removal • Habitat simplification affected age 1+ and older fish more than age 0+ • LWD provided important hydraulic cover during winter	Dolloff 1986

Table A-11. The effect of LWD management on fish habitat in various geographic locations and channel network positions (arranged in chronological order).

LOCATION	CHANNEL NETWORK POSITION	RESULTS	REFERENCES
Southeast Alaska	• 1.9 m average channel width • 9 km^2 channel width • 6.5 km long	• Removal logging debris reduced wetted width and areas from $874m^2$ and $726m^2$ • Dolly Varden (*Salvelinus malma*) population decreased from 748 to 458 to 100 two years after debris removal • Decrease in fish size after clearance, before debris removal, fish occupied mid channel pools and tangles of debris, after removal occupied backwaters and stream margins • Removal of logging debris changed morphology, briefly reduced food supply and eliminated most cover, reducing number and mean length of fish, leaving small fish susceptible to displacement • Decrease in benthos abundance, reduced amount of food eaten by Dolly Varden (*Salvelinus malma*) and may have contributed to numerical decline	Elliott 1986
Southeastern Alaska	• 0.02 to 0.03 channel gradients • 2nd to 4th order streams	• Most fish regardless of species or age were in pools • Amounts of LWD and cobble higher in occupied pools than in unoccupied pools • LWD caused 73% of all pools • Juvenile salmonids (in winter) preferred pool with cover (upturned roots, accumulation of logs, cobble substrate) • Amount of preferred winter habitat depends on amount of LWD • Clearcut reaches less LWD and pool area • Buffers protect habitat by providing LWD	Heifietz et al. 1986
Oregon	• 9.2 km^2 drainage area • 0.03 average channel gradient	• LWD in logged section (6/100m) showed an increased in undisturbed section (46/100m) • LWD most important factor controlling differences in channel morphology LWD created stair step morphology, secondary channels, and meanders • Undisturbed sections, LWD improved pool quality and # of pools • After LWD additions, gravel increased by 233%, gravel areas increased 25 fold in area • 3 times more coho ($0.88/m^2$) and steelhead ($0.59/m^2$) in undisturbed sections • Positive correlation between fish populations (spawning and rearing habitat) and LWD	House and Boehne 1986
Southeastern Alaska	• 0.10 to 0.30 channel gradient • 5 m to 7 m channel width	• Winter fry density best modeled by summer periphyton biomass and volume of instream debris • Parr abundant where debris was abundant • In both summer and winter, density of Dolly Varden (*Salvelinus malma*) parr directly related to LWD volume • Cover (LWD and undercut banks) more important for all parr in winter	Murphy et al. 1986
Northern Colorado	• 0.01 to 0.024 channel gradients • 3 m to 6 m channel widths	• Pool volume after drop structures installed • Amount of cover increased significantly after addition of log drop structures • Treatment sections were deeper and had lower velocity than control sections • Abundance and biomass of age 2 and older cutthroat (*Oncorhynchus clarki*) increased significantly after installation of drop structures • Log drop structures increased abundance of adult brook trout (*Salvelinus fontinalis*) and possibly survival, although data not conclusive	Riley and Fausch 1995
North Carolina	• 0.03 to 0.06 channel gradients	• Pool formation after log addition • Enhanced reduction upstream from debris dams • Invertebrate abundance and biomass increased significantly after log addition • Scraper and collector/filterer abundance increased after log addition • Secondary production of scrapers and filterers decreased • Shifts in functional group abundances, biomass, and abundance accentuate the importance of local abiotic factors in structure of invertebrate communities within patches	Wallace et al. 1995

Table A-11. The effect of LWD management on fish habitat in various geographic locations and channel network positions (arranged in chronological order).

LOCATION	CHANNEL NETWORK POSITION	RESULTS	REFERENCES
Northern California	• 4.2 km^2 and 4.7 km^2 drainage areas	• Increase in LWD volume after timber harvest • LWD increased habitat are for steelhead (*Oncorhynchus mykiss*), coho (*Oncorhynchus kisutch*), and Pacific Giant salamanders (*Dicampton tenebrosus*) • As logging derived LWD decreases through decay, and as natural inputs recover, habitat conditions may not persist	Nakamoto 1998

Table A-12. The effect of roads on LWD characteristics in various geographic locations and channel network positions (arranged in chronological order).

LOCATION	CHANNEL NETWORK POSITION	RESULTS	REFERENCES
Oregon	• N/A	• Logging debris in stream channels is a major contributor to flood damage • Logging residue tends to be concentrated in draws and depressions that carry water during flood conditions • Problem of wood transport through channels compounded by roadways that place restriction on movement • Culverts and bridges obstruct wood movement and cause damage to road system • Damage to road system is major item in calculation of flood losses • Cost of problem is unknown, but included damage to roads and design of structures to pass debris • Aside from removing all debris, alternatives are to modify or build structures to pass wood, mechanically remove large jams, build roads to act as debris barrier	Froehlich 1970
N/A	• N/A	• Clearing and snagging done for three reasons: drain floodplains for agricultural development, protect citizens from floods, maintain navigable waterways • Clearing and snagging in high order streams reduces roughness coefficient	Marzolf 1978
Western Oregon	• 0.02 to 0.50 channel gradients	• Higher levels of debris torrent activity in areas with high road area relative to forest area	Swanson and Lienkaemper 1978
Central California	• 104 km^2 drainage area	• Flood damages significantly reduced if all bridges kept free of log jams • No practical way to prevent all trees from entering channel since most come from debris flow triggered by storms • Only feasible solution to prevent accumulation at bridges is to modify or replace bridges son that logs will flow under without catching • Stream clearance is not a solution as most logs come form debris flows that occur during the storm • Studies should include log passing capacity of all downstream bridges	Singer and Swanson 1983
N/A	• N/A	• LWD and vegetation removed to increase hydraulic capacity	Shields and Nunnally 1984
California	• N/A	• Clear water design of flood control channel ignores or underestimates role of floating debris in increasing flood elevations • Debris impedes or blocks small to medium sized culverts in small to medium sized culverts in smaller streams, and bridges and larger culverts in main channels, causing significant increases in flood elevations • Conveyance programs that encourage removal of wood rarely undergo technical scrutiny; an approach that considers hydrologic, geomorphic, and biological factors is needed	Williams and Swanson 1989
N/A	• N/A	• Crossings should be designed to transmit debris downstream	Furniss et al. 1991

Table A-12. The effect of roads on LWD characteristics in various geographic locations and channel network positions (arranged in chronological order).

LOCATION	CHANNEL NETWORK POSITION	RESULTS	REFERENCES
Australia	• 0.46 m (w) by 8 m (l) by 0.27 (d) artificial channel	• The average amount of LWD found in Australian lowland rivers seldom has a significant on flood levels • Where large log jams form or at channel constriction will effects be significant • Where consumptive uses reduce flow levels, LWD removal may be required more frequently to prevent jam formation • As a compromise between LWD removal for hydraulic reasons and habitat preservation, it may by possible to rearrange LWD for minimal hydraulic influence	Young 1991
Australia	• 3540 km^2 drainage area	• Results suggest that de-snagging would reduce banktop flood height by 0.2% • Average debris pieces would have minimal influence on flow hydraulics, although large pieces may be significant • Re-introduction of wood into cleared rivers unlikely to result in loss of conveyance	Gippel et al. 1996
United States	• N/A	• Floating debris increases lateral forces on bridges, promoting scour • Drift accumulation depends on channel, basin, and bridge characteristics • Drift accumulates against bridge piers, and obstacles separated by narrow gaps trap drift most effectively • Gaps between two pieces are not blocked unless logs can span pier to pier • Suggested design features to reduce drift accumulation: adequate freeboard, wide spans, solid piers, rounded pier noses, and pier placement out of path of drift (thalweg)	Diehl 1997
Oklahoma	• N/A	• Debris entrapment increased Manning's n by 39% • Effect of debris on flow resistance decreased with increased discharge • Results limited to channel <0.6 m depth (floodplains or low order channels)	Dudley et al. 1998
California	• N/A	• Plugging of culverts by LWD is a common failure mechanism • Pieces initiating plugging are often not much longer than culvert diameter • Culverts sized equal to the channel width will pass a significant portion of wood • Wood debris capacity of culverts can be assessed by taking ratio of culvert diameter to channel width (w*) • Crossings with low w* values (<1) are prone to debris plugging • Inlet basin configuration also influences wood plugging; channel widening upstream of culverts ponds water and creates eddies that orients wood perpendicular to flow and promoted accumulation of debris pieces, forming large jams upstream of the culvert • When channel enters culvert at an angle, wood cannot rotate parallel to flow and pass through culverts	Flanagan et al. 1998

Table A-13. The implications of LWD management actions in various geographic locations and channel network positions (arranged in chronological order).

LOCATION	CHANNEL NETWORK POSITION	RESULTS	REFERENCES
Western Washington	• 0.07 channel gradient	• Downstream impacts should be considered in assessing trade-offs associated with debris removal and increased sedimentation	Beschta 1979
Southeast Alaska	• 15 km^2 to 75 km^2 drainage areas • 4th through 5th order streams	• Length of piece, percent of piece in water, angle of orientation to flow, and location of anchor point all influence stability of instream wood • Suggest general guidelines based on age of debris and stream gradient	Bryant 1983
Eastern Washington	• 0.015 channel gradient • 11.5 m bankfull width	• Indiscriminant removal of LWD has major short term influences on channel stability • Knowledge of size and other features common to stable debris provided as basis for management guidelines • Proposed dichotomous key to determine whether to leave or remove LWD	Bilby1984
Pacific Northwest	• N/A	• Active streamside vegetation can increase fish biomass by managing for larger light flecks and maintaining input of LWD	Sedell and Swanson 1984
Pacific Northwest	• N/A	• In wood reintroduction must consider three things: 1) what kind of wood is desirable, 2) where should LWD be placed, 3) how much wood is enough • Small accumulations of various sized pieces of wood provide most complex and best utilized habitats in all sizes of rivers and streams • Wood accumulates at tributary junctions, where valley floor widens, at channel bends, and at geologic constrictions • Stream reaches in widened valley floors and areas below tributary junctions can be better enhanced by introduction of multiple trees in different configurations	Sedell et al. 1988
Pacific Northwest	• N/A	• Leave undisturbed buffer strip of old growth timber to ensure long-term supply long, large diameter logs • Leave predetermined fraction of timber in buffer strip that is adequate to satisfy stream habitat needs and allow wood to enter through natural processes • Remove timber from streamside management zone on double rotation basis, where trees are harvested every other rotation (100 to 150 years) • Design and engineer buffers that maintain LWD input, provide mix of riparian species • Variable width buffers offer chance to tailor streamside buffers to local stream conditions • Selectively logged buffers must leave stable logs for contribution to the stream channel • LWD is scarce when: 1) lack of quality pools 2) lack of LWD storage sites 3) presence of unstable debris which poses environmental hazard 4) lack of escape cover; scarcity best determined by before and after studies • LWD is too excessive when: 1) blocks fish migration 2) impairs water quality 3) presence of unstable debris which poses environmental hazard 4) interference with recreational uses • Need thorough long-term testing	Bisson et al. 1987
Pacific Northwest	• N/A	• LWD additions can be effective in enhancing fish habitat in the short-term • Structures mimic effect of natural obstructions in streams • The need for structural elements varies with channel gradient: 1) <0.01 gradient channels have low to moderate need, 2) 0.01 to 0.010 gradient channels have high need, 3) >0.10 gradient channels have low need	Sullivan et al. 1987

Table A-13. The implications of LWD management actions in various geographic locations and channel network positions (arranged in chronological order).

LOCATION	CHANNEL NETWORK POSITION	RESULTS	REFERENCES
Western Washington	• 0.13 channel gradient (<7 m channel width) • 0.08 channel gradient (7 m to 10 m channel width) • 0.03 channel gradient (>10 m channel width)	• Procedures to ensure LWD supply must consider: 1) cleaning prescriptions leave appropriate amount of wood of proper size in stream, 2) remaining streamside vegetation should provide for long-term input • LWD data must be applied to similar streams • Data on variations in size and amount of woody debris with changing stream size could be used to develop plans for numbers and sizes of trees to be retained • Effective management will depend on information relating vegetative and physical characteristics of riparian area to input of LWD	Bilby and Ward 1989
N/A	• N/A	• Structures tend to lock streams into a relatively fixed location and condition • Improved management of streamside vegetation offers most promise for developing valuable and productive riparian systems	Elmore and Beschta 1989
UK	• N/A	• LWD management should be undertaken with knowledge of natural LWD conditions • Logging should minimize disruption to channel processes • Management should optimize maintenance of habitat and minimize ecological disturbance • Some areas may require addition of LWD	Gregory and Davis 1992
N/A	• N/A	• No-net loss policy in forested basins in temperate USA should include four goals: 1) maintain geomorphic complexity 2) retain LWD along channel 3) maintain riparian vegetation 4) preservation of hydrological function of watershed • Stream classification systems based on geomorphic characteristics can provide means of identifying critical riparian areas for resource use • To re-establish large riparian trees suggest planting fast growing conifers and thinning of alder (Alnus rubra) overstory to promote growth of trees	Bryant and Sedell 1995
N/A	• N/A	• Hydraulic models can be used to help plan debris management programs • Channel roughness depends on many factors, it is unlikely that the approach of measuring changes in roughness coefficient will yield universal relations between debris type, quantity, and hydraulic effect • Claim of reduced frequency of duration of overbank flooding used to justify debris removal is not unequivocally proven in field	Gippel 1995
N/A	• N/A	• Problem of debris management resulting from logging best dealt with selective removal to ensure maintenance of channel stability, fish access, and fish habitat • Guidelines for removal take into account amount, size and age of debris present • Effect of previous debris clearance can be reversed by addition of debris to the river • Variability in size and spacing of LWD accumulations that occur locally in unmanaged channels should guide introduction of LWD • Introduction of LWD is short-term solution, production of natural inputs is preferable • Maintain buffer zone to ensure supply of wood • Active management of buffer zone can yield additional benefits such as light, temperature, flow, sediment transport, and sediment conditions	Gurnell et al. 1995
Southwest Alaska Western Washington	• 0.002 to 0.085 channel gradients • 2.5 to 38 m channel widths	• <40% of in-channel LWD active in pool formation, so effective riparian zone management must consider natural inefficiency in recruiting dominant LWD • Natural recruitment of many logs is required to provide a piece that is situated to form a pool, • The size and placement of LWD may be engineered to more efficiently catalyze pool formation • Could use pool spacing (channel widths per pool) against LWD frequency (pieces per meter) to define management objectives regarding pool spacing and LWD frequency	Montgomery et al. 1995

Table A-13. The implications of LWD management actions in various geographic locations and channel network positions (arranged in chronological order).

LOCATION	CHANNEL NETWORK POSITION	RESULTS	REFERENCES
Northwest Washington	• 0.005 to 0.01 channel gradients • 30 m to 80 m bankfull widths • 75 km^2 to 225 km^2 drainage areas	• Management activities must ensure adequate recruitment of largest LWD from riparian forest • Selective removal of largest trees from riparian and floodplain forests will have major impacts on in-channel habitat characteristics	Abbe and Montgomery 1996
Northwest Washington	• 0.002 to 0.05 channel gradients • 5 m to 20 m channel widths • 2 km^2 to 120 km^2 drainage areas	• Predict decline in number and area of pools in low to moderate slope channels with reduction in LWD • Given same decrease in LWD, predict greater decreases in number and area of pools in moderate slope channels than low slope channels • Expect decreases in abundance of species that show strong preference for pools as rearing locations (Oncorhynchus kisutch) and increases in abundance of species suited to rearing in riffle environments (Oncorhynchus mykiss) • After logging expect increases in number and area of pools to be more rapid in moderate slope channels than in low slope channels • When LWD pieces per meter exceeds 0.4, pool spacing is less sensitive to increased loading • Found relationship between channel width and size of LWD forming pools • In channels <10 m width, logs of 20 cm diameter formed pools; LWD from second growth will form pools sooner in small channel; pool abundance may increase after 25 years through inputs of deciduous vegetation • In channels 20 m wide, pools do not form until LWD exceeds 60cm; significant increases in pool number and area may not begin for 75 years until the recruitment of large conifers • May be possible to accelerate recovery of pre-logging conditions through management of riparian forest • Thinning may benefit large streams which require large logs to form pools • Thinning may not benefit smaller streams, as small wood is sufficient to form pools	Beechie and Sibley 1997
N/A	• N/A	• Debris roughness could be quantified from a knowledge of channel geometry, and tree height and diameter • Studies show how wood structure and transport should change as a function of position within the channel network; this geomorphic context needs to be understood to guide effective placement of wood for long-term stability • Quantitative understanding of wood movement is needed to assess stability of wood added, and to prevent congested transport from posing environmental hazard	Braudrick et al. 1997
Southeastern France	• 0.028 to 0.031 channel gradients • 1640 km^2	• Methodological approaches can be proposed to help managers identify reaches on which vegetation corridors could be conserved, rehabilitated, or used for soft maintenance • Development of increasingly mature riparian forest, due in part to incision and decreased lateral migration, has led to increased transport of wood debris, increasing risk of log jam formation • Need to maintain lateral connectivity between river and riparian vegetation • Propose a sectored maintenance plan based on mapping of woody debris supply areas, areas where log jam formation is most probable, and floodplain occupation to determine vulnerability to flooding	Piegay and Landon 1997
Pacific Northwest	• N/A	• Management approach must recognize processes responsible for LWD delivery • Approach must also address management related changes in LWD characteristics • Recommend adaptive management process	Bilby and Bisson 1998

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