AN ABSTRACT OF THE THESIS OF

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Title: THE SOURCE AREA FOR COARSE WOODY DEBRIS IN SMALL STREAMS IN WESTERN OREGON AND WASHINGTON

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Abstract Approved:

Jerry F. Franklin

Large organic debris has important biological and physical roles within the stream ecosystem. In order to determine the source area of large organic debris in streams, thirty-nine streams in the Cascade and Coast Ranges of Oregon and Washington were sampled. The distance from point-of-origin to channel was measured for thirty pieces of debris located within or straddling each stream. Streams varied in order (first- through third-order), age of surrounding timber (old-growth or mature stands), and sideslope steepness (steep or gentle slopes).

The distribution of source area was similar in all streams, with 11% of the total number of debris pieces originating within one meter of the channel, and 90% originating within thirty meters in 29 of the 39 streams. Debris originating as far as 60.5 meters from the channel was noted. Distance from origin to channel was significantly greater for streams draining old-growth forests, for third-order channels, and for conifer as opposed to hardwood debris pieces. There were no significant differences in distance from origin to channel for steep and gentle sloped areas.

Other variables were also compared with respect to stream order, stand age, and sideslope steepness. These include movement of the piece from the point-of-origin, bench width, length of piece, diameter of piece, and average sideslope steepness.

The distance the piece moved from its origin and the diameter of debris were larger in steeper areas, whereas the length of debris and bench width were greater in gentle areas. Debris originating in old-growth stands moved further from the origin and was larger in both diameter and length than debris originating in mature stands. There were no significant differences in bench width or slope steepness for old-growth and mature stands. Conifer debris pieces moved further downhill, were longer and larger in diameter, and originated on steeper slopes than did hardwood debris. There were no differences in bench width for conifer and hardwood pieces. Length and diameter of debris were greater for third-order channels in comparison to lower order channels, although no differences in these variables were noted between first- and second-order channels. Third-order channels had more gentle sideslopes than smaller streams. Bench width increased significantly as stream order increased. There were no significant differences in movement of debris from the origin with respect to stream order.

Management implications of the study are discussed.

The Source Area for Coarse Woody Debris in Small Streams in Western Oregon and Washington

by

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INTRODUCTION

The coniferous forest biome of the Pacific Northwest has many unique characteristics. Climatic factors (mild, wet winters and warm, dry summers) favor the development of evergreen coniferous forests which yield the largest biomass accumulations of any forest in the world (Franklin and Waring, 1979). However, many of the area's old-growth forests have been harvested to meet timber demands. Timber harvesting, as well as other management activities affects stream ecosystems as well as the terrestrial ecosystem.

Under natural conditions, forests in the Pacific Northwest contribute substantial amounts of debris to the forest floor and stream systems through the processes of windthrow, streambank undercutting, and hillslope mass movements (Swanson et. al., 1976; Swanson and Lienkaemper, 1978; Keller and Swanson, 1979). Froehlich et. al. (1972) estimated the levels of debris loading in forested streams in Western Oregon to be as high as 25 tons per 100 feet of stream channel. Once in the stream system, the debris may remain in place for significant periods of time (over 100 years) due to slow rates of decomposition and the inability of the stream to move the material (Swanson and Lienkaemper, 1978). Although flotation during high flow periods and debris torrents may account for some movement of large organic debris within the stream system, most debris is eventually exported as fine particulate and dissolved organic matter, as a result of decompostion by wood processing and decomposer organisms (Swanson and Lienkaemper, 1978).

A variety of papers have discussed the biological and geomorphic role of large organic debris within the stream ecosystem (a review of literature follows), but this is the first study to evaluate in quantitative terms the origin of coarse woody debris in small forest streams in the Pacific Northwest. For this paper, 39 first- to third-order streams in the Cascade Range and Coast Range of Oregon and Washington were studied to determine the source area of in-stream debris, and how this area might be affected by topography, stream order, and forest age class. Is most of the debris within the stream originating in areas adjacent to the channel or at some distance from the stream? Obviously, the source area of debris has implications for management activities near streams. If a goal of management is protection of the stream ecosystem and its maintenance in as near natural condition as possible, then knowledge of source areas for debris will influence guidelines regarding management of streamside zones. Thus, the primary purpose of this study was to provide managers with quantitative information regarding origins of in-stream debris, so that this knowledge may then be incorporated into streamside management practices.

REVIEW OF THE LITERATURE

Movement of LOD Into Streams

Large organic debris (LOD) enters streams through a variety of processes. Much of the stream debris enters as top, limbs, or whole trees blown down by strong winds. These pieces may land in the stream channel, or on adjacent hillslopes and slide into the streams. Thus, streams with narrow, steep, V-shaped valley walls may tend to receive more debris from greater distances as a result of sliding than streams flowing through more gentle terrain.

Undercutting of streambanks may also cause trees to tip into the channel. However, this process is more important in larger streams which can rework the floodplain. Smaller streams in the Western Cascades and Coast Range of the Pacific Northwest commonly flow on bedrock so that undercutting is minimal (Swanson et. al., 1976). In studying the source location of debris in first- through fifth-order streams in the Cascade Range in Oregon, Lienkaemper and Swanson (1987) found that only 34% of the total number of debris pieces which entered the stream over a 7 to 9 year period grew adjacent to the stream. The remaining 66% grew in areas not subject to bank erosion. In steep headwater channels, they found that all debris entering the channel, with one exception, originated in areas away from the channel, and therefore was not subject to bank erosion. They concluded that lateral cutting in these high gradient channels is minimal.

Slumps and earthflows along stream channels may lead to loading of limited areas of the channel with large organic debris. Earthflow tips trees, making them more vulnerable to windthrow. Earthflows also constrict the stream channel, which, when high flows undermine the area and cause several small slumps and slides, will carry large debris into the channel (Swanson et. al.,1976).

Debris slides and avalanches from hillslopes also introduce large debris into the channel. These may then trigger debris torrents, which pick up organic debris along the channel as they move rapidly downstream. These torrents usually originate in steep first- or second-order streams, and move large quantities of debris from smaller to intermediate sized streams (Swanson et. al., 1976).

Effects of LOD on Stream Systems

Geomorphic effects

Physical characteristics of small streams are strongly influenced by the presence of LOD (Swanson et. al., 1976; Swanson and Lienkaemper, 1978; Keller and Swanson, 1979; Keller and Tally, 1979). Debris affects channel morphology, storage of sediments and organic materials, and stability of streambed and banks.

LOD helps form a stepped profile in streams, in which the stream is composed of a series of long, low-gradient reaches separated by short, steep falls and cascades (Swanson et. al., 1976; Swanson and Lienkaemper, 1978; Keller and Swanson, 1979; Keller and Tally, 1979). In small streams studied in Western Oregon, 30 to 85% of the total drop in stream gradient is debris related (Keller and Swanson, 1979). Thus, a large proportion of the potential energy of the stream is dissipated in short, steep reaches which occupy a small percent of the total stream length. The result is a decrease in the energy available for erosion, decreased sediment transport capabilities, slower routing of detritus and greater habitat diversity than in channels with more even gradients (Swanson and Lienkaemper, 1978).

LOD also provides for significant in-stream sediment storage over long periods of time (Beschta, 1977; Keller and Swanson, 1979; Keller and Tally, 1979; Mosley, 1981; Megahan, 1982). Studies by Swanson and Lienkaemper (1978) have shown that, for several small forests streams, annual sediment yield is generally less than ten percent of the total sediment stored in the channel. This high sediment storage capacity serves as a buffer, reducing the effects of sedimentation on downstream areas during periods of high sediment input (Meehan et. al., 1977; Swanson and Lienkaemper, 1978; Keller and Tally, 1979). Were it not for the storage sites provided by LOD, introduced sediment would be rapidly transported downstream, where it might significantly decrease both fish and invertebrate production (Baker, 1977; Meehan et. al., 1977).

Biological Effects

In many steep, montane streams, LOD may be the principal factor in creating habitat (Swanson and Lienkaemper, 1978). In fact, more than half the habitat in streams may be wood or wood-created habitat, which allows for the development of a diverse, highly productive biological community. In low-order streams which lack the hydraulic force and volume of flow needed for flotation, individual pieces create habitat (Meehan et. al., 1977; Swanson and Lienkaemper, 1978). Pools and riffles form behind debris, facilitating the development of a community which is highly effective at processing fine organic matter. Higher order streams may possess sufficient hydrologic force and discharge to move debris. Thus, distinct accumulations of debris may be formed, which trap sediment and organic material, forming areas of rich biological habitat.

LOD serves as habitat for a large variety of invertebrates, primarily insects. Although few of these organisms actually ingest the wood, some obtain nutrients by scraping autotrophic epiphytes from the wood surface (Anderson et. al., 1978). Still others use the protective niches of LOD for oviposition, as a site for feeding or pupation, as a nursery area for early instars, or for molting or refuge (Meehan et.al., 1977; Sedell and Triska, 1977).

Fish production is also highly dependent on habitat created and maintained by LOD (Hall and Baker, 1975; Meehan et. al., 1977; Naiman and Sedell, 1981; Sedell et. al., 1982) Large debris is extremely important in providing winter cover (Everest et. al., 1984; Murphy et. al., 1985; Heifetz et. al., 1986), essential for the maintenance of overwintering fish populations (Hall and Baker, 1975). A distinct decrease in fall and winter densities of some fish has been observed where log cover is absent (Hall and Baker, 1975). Adult fish depend on pool habitat for resting or hiding, and LOD may be responsible for a significant proportion of quality pools formed in streams (Rainville, 1978; Naiman and Sedell, 1981; Lisle and Kelsey, 1982; Grette, 1985). Debris also provides protection from predation, rearing areas, and may help create spawning areas by trapping gravel in high gradient streams, where gravel accumulations might not otherwise occur (Hall and Baker, 1975; Rainville, 1978; Naiman and Sedell, 1981; Lisle and Kelsey, 1982). Large debris has also been associated with the occurrence of cool water pockets (Keller and Hofstra, 1982; Bilby, 1984b) which may act as thermal refuges for fish during periods of high summer temperature.

One of the most important roles of LOD in streams is that of retention of sediment and organic detritus (Marzolf, 1978; Triska and Cromack, 1980). Small headwater streams in forested areas are generally heavily shaded, limiting light availability for in-stream primary production. Thus, these streams are largely heterotrophic, with the majority of organic material entering from the terrestrial environment in the form of litterfall (Cummins, 1974; Vannote et. al., 1980). In order for this material to be utilized as an energy source, it must be biologically processed by stream organisms. Processing is dependent on the streams' capacity to retain fine organic debris (Triska and Sedell, 1975), allowing sufficient time for invertebrate consumption. The key to retention in many streams is the presence of large amounts of LOD, which slows the routing of fine organic matter through the stream, allowing greater time for biological processing (Triska and Sedell, 1975; Swanson and Lienkaemper, 1978). Retention is particularly important in litter processing because microbial colonization is prerequisite to invertebrate consumption of many forms of litter (Cummins, 1974; Cummins and Klug, 1979; Vannote et. al., 1980).

LOD also serves as a source of refractory carbon in the stream environment (Meehan et. al., 1977). High lignin and cellulose content, coupled with high carbon:nitrogen ratios, results in extremely slow rates of wood decomposition (Meehan et.al., 1977; Sedell and Triska, 1977). Thus, essential nutrients are released into the stream over a long period of time. Additionally, the occurrence of nitrogen fixation on some wood substrates (Anderson et. al., 1978) may significantly increase the nitrogen input to the stream environment, as well as facilitate decomposition by lowering the carbon:nitrogen ratio.

Effects of Management Activities

Forest management activities have a significant impact on the presence of LOD in streams. However, in considering the potential effects of these various activities within the stream ecosystem, it is important to remember that changes in the biology or geomorphology of headwater areas as a result of management activities may also have a significant effect on downstream areas (Vannote et. al., 1980). A river drainage system may be viewed as a continuum of physical environments and associated biotic communities as one moves from headwaters to mouth (Vannote et. al., 1980). The processes which occur in downstream reaches are linked to the processes which occur in upstream areas. Thus, in examining management-induced alterations of stream environments, both downstream reaches as well as reaches immediately adjacent to managed areas must be considered.

Management Induced Reductions in LOD

Management activities may directly affect the amounts of debris by addition or removal of debris from the streams. Management-caused reductions of debris levels can occur in several ways. Several studies have documented decreases in LOD following logging. Swanson et. al. (1976) mapped LOD in forested and clearcut sections of Mack Creek, in H. J. Andrews Experimental Forest in Western Oregon. They found that forested reaches contain large amounts of stable debris, which has significant impacts on both biology and geomorphology of the stream. In contrast, logged sections contain little debris, all of which appeared unstable, and had no effect on sediment storage or the pattern of pools, riffles, and falls. Froehlich et. al. (1972) measured volumes of LOD in the same stream, and found that the clearcut sections contained only about four percent as much natural debris as the forested section.

A study on the effects of streamside logging on LOD in third-order Carnation Creek, Vancouver, B.C., has shown that debris is less stable, total debris volume is reduced, and the average piece size is smaller following logging (Toews and Moore, 1982).

In studying maps of the same creek over a twenty-nine year period, Bryant (1980) found that logging debris tended to destabilize existing natural accumulations, so that many natural accumulations were subsequently washed out. The majority of LOD after logging was easily floated and not as stable as pre-existing debris. These effects appear to result from removal and disruption of stable in-stream debris during logging and yarding operations, as well as the addition of unstable logging debris. Additionally, negligible amounts of LOD entered the stream system after logging since streamside forests had been removed. Direct removal of stream debris coupled with streamside logging may result, therefore, in a significant long-term decrease in stream debris loading.

Management activities may indirectly affect the quantity of LOD in the stream by increasing the probability of debris torrents which may scour the stream channel and flush debris out of smaller order streams into the larger, lower gradient channels and onto floodplains. Swanston and Swanson (1976) found higher levels of debris torrent activity in clearcut and road right-of-way areas than in forested areas in the same watershed. This results primarily from increased probability of rapid hillslope failure in areas disturbed by management activities. The failed material may enter the stream channel and continue downstream, triggering a debris torrent.

The decreases in natural debris loading following logging and road construction can have significant impacts on both physical and biological properties of the stream.

Effects of Debris Removal on Geomorphology

Removal of LOD from streams significantly affects channel morphology. A stream can be converted from a series of organic steps to a more uniformly steep profile (Swanson et.al., 1976; Marzolf, 1978). A significant reduction in the number and area of pools after stream cleanup of LOD has been reported (Bilby, 1984a). Increased water velocity causes accelerated transport of particulate organic matter, downcutting and channelization, and decreased sediment storage. Several studies have documented large increases in sediment transport following removal of LOD in streams (Baker, 1977; Beschta, 1977; Heede, 1985). Beschta (1977) has reported the erosion of approximately 4000 tons of sediment along 100 yards of channel as a result of scouring following debris removal. Baker (1977) found that 29-97% of stored sediment was released within two years of complete removal of LOD in streams. Subsequent sediment deposition in downstream reaches may alter fish habitat, as will be discussed.

Biological Effects of Debris Removal

Removal of LOD results in a decrease in habitat diversity, producing, in turn, a decrease in diversity and density of stream organisms. Debris removal significantly reduces habitat available to invertebrates, which may greatly reduce invertebrate populations (Marzolf, 1978). A reduction in available shelter cover for fish greatly reduces overwinter survival rates (Bustard and Narver, 1975). Bryant (1980) found reduced densities of fish populations in two Alaska streams after removal of debris.

Sediment released and transported to downstream reaches as a result of debris removal may result in decreased intragravel oxygen levels, resulting in reduced egg and fry survival (Hall and Lantz, 1969; Baker, 1977; Meehan et. al., 1977). Sediment deposition may also destroy a large proportion of invertebrate habitat, resulting in decreased invertebrate production and subsequent decrease in fish food resources (Baker, 1977). In addition, sediment transport may increase turbidity of stream waters, and decrease light penetration in downstream areas where primary production is important.

Reduction in the amount of LOD present accelerates transport of fine organic matter through the channel, reducing the opportunity for colonization and processing of the material (Swanson et. al., 1976; Bilby and Likens, 1980; Reice, 1980). Recent experiments by Gregory (unpubliblished, 1981) point to the significance of LOD in both storing and trapping detritus. Following removal of all LOD from a 45 meter reach in a second-order, steep gradient mountain stream in a coniferous forest, 100% of the released marker leaves were trapped within four meters of the control (non-pulled) section during base-flow periods, whereas up to 76% of the marker leaves passed completely through the debris-pull section. Within two years following removal, total detrital storage in the pulled section had decreased to 21% of the total storage in the control section.

Other experiments performed by Likens and Bilby (1982) and Speaker et. al. (1984) produced similar results. Following removal of all debris from a 175 meter stream reach, Likens and Bilby (1982) observed a six-fold increase in the export of fine organic and inorganic material, as well as a loss in the streams' ability to retain leaf-sized material. Speaker et. al. (1984) found that stream reaches with LOD dams retained debris approximately ten times more efficiently than those lacking LOD accumulations.

Rapid flushing of litter and particulate organic matter through the system as a result of debris removal has significant effects on the stream community. Material is no longer retained for sufficient periods to allow for biological processing, resulting in an increase in detrital input to downstream reaches (Marzolf, 1978; Naiman and Sedell, 1979). However, the downstream organisms may not be able to utilize the material due to a lack of shredder organisms as well as a lack of retention mechanisms (Bilby and Likens, 1980; Vannote et.

al., 1980). As this material is the primary food source for many stream organisms, a decreased ability of the stream to process this material significantly decreases the energy base of the stream (Bilby and Likens, 1980). Decreased food availability obviously reduces invertebrate production and, consequently, decreases fish production.

Lastly, it is necessary to consider the effects of debris removal on long-term nutrient availability (i.e. refractory carbon). In reducing the amount of LOD, the stream system loses an important long-term reserve of essential nutrients (Triska and Cromack, 1980). Removal of debris also results in a loss of algae and nitrogen fixing bacteria specific to woody substrates, producing additional losses of more labile carbon and nitrogen sources (Franklin et. al., 1982).

STUDY AREAS

A total of 39 streams, 37 located in the Cascade Range of Oregon and Washington and 2 located in the Coast Ranges of Oregon, were selected for study (Table 1 and Figure 1). Streams ranged in size from first- through third-order (Strahler, 1957) with mean sideslope steepnesses from 3 to 40 degrees. All of the streams were located in natural stands, approximately half in old-growth (>200 years old) stands, and half in mature (80 to 200 years old) stands (Table 1 and Figure 1).

Detailed descriptions of study site locations are available from Forest Sciences Data Bank, Quantitative Sciences Group, Forest Science Department, Oregon State University, Corvallis.

Coast Range Streams

Calf Creek is located within the Neskowin Crest Research Natural Area, Cascade Head Experimental Forest, approximately 2.5 kilometers east of the Pacific Coast, along a major headland extending into the sea. The stream lies within the coastal *Picea sitchensis* zone (Franklin and Dryness 1973). The dominant vegetation of the area is Sitka spruce (*Picea sitchensis*) and western hemlock (*Tsuga heterophylla*) forest approximately 145 years of age, with a dense understory of vine maple (*Acer circinatum*) and salmonberry (*Rubus spectabilis*). Red alder (*Alnus rubra*) is common along the

TABLE 1. Physical description and location of sampled streams.

Stream	Order	Age Class	Mean Sideslope (deg)	Approximate Elevation (meters)	Aspect	Location	Study Site*
Devil's Club	1	old growth	36	830	W	T15S R5E Sec 36	HJA
Gypsy	1	old growth	28	540	S	T15S R5E Sec 28-29	HJA
Watershed 2	1	old growth	40	630	SW	T15S R5E Sec 32	HJA
Middle Santiam	1	old growth	30	-	N	T12S R5E Sec 19	MS
Watershed 8 - A	1	old growth	9	1020	SSW	T15S R5E Sec 14	HJA
Mack Creek	1	old growth	9	830	NW	T15S R5E Sec 25	HJA
Ohanopecosh	1	old growth	7	-	NW	-	MR
North Fork Hagan	1	mature	37	610	NW	T16S R3E Sec 14	HJA
Mouse Creek	1	mature	30	610	SW	T4N R8E Sec 8	HJA
Lush Creek	1	mature	28	540	SW	T5N R6E Sec 25	WR
McRae Creek	1	mature	9	850	SW	T15S R5E Sec 14	HJA
Foley Ridge	1	mature	6	870	S	T16S R7E Sec 31	HJA
Watershed 8 - B	1	mature	8	1020	SSW	T15S R5E Sec 14	HJA
Mack Creek	2	old growth	35	950	SW	T15S R5E Sec 36	HJA
Gypsy Creek	2	old growth	29	540	S	T15S R5E Sec 28-29	HJA
Watershed 2	2	old growth	40	550	NW	T15S R5E Sec 32	HJA
Trapper Creek	2	old growth	9	400	NE	T5N R7E Sec 31	WR
McRae Creek - A	2	old growth	9	850	SW	T15S R5E Sec 14	HJA
McRae Creek - B	2	old growth	5	610	NW	T15S R5E Sec 22	HJA
North Fork Hagan	2	mature	29	540	SW	T16S R3E Sec 14	HJA
Mouse Creek	2	mature	31	660	W	T4N R8E Sec 8,17	WR
Lush Creek	2	mature	27	560	S	T5N R6E Sec 24	WR
Roney Creek	2	mature	10	710	WNW	T17S R6½E Sec 9	HJA
Carpenter 75-B	2	mature	20	800	NW	T15S R5E Sec 1	HJA
Trapper Creek	2	mature	3	370	SSW	T5N R7E Sec 30-31	WR
Flynn Creek	2	mature	15	210	S	T12S R10W Sec 12	FC
Calf Creek	2	mature	20	-	NNW	T6S R11W Sec 1	CH
Mack Creek	3	old growth	26	830	W	T15S R5E Sec 35	HJA
Trapper Creek	3	old growth	26	780	NE	T5N R6E Sec 25	WR
Upper Lookout A	3	old growth	25	460	WNW	T15S R5E Sec 25	HJA
Lush Creek	3	old growth	10	410	SSW	T5N R6E Sec 25	WR
Upper Lookout B	3	old growth	8	930	WNW	T15S R6E Sec 29	HJA
East Fork	3	old growth	6	1020	N	T17S R6E Sec 17	HJA
South Fork Hagan	3	mature	25	490	NW	T16S R3E Sec 22	HJA
North Fork Hagan	3	mature	29	480	SW	T16S R3E Sec 15,22	HJA
Mouse Creek	3	mature	30	370	NW	T4N R7½E Sec 13	WR
McLenneu	3	mature	5	680	SW	T17S R5E Sec 2,3,10	HJA
North Fork Elk	3	mature	4	1020	WNW	T19S R6E Sec 15	HJA
Rainbow Creek	3	mature	2	1130	W	T16S R7E Sec 33	HJA

*Study site indicates sites as shown in Figure 1.
HJA = in or near H.J. Andrews Experimental Forest.
WR = Wind River Experimental Forest.
MR = Mt. Ranier National Park.
MS = Middle Santiam area.
FC = Flynn Creek Research Natural Area.
CH = Cascade Head Experimental Forest.

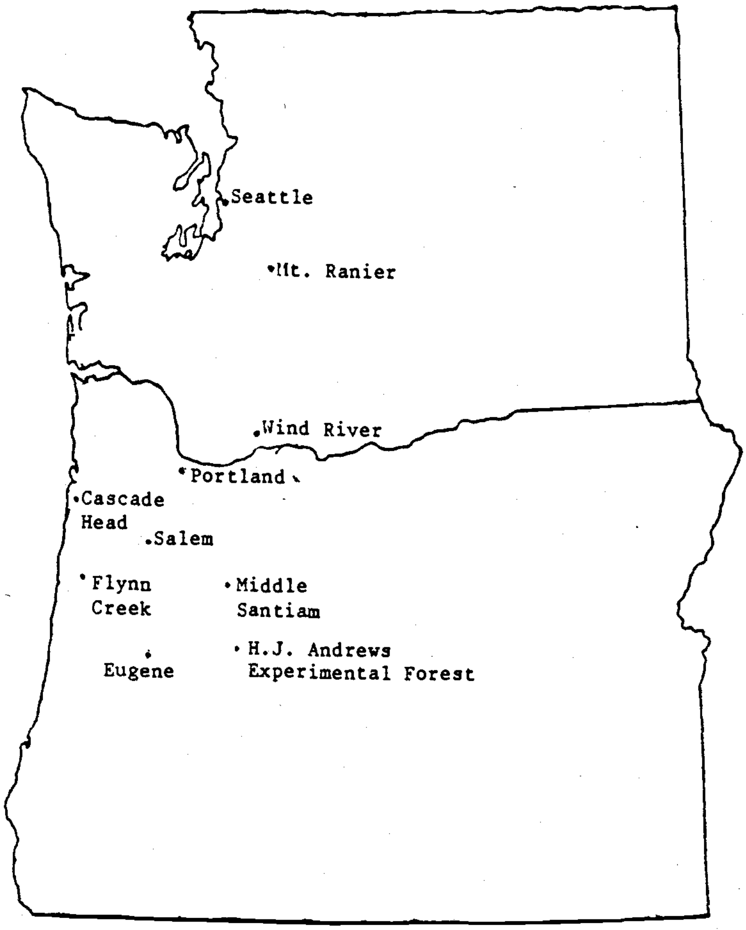

FIGURE 1. Map of Oregon and Washington showing goegraphical location of study areas.

edges of perennial streams. The area is underlain with basaltic bedrock with a capping of sedimentary clay- and siltstones (Franklin and Dryness, 1973).

Flynn Creek is located within the Flynn Creek Research Natural Area, 16 kilometers east of the Pacific Ocean on the western slopes of the Coast Range. The area is densely forested with Douglas-fir (Pseudotsuga menziesii) and red alder; the understory is composed primarily of vine maple and salmonberry (Franklin and Dryness, 1973; Anderson et. al., 1978). Geology of the area is typical of the extensive Tyee Sandstone Formation of the Coast Range, and is composed almost entirely of sandstones deposited under marine conditions in the Eocene (Franklin and Dryness, 1973). The area is topographically rugged with steep slopes and V-shaped valleys.

The coastal region has a typical maritime climate with mild, wet winters and warm, dry summers. Temperature extremes are minimal; temperatures less than -6 degrees C. or greater than 38 degrees C. are uncommon (Anderson et. al., 1978). Average annual temperature, mean January and July temperatures, mean January minima and mean July maxima are shown in Table 2. Precipitation averages 2000-3000 mm annually, most of which occurs during the fall and winter months (Franklin and Dryness, 1973). Neither site experiences significant snowfall.

Frequent summer fog at the Calf Creek site condenses on vegetation and falls to the ground as fog-drip, thus helping to reduce summer moisture stress. The Flynn Creek site is too far inland to be affected by coastal fogs, and summer drought is common.

Table 2. Climatic Characteristics of the Coast Range (Neskowin Crest Research Natural Area, Oregon) and Cascade Range (Wind River Research Natural Area, Washington) study sites (Franklin, et. al., 1972).

Parameters	Coast Range	Cascade Range
Average annual temperature (°C)	13.3	8.8
Mean January temperature (°C)	5.3	0.
Mean July temperature (°C)	15.3	17.5
Mean January Minimum temperature (°C)	2.2	-3.7
Mean July maximum temperature (°C)	20.9	26.9
Average annual precipitation (mm)	2496	2528
June - August precipitation (mm)	163	119
Average annual snowfall (cm)	0	233

Cascade Range Streams

Twenty-seven of the Cascade Range streams were located in the Western Cascades of Central Oregon, in or near the H. J. Andrews Experimental Forest. The remaining streams, with one exception, were located in the vicinity of the Wind River Experimental Forest, near Carson, Washington. The remaining stream is located in the Mount Ranier National Park, Washington.

The dominant forest vegetation surrounding the streams is Douglas-fir, western hemlock, and western redcedar (*Thuja plicata*) (Franklin and Dryness, 1973). Larger, lower-elevation streams often have a border of red alder and maple (*Acer macrophyllum*).

Geologically, the Cascades are composed primarily of lava flows and pyroclastic rocks of the Miocene to Recent age. Basalt, andesite, and associated breccias and tuffs are the most common bedrock (Rothacher et. al., 1967; Franklin and Dryness, 1973)

Fluvial and soil mass movement processes have been important in shaping the rugged mountain topography of the Cascades. Upper elevation slopes have been deeply incised by streams, and in combination with soil mass movements (creep, slides) have created steep gradient, V-shaped channels. More gentle gradients and terraces on the valley floor characterize many of the lower-elevation streams (Swanson and James, 1975).

The climate of the Cascades is maritime, with mild wet winters and warm, dry summers. Temperature and moisture extremes are greater than in the Coast Range (Table 2). Precipitation averages

2000-3000 mm annually, and is strongly seasonal, with less than 10% of the annual precipitation occuring within the summer months. Average annual temperatures range from 8 to 9 degrees C. Permanent winter snowpacks generally occur above 1000-1200 meters, while, below these elevations, snow is typically transient (Swanson et.al., 1976; Anderson et. al., 1978).

Debris Concentrations in Streams

First-order streams are small, steep-gradient streams. The channel is generally rich with organic debris, derived from litter-fall of surrounding vegetation and fallen logs. Large organic debris is distributed randomly within the channel, remaining essentially where it fell, as the streams lack the hydrologic force necessary to move debris. Organic debris may block the flow of water, creating a series of pools separated by free fall zones. These "stairsteps" of organic debris serve to reduce the effective gradient of the stream (Swanson et.al., 1976).

Second-order streams are similar in morphology to first order. These streams are somewhat larger and gradients vary considerably. Increased streamflow may result in greater floating and redistribution of smaller debris during periods of high flow.

Third-order streams are larger and have lower gradients. Debris is moderately abundant, although concentrations are low in comparison to smaller streams (Table 3). A smaller portion of the

TABLE 3. Physical characteristics of a first-, second-, and third-order Cascade Range stream and second-order Coast Range stream (Anderson, et. al., 1978, and Keller and Swanson, 1979).

Stream	Order	Coarse Debris (kg/m^2)	Approximate Elevation (meters)	Watershed Area (km^2)	Gradient (deg)	Average Width (meters)	Discharge Summer	Discharge Winter (m^3/sec)	Discharge Annual
Devil's Club	1	43.5	830	0.2	22	1.0	.001	.15	.03
Watershed 2	2	38.0	530	0.8	14	2.6			
Mack Creek	3	28.5	800	6.0	7	12.0	.10	2.2	.60
Flynn Creek (Coast Range)	2	0.97	210	2.0	1.4	3.0	.01	.80	.12

stream area is occupied by woody debris. These streams are large enough to float and redistribute much of the debris falling into them, forming distinct accumulations along stream banks and against obstructions in the channel. These debris accumulations may affect the entire channel width, creating organic steps and free fall zones and pools which alter the stream gradient over short reaches (Swanson et.al., 1976; Keller and Swanson, 1979; Frankin et. al., 1982).

Debris concentrations in streams are controlled by stand age as well as stream order. Total concentrations of large organic debris in streams flowing through mature post-fire stands is only about 50% of the values for streams flowing through old-growth stands. Furthermore, 75% of the debris in these post-fire stands is composed primarily of large, decomposed material originating from the pre-fire ecosystem (Swanson and Lienkaemper, 1978; Franklin et. al., 1982). Most of the old-growth stands in this study were 400 to 500 years old. Mature stands were typically 80 to 145 years old.

Streamflow

The streamflow pattern in the Pacific Northwest streams studied is characteristic of drainages in which the precipitation occurs primarily as rain. That is, the annual hydrograph closely follows annual precipitation patterns. All streams experience high flows during the fall and winter months and low flows in summer (Rothacher et. al., 1967; Harr, 1976). Mean monthly streamflows reach a maximum between November and March, when storms are frequent and large. Streamflows may be extremely variable during these months due to irregularity of storm patterns (Table 3). Minimum monthly streamflows occur in late summer to early fall (Harr, 1976). In most years, the peak flows are 1500-2000 times higher than summer low flows, although peak flows as much as 5000 times greater than summer low flows have been observed (Harr, 1976).

METHODS

Field Measurements

The study area on each stream consisted of a reach of approximately 0.4 kilometers to 2 kilometers in length. For the purposes of this study, a reach was defined as the length of stream required to locate thirty (30) tree falls contributing large woody debris to the stream (debris pieces greater than 10 centimeters in maximum diameter and at least 1 meter in length) for which the origin of the fallen material could be determined. Debris pieces which straddled the stream but identifiable as to source location were included in the study, as they eventually influence the stream. In some cases, a single tree fall produced more than one debris piece within the channel due to breakage. These pieces were counted as multiple debris pieces from a single tree fall, resulting in a slightly higher number of debris pieces in some reaches.

Each reach was classified according to three variables: stream order (first-, second-, or third-order), stand age (old-growth or mature timber), and average steepness of sideslopes (steep slopes > 25 degrees, gentle slopes < 25 degrees). The study design was a completely crossed 2 X 2 X 3 factorial and study reaches were selected in such a way that there were a minimum of three reaches in each cell of the matrix (Table 4).

TABLE 4. Classification of streams according to order (first, second, or third order), sideslope steepness (steep or gentle sideslopes) , and forest age class (old growth or mature stands).

Slope Steepness Class and Timber Age Class	Order		
	First	Second	Third
	1	1	1
Steep slopes, Old Growth	Devil's Club	Mack Creek	Mack Creek
	Gypsy	Gypsy	Trapper Creek
	Watershed 2	Watershed 2	Upper Lookout - A
	Middle Santiam		
Gentle Slopes, Old Growth	Watershed 8	Trapper Creek	Lush Creek
	Mack Creek	McRae Creek - A	Upper Lookout - B
	Ohanopecosh	McRae Creek - B	East Fork
Steep Slopes, Mature	North Fork Hagan	North Fork Hagan	South Fork Hagan
	Mouse Creek	Mouse Creek	North Fork Hagan
	Lush Creek	Lush Creek	Mouse Creek
Gentle Slopes, Mature	McRae Creek	Roney Creek	McLennen
	Foley Ridge	Carpenter 75-B	North Fork Elk
	Watershed 8	Trapper Creek	Rainbow
		Flynn Creek	
		Calf Creek	

For each piece of debris within or straddling the stream, an attempt was made to determine the origin of the material. Pieces not identifiable as to source were not sampled. An average (for all streams) of 29.5 debris pieces (or 47.7% of the total number of debris pieces encountered) were not identifiable as to origin and were not sampled. The average number of debris pieces passed over due to unknown origin was significantly greater for steeper areas (mean = 42.5 debris pieces or 56.1% of the debris pieces encountered) in comparison to gentle areas (mean = 22.3 pieces or 43.2% of debris pieces encountered, $p < .05$, ANOVA). No significant differences were noted in the number of debris pieces passed with respect to stand age (old-growth stands, mean = 30.6 debris pieces or 48.3% of debris pieces encountered; mature stands, mean = 28.5 debris pieces or 47.3% of pieces encountered). First-order streams had fewer debris pieces for which the source could not be determined (mean = 21.2 pieces or 39.4% of pieces encountered) than did either second- (mean = 33.2 pieces or 50.8% of pieces encountered) or third- (mean = 35.0 pieces, or 52.2% of pieces encountered) order channels, although these differences were not statistically significant at the 5% level (ANOVA).

If the origin could accurately be determined, the distance between the stream and the base of the tree supplying the material was measured. In cases of uproots, the distance from the root pit to the stream was measured. In areas of steep sideslopes, the debris often slides some distance downhill, but the original location of the material could often be determined. Although sampling occurred during the summer low flow, the high flow channel width (or bank-full width) was considered to be the outer edges of the stream, and distances were measured from the origin to bank-full width.

Distances were measured perpendicular to the stream (in a direct line from origin to stream), and consisted of two separate distances: the horizontal (bench) distance and the slope distance. (The bench is defined as the relatively flat floodplain or terrace area adjacent to the stream, the outer edge of which is marked by a distinct change in slope). For the purposes of comparison, and because many managers utilize maps and aerial photographs in making predictions and decisions about streams, all slope measurements were converted to horizontal distances by simple trigonometry and added to the bench distance. The resulting distance, the shortest total horizontal distance from origin to stream channel, was the parameter used for analysis in this study (Figure 2).

For each piece of debris under study, additional data were collected describing the species, length of debris, diameter at breast height, debris category (uproot, top, or log), distance the piece moved from origin, and length of piece in channel. Sideslope angle was measured using a hand held clinometer.

All data are available from the Forest Sciences Data Bank, Quantitative Sciences Group, Forest Science Department, Oregon State University, Corvallis.

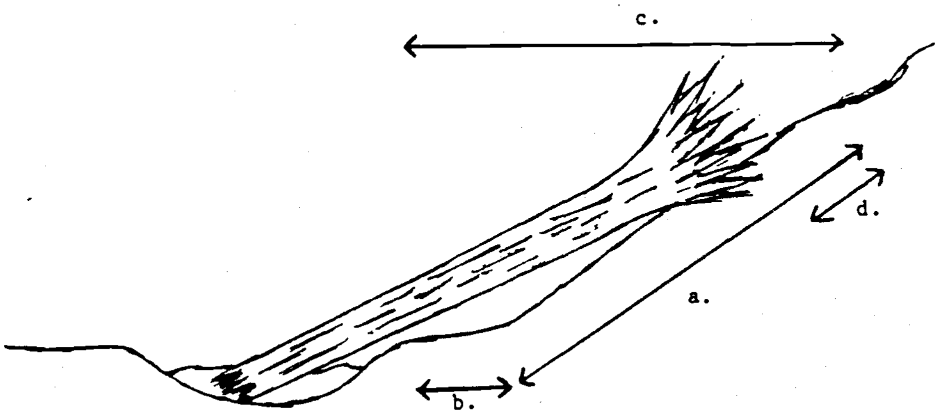

FIGURE 2. Diagram indicating measurements of (a) slope distance and (b) horizontal (bench) distance from origin to channel, and (c) the shortest horizontal distance from origin to channel. Downslope distance from point-of-origin to end of piece nearest origin is indicated by (d).

Statistical Analysis

Data were analyzed in terms of the proportion of large woody debris entering the stream from within one meter, one to five meters, and subsequent five meter intervals from the stream. Regresssion analysis and analysis of variance were performed to examine the relationships between the location of the origin of debris and the following variables: stream order, age class of surrounding forest, average bank slope steepness, and bench width. Tests of significance were performed to compare groups of data.

RESULTS

Frequency Distribution

The distribution of source distance was similar in all streams, with over 70% of the woody debris originating within 20 meters of the channel in all streams, and 90% of the debris originating within 30 meters of the stream in 74% (29 out of 39 streams) of cases (Figure 3). Eleven percent of the large woody debris pieces within the stream system originated within one meter of the stream. The majority of this probably entered the stream as a result of windthrow, bank undercutting, soil mass movements, and battering by floating debris. Seventy-three percent of the large woody debris pieces originated within 20 meters of the stream's edge, although woody debris originating from as far away as 60.5 meters (horizontal distance) from the channel was found in the stream system (Figures 3-9 and Tables 5-8).

Gentle and Steep Sloped Areas

Average sideslope steepness did not significantly affect the distance from origin of debris to stream channel (ANOVA, $p < .05$). However, other differences were noted in comparing steep and gentle areas (Table 9). The total distance the piece moved from the origin

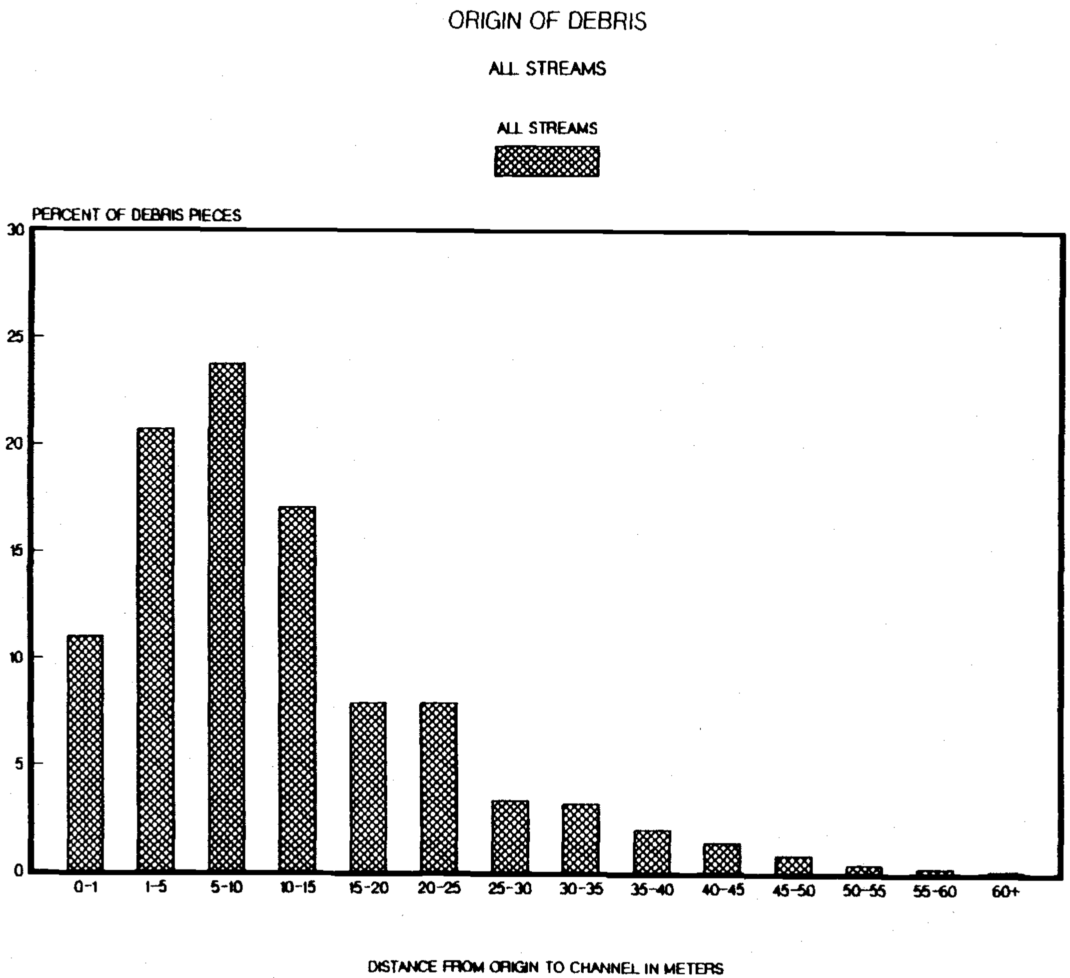

FIGURE 3. Percent of total number of debris pieces originating 0 - 1 meter, 1 - 5 meters, and subsequent five meter intervals from the stream's edge, for all streams totaled (n=1258).

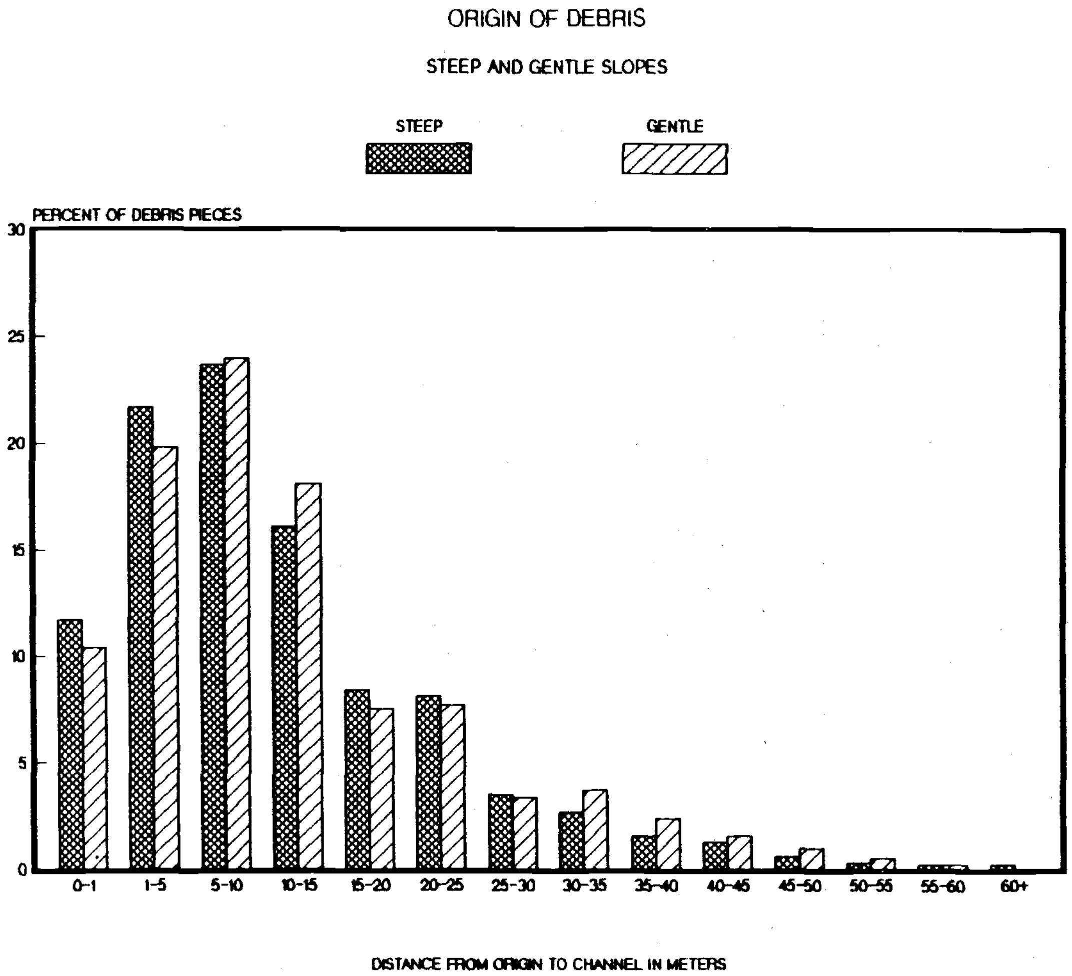

FIGURE 4. Percent of total number of debris pieces originating 0 - 1 meter, 1 - 5 meters, and subsequent five meter intervals from the stream's bank full edge, for streams with steep (n=632) and gentle (n=626) sideslopes.

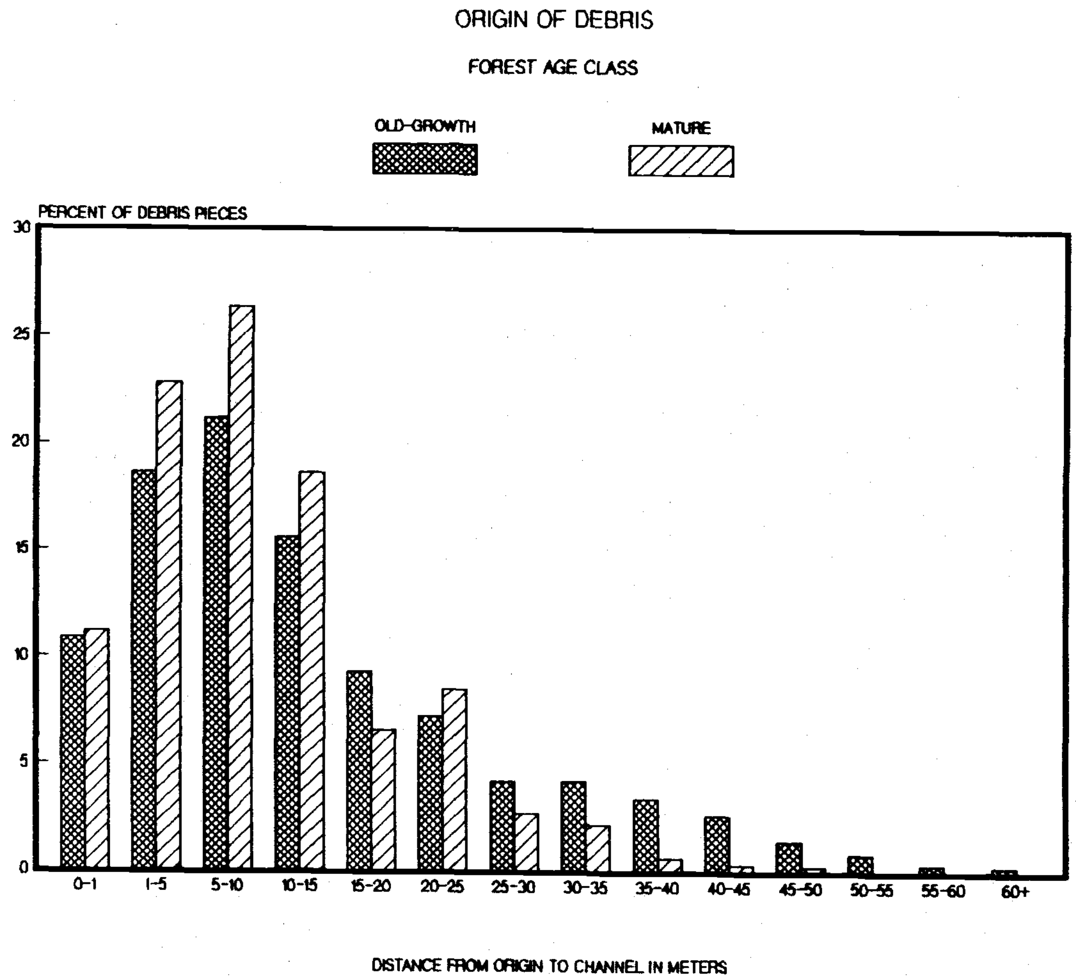

FIGURE 5. Percent of total number of debris pieces originating 0 - 1 meter, 1 - 5 meters, and subsequent five meter intervals from the stream's bank full edge, for streams draining old-growth (n=622) and mature (n=636) forests.

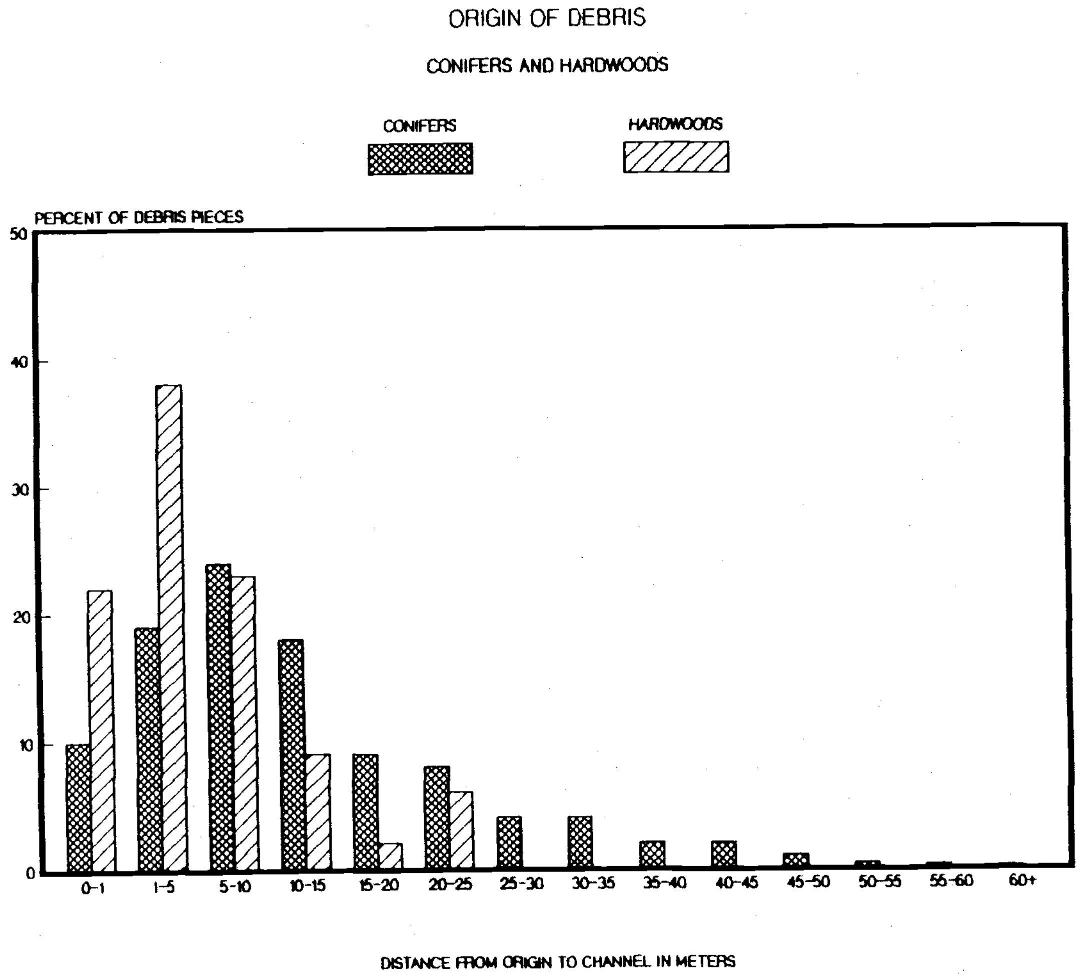

FIGURE 6. Percent of total number of conifer (n=1130) and hardwood (n=87) debris pieces originating 0 - 1 meter, 1 - 5 meters, and subsequent five meter intervals from the stream's bank full edge.

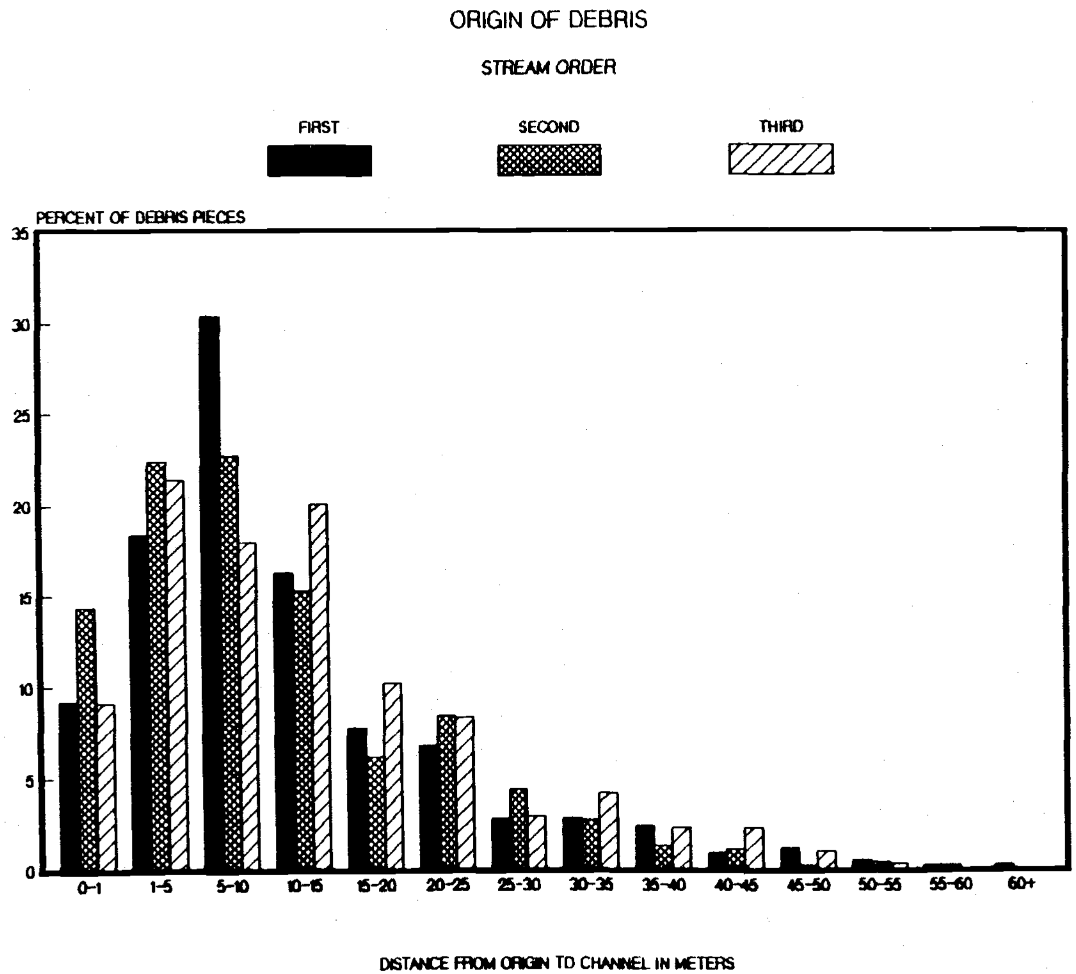

FIGURE 7. Percent of total number of debris pieces originating 0 - 1 meter, 1 - 5 meters, and subsequent five meter intervals from the stream's bank full edge, for first- (n=424), second- (n=450), and third- (n=384) order channels.

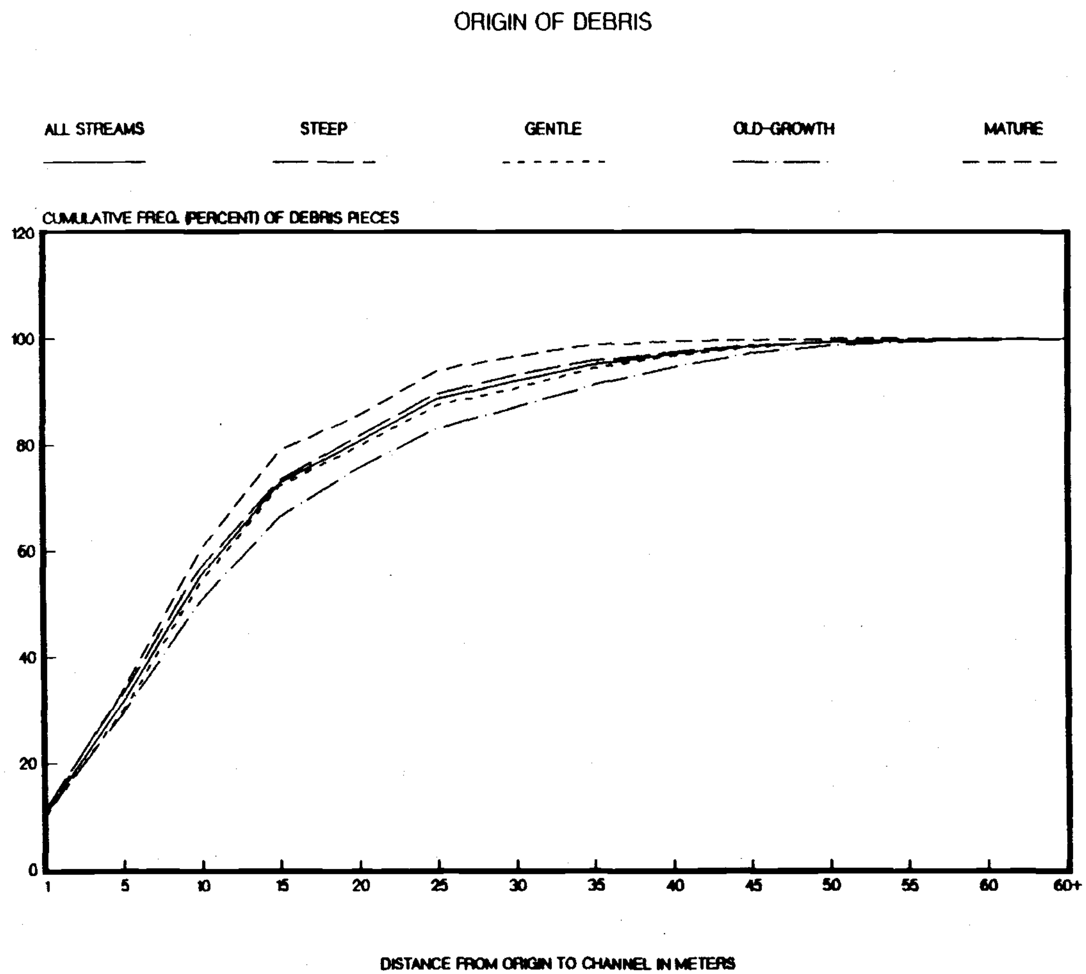

FIGURE 8. Cumulative frequency (percent) of distances between origins of debris and the stream bank for all streams totalled (n=1258 pieces), for streams with steep (n=632 pieces) and gentle (n=626 pieces) sideslopes, and for streams draining old-growth (n=622 pieces) and mature (n=636 pieces) forests.

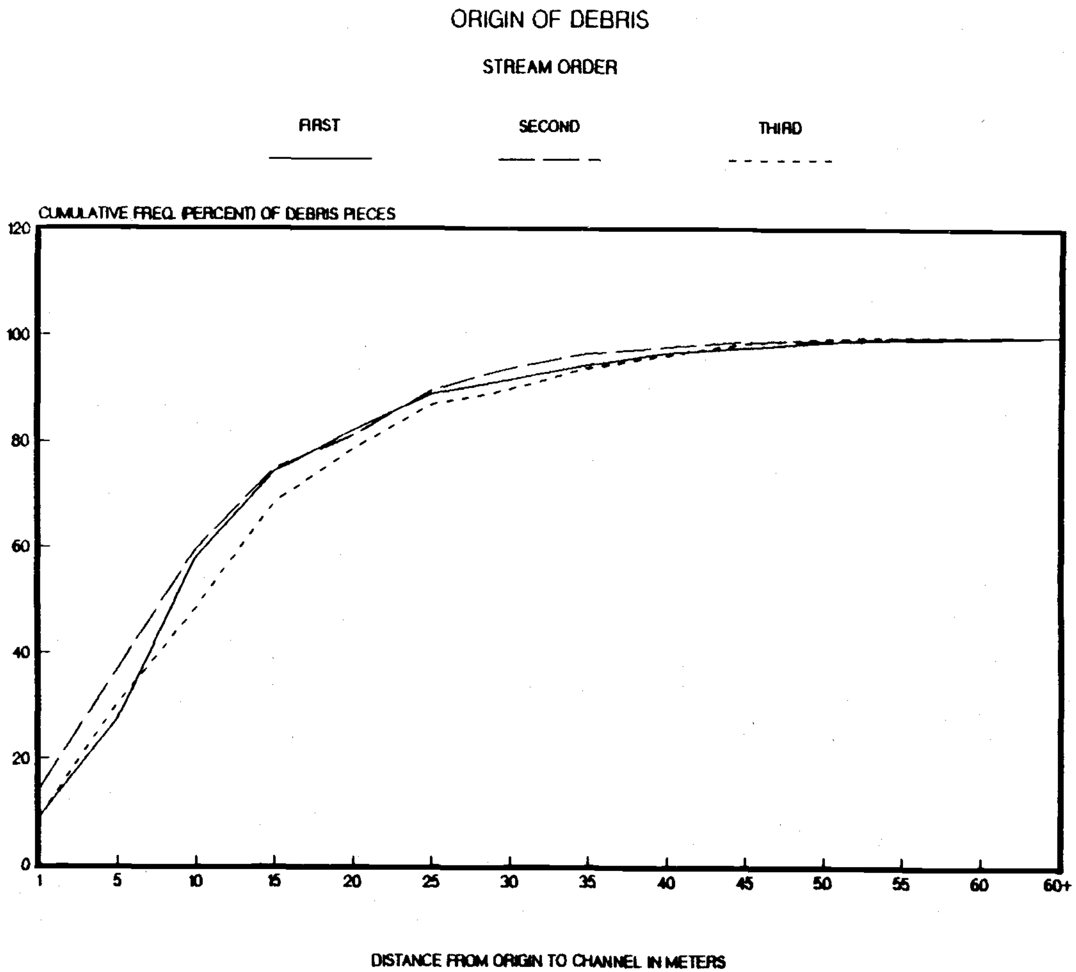

FIGURE 9. Cumulative frequency (percent) of distances between origins of debris and the stream bank for first- (n=424 pieces), second- (n=450 pieces), and third- (n=384 pieces) order channels.

TABLE 5. Total number of debris pieces originating 0 - 1 meter, 1 - 5 meters, and subsequent 5 meter intervals from the stream's bank full width for various groups of streams. The mean distance from origin to channel in meters (and standard error), as well as total number of debris pieces in each group (n) are also shown.

Stream	0-1 meters	1-5 meters	5-10 meters	10-15 meters	15-20 meters	20-25 meters	25-30 meters	30-35 meters	35-40 meters	40-45 meters	45-50 meters	50-55 meters	55-60 meters	60+ meters	Mean ± SE (meters)	n
Total All Streams	139	261	300	215	100	99	43	40	25	18	10	5	2	1	11.73 (0.53)	1258
Steep Slopes	74	137	150	102	53	51	22	17	10	8	4	2	1	1	11.31 (0.43)	632
Gentle Slopes	65	124	150	113	47	48	21	32	15	10	6	3	1	-	12.14 (0.44)	626
Old Growth	68	116	132	97	58	45	26	26	21	16	9	5	2	1	13.55 (0.50)	622
Mature	71	154	168	118	42	54	17	14	4	2	1	-	-	-	9.94 (0.37)	636
Conifers	110	211	272	202	96	94	41	40	25	18	10	5	2	1	12.43 (0.33)	1130
Hardwoods	19	33	20	8	2	5	-	-	-	-	-	-	-	-	5.44 (0.60)	87
First Order	39	78	129	69	33	29	12	12	10	4	5	2	1	1	11.83 (0.53)	424
Second Order	65	101	102	69	28	38	20	12	6	5	1	2	1		10.82 (0.49)	450
Third Order	35	82	69	77	39	32	11	16	9	9	4	1	-	-	12,68 (0.56)	384

TABLE 6. Total number of debris pieces originating 0 - 1 meter, 1 - 5 meters, and subsequent 5 meter intervals from the stream's bank full width for each first order stream reach sampled. The mean distance from origin to channel in meters (and the standard error), as well as the total number of debris pieces in each reach (n) are also shown.

Stream	0-1 meters	1-5 meters	5-10 meters	10-15 meters	15-20 meters	20-25 meters	25-30 meters	30-35 meters	35-40 meters	40-45 meters	45-50 meters	50-55 meters	55-60 meters	60+ meters	Mean ± SE	n
FIRST ORDER Old Growth																
Devil's Club	1	12	12	7	3	-	1	-	-	2	-	-	-	1	11.31 (2.02)	39
Gypsy	6	8	7	2	2	2	2	1	-	-	-	1	-	-	10.27 (2.10)	31
Watershed 2	7	8	11	2	3	2	-	-	-	1	-	-	-	-	9.63 (1.77)	36
Middle Santiam	-	4	8	3	2	6	3	2	3	-	1	-	-	-	17.85 (2.18)	32
Watershed 8, Reach 1	4	3	7	8	4	2	1	4	1	1	2	-	-	-	16.51 (2.11)	37
Mack Creek	1	3	9	8	1	3	1	1	-	1	1	1	1	-	16.97 (2.75)	31
Ohanopecosh	3	1	9	8	4	2	1	1	1	-	-	-	-	-	12.54 (1.60)	30
FIRST ORDER Mature																
North Fork Hagan	3	4	9	6	4	5	-	-	-	-	-	-	-	-	10.61 (1.32)	31
Mouse Creek	6	6	16	4	1	1	-	-	-	-	-	-	-	-	6.72 (0.92)	34
Lush Creek	2	5	15	6	2	-	-	-	-	-	-	-	-	-	8.00 (0.80)	30
McRae Creek	3	2	8	6	4	3	-	1	2	1	-	-	-	-	15.89 (2.27)	30
Foley Ridge	-	12	8	3	2	-	2	-	-	-	-	-	-	-	10.07 (1.65)	31
Watershed 8, Reach 2	3	10	10	6	3	-	-	-	-	-	-	-	-	-	7.39 (0.92)	32

TABLE 7. Total number of debris pieces originating 0 - 1 meter, 1 - 5 meters, and subsequent 5 meter intervals from the stream's bank full width for each second order stream reach sampled. The mean distance from origin to channel in meters (with standard error), as well as the total number of debris pieces in each reach (n) are also shown.

Stream	0-1 meters	1-5 meters	5-10 meters	10-15 meters	15-20 meters	20-25 meters	25-30 meters	30-35 meters	35-40 meters	40-45 meters	45-50 meters	50-55 meters	55-60 meters	60+ meters	Mean ± SE	n
SECOND ORDER Old Growth																
Mack Creek	12	8	5	-	1	4	1	1	1	-	-	-	-	-	9.51 (2.31)	34
Gypsy Creek	6	6	5	7	4	3	-	-	-	-	1	-	-	-	9.90 (1.68)	32
Watershed 2	-	6	9	5	3	3	1	-	2	-	-	-	1	-	15.71 (2.22)	33
Trapper Creek	2	8	6	7	4	1	-	-	-	1	-	1	-	-	12.09 (2.14)	30
McRae Creek - A	1	7	9	2	4	4	-	2	-	-	-	-	-	-	13.67 (2.01)	30
McRae Creek - B	5	2	5	8	4	-	3	2	1	1	-	-	-	-	14.21 (2.12)	31
SECOND ORDER Mature																
North Fork Hagan	4	4	7	5	2	6	3	2	-	-	-	-	-	-	13.65 (1.76)	33
Mouse Creek	2	9	7	9	2	2	3	-	1	-	-	-	-	-	11.39 (1.56)	35
Lush Creek	4	7	7	5	1	4	4	-	-	-	-	-	-	-	10.64 (1.62)	32
Roney Creek	9	12	5	4	-	1	-	1	-	-	-	-	-	-	5.73 (1.33)	32
Carpenter 75-B	7	6	8	7	2	1	-	-	-	-	-	-	-	-	7.24 (1.00)	31
Trapper Creek	7	8	7	2	2	1	-	2	-	1	-	-	-	-	8.95 (2.00)	30
Flynn Creek	2	9	10	5	1	4	1	1	1	-	-	-	-	-	11.16 (1.69)	34
Calf Creek	4	9	13	3	1	3	-	-	-	-	-	-	-	-	7.51 (1.09)	33

TABLE 8. Total number of debris pieces originating 0 - 1 meter, 1 - 5 meters, and subsequent 5 meter intervals from the stream's bank full width for each third order stream reach sampled. The mean distance from origin to channel in meters (with standard error), as well as the total number of debris pieces in each reach (n) are also shown.

Stream	0-1 meters	1-5 meters	5-10 meters	10-15 meters	15-20 meters	20-25 meters	25-30 meters	30-35 meters	35-40 meters	40-45 meters	45-50 meters	50-55 meters	55-60 meters	60+ meters	Mean ± SE	n
THIRD ORDER Old Growth																
Mack Creek	1	7	5	7	6	3	-	3	-	3	2	-	-	-	17.38 (2.24)	37
Trapper Creek	3	12	7	3	5	-	2	1	-	-	-	-	-	-	9.29 (1.52)	33
Upper Lookout - A	7	10	3	4	3	3	1	1	2	-	-	-	-	-	10.31 (1.84)	34
Lush Creek	2	5	5	7	2	2	3	1	-	1	2	-	-	-	15.65 (2.44)	30
Upper Lookout - B	3	1	5	7	4	2	2	1	5	2	-	-	-	-	18.68 (2.36)	32
East Fork	4	5	6	2	2	2	1	3	2	2	-	1	-	-	16.94 (2.80)	30
THIRD ORDER Mature																
South Fork Hagan	2	9	3	8	1	4	1	2	-	1	-	-	-	-	13.01 (1.92)	31
North Fork Hagan	3	9	6	8	2	2	1	-	-	-	-	-	-	-	9.10 (1.35)	31
Mouse Creek	5	3	8	11	6	1	-	-	-	-	-	-	-	-	10.04 (1.08)	34
McLennen	1	8	6	9	-	5	1	-	-	-	-	-	-	-	10.25 (1.26)	30
North Fork Elk	2	6	10	2	5	3	-	2	-	-	-	-	-	-	10.29 (1.53)	30
Rainbow	2	7	5	9	3	5	-	1	-	-	-	-	-	-	11.42 (1.39)	32

TABLE 9. Mean values (with standarad error in parentheses) for distance from origin to stream channel and origin to piece, mean bench width, length of debris, diameter at breast height, and sideslope steepness for streams with steep and gentle slopes, streams draining old-growth and mature forests, for conifer and hardwood debris pieces, and for first-, second-, and third-order streams. Lines connect mean values which are significantly different at p<.05 (ANOVA with mean comparison). Double lines under first- and third-order stream values indicate that these values differ significantly from each other. Distance from origin to stream is the shortest horizontal distance from origin to stream channel. Distance from origin to piece is the downslope distance from origin to end of piece nearest the origin (see Figure 2).

	Sideslope Class		Age Class		Species Class		Stream Order		
	Steep	Gentle	Old Growth	Mature	Conifers	Hardwoods	First	Second	Third
Distance, Origin to Stream (m)	11.31 (0.43)	12.14 (0.44)	13.55 (0.50)	9.94 (0.37)	12.43 (0.33)	5.44 (0.60)	11.82 (0.53)	10.82 (0.49)	12.68 (0.56)
Distance, Origin to Piece (m)	5.67 (0.34)	2.52 (0.27)	4.93 (0.38)	3.29 (0.23)	4.40 (0.24)	1.70 (0.46)	4.07 (0.36)	4.18 (0.36)	4.04 (0.43)
Bench Width (m)	2.11 (0.21)	2.94 (0.24)	2.60 (0.25)	2.45 (0.20)	2.50 (0.17)	3.53 (0.56)	1.41 (0.65)	2.17 (0.59)	4.16 (0.66)
Length of Piece (m)	17.73 (0.48)	22.39 (0.54)	22.87 (0.58)	17.29 (0.42)	20.82 (0.39)	13.16 (0.86)	19.65 (0.65)	19.02 (0.59)	21.70 (0.66)
Diameter at Breast Height (cm)	79.70 (1.63)	73.90 (1.64)	95.45 (1.67)	58.57 (1.23)	80.05 (1.23)	44.98 (1.72)	72.60 (2.02)	75.30 (1.78)	83.21 (2.26)
Sideslope Steepness (degrees)	30.71 (0.56)	8.76 (0.38)	20.64 (0.65)	18.95 (0.65)	20.51 (0.48)	7.80 (1.50)	21.50 (0.75)	20.72 (0.78)	16.74 (0.85)

to its present location was significantly greater along steep slopes, whereas the average length of the piece was greater in gentler terrain.

Old Growth and Mature Forest Areas

The average distance from origin of material to stream channel was significantly greater in old-growth stands (Table 9). The average distance from origin to end of debris piece nearest origin, maximum diameter, and total length of debris were also significantly greater in old-growth than in mature stands. No significant differences were found in bench width or average slope steepness with respect to stand age.

Species Comparison - Hardwoods and Conifers

The average distance from origin of material to the stream bank was significantly greater for conifer than for hardwood species (Table 9, Figures 6 and 10). Over 83% of hardwoods originated within 10 meters of the stream channel, whereas only 53% of conifers originated within this distance. All of the hardwoods originated within 25 meters of the stream channel, but only 87% of conifers originated within this same distance (Figure 10). The total length of the piece, average slope steepness, and diameter at breast height

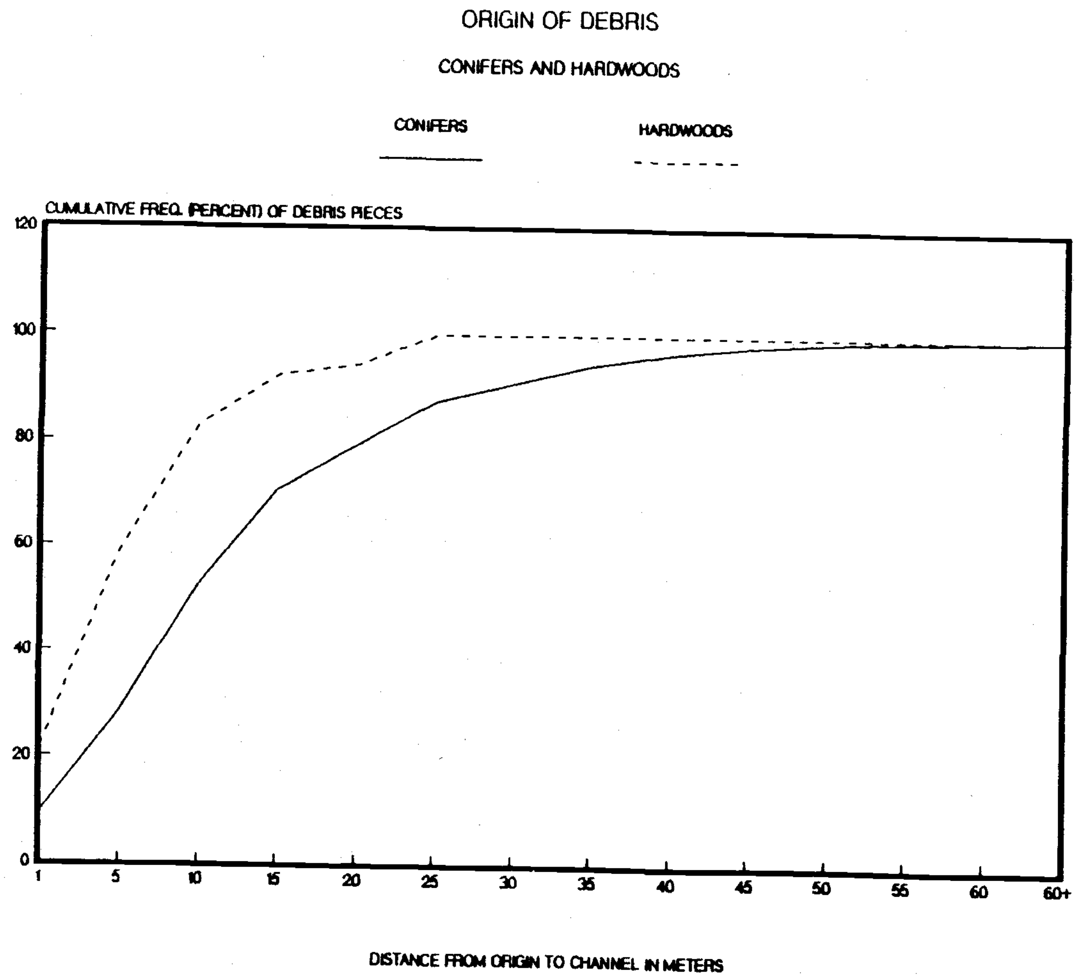

FIGURE 10. Cumulative frequency (percent) of distances between origins of conifer (n=1130 pieces) and hardwood (n=87 pieces) debris pieces and the stream bank.

were also significantly greater for conifer than for hardwood species (Table 9).

Stream Order

The average distance from origin of debris to stream channel was significantly greater for third-order streams than for second-order streams (Table 9; ANOVA, $p < .05$). However, no significant differences were found in distance from origin to channel between first-order channels and larger channels. Third-order streams had more gentle sideslopes and longer debris pieces than either first- or second-order streams, although no significant differences were found in slope steepness or length of debris between first- and second-order streams. Bench width increased significantly as stream order increased. No significant differences were found in distance from origin to end of piece with respect to stream order.

Regression Analysis

An attempt was made to identify the best fitting regression model (dependent variable = the distance from origin to the stream, independent variables = stream order, average sideslope steepness, stand age, and bench width). The variables showed little predictable interaction with each other or with the dependent variable, and accounted for only 7% of the total variation in distance observed. Thus, it is apparent that these variables alone are not adequate to predict the origin of woody debris which enters the stream system.

DISCUSSION

Distribution of Source Distance

The overall distribution of distance from origin to channel was similar for all streams (Figures 8 and 9). Eleven percent of the total number of debris pieces originated within one meter of the stream. The remaining 89% originated further from the stream. These findings are similar to those of Lienkaemper and Swanson (1987), who directly observed debris input into first- through fifth-order streams in the Western Cascades, Oregon, over a 7 to 9 year period. They found that the majority (66%) of total number of debris pieces entering the stream grew "in areas not subject to bank erosion", with the remaining 34% growing "adjacent to the stream". The distribution of sources is similar in their study and this study (with the majority of debris originating in areas not subject to bank erosion). However, Lienkaemper and Swanson (1987) reported a larger proportion of debris pieces originating adjacent to the stream than was found in this study. There may be two factors which account for this: first, Lienkaemper and Swanson's (1987) direct observations included a shorter period of debris input than did this retrospective study. This study included debris which may have entered the stream years or decades ago, and thus represents a larger sample size as well as a longer period of input. Second, Lienkaemper and Swanson (1987) included a proportionately larger number of higher order channels (one first-order, one second-order, two third-order, and one fifth-order), where bank cutting is more likely to be a major factor in debris input. In fact, they found that LOD entering the steep, narrow first- and second-order study channels originated entirely in areas not influenced by stream channels, with the exception of one tree rooted at the streambank. In third-order channels, material originated from a variety of sites equally distributed between areas at and away from the stream. At the fifth-order site, all but one occurrence of debris entry involved trees originating at the stream, and in this stream, bank erosion was probably a major factor. They concluded that lateral cutting by streams appeared to be rare and that wind was the major agent of delivery of debris to the channel.

As in Lienkaemper and Swanson's (1987) study, lateral cutting appeared to be minimal in this study, as evidenced by the small proportion (11%) of debris pieces originating adjacent to the stream. These streamside pieces may be especially prone to falling into the channels, even without bank-cutting. Instability imposed by asymettric rooting environments and the tilt of trees growing into the open canopy above larger streams may make these trees highly susceptible to windthrow (Lienkaemper and Swanson, 1987).

Steep and Gentle Sloped Areas

The results of comparing steep and gentle sloped areas were initially surprising. It was expected that the distance from point-of-origin to the channel would be significantly greater for streams with steeper sideslopes, primarily due to sliding of the debris down the slope toward the channel. However, there was no difference in the distance from origin to channel, although the distance the piece moved from its origin was significantly greater in steeper areas. Thus, woody debris originating on steeper slopes apparently does slide further downslope than does debris originating in flatter areas, as was expected.

Streams located in more gentle terrain not only have lower sideslope steepness, but are also more likely to have wider, relatively flat benches, resulting in more debris remaining where it initially fell, with little, if any, movement. Thus, although sliding does account for increased movement from origin in steeper areas, the average distance from origin to the stream was not found to be significantly greater in steeper areas. However, in considering this, it must be remembered that all distances were converted to horizontal distances (by simple trigonometry) before data analysis was performed. Conversion to horizontal distances minimizes distances along steep slopes (as the cosine decreases with increasing angle), thus minimizing the effects of sliding along steep slopes, and maximizes distances along gentle slopes and flat terraces. Debris originating 35 meters upslope from the stream on a 45 degree slope is actually closer to the stream in horizontal distance than debris originating 25 meters from the stream on a 10 degree slope.

In terms of management practices, if the results of this study are to be used in predicting the origin of large debris in streams or in determining appropriate buffer strip widths, the manager must remember that these results are based on measurements converted to horizontal distances. For this reason, it is strongly recommended that the manager convert all field measurements to horizontal distances. Failure to do so may result in buffer strips which are significantly narrower than intended.

Shorter debris pieces in steeper areas obviously result from more breakage of debris as it falls into steeper valleys.

Old Growth and Mature Areas

The greater distance from origin to channel noted in old-growth stands may be primarily due to tree size and healthiness of the stands. Old-growth stands suffer greater amounts of age-associated disease, including root- and heartrots, which increase susceptibility to blowdown. Larger-sized trees appear more prone to windthrow simply due to their larger size (Harcombe and Marks, 1983). Thus, a significant portion of the debris entering streams from old-growth stands may originate as blowdown many meters from the stream, whereas blowdown (as a debris delivery mechanism) may be less important in healthier, more windfirm mature stands. Processes other than blowdown, such as soil mass movement activities, battering by floating debris, or streambank undercutting may be more important in contributing debris to streams in mature stands. The latter two of these processes occur immediately adjacent to the channel, as a result of stream activity. The result may then be an increased number of pieces originating immediately adjacent to the stream. In studying small coastal streams in Western Washington, Grette (1985) found that the primary debris delivery mechanism in mature forests was bank undercutting, whereas mortality of older, sensecent trees was believed to be more a important method of debris entry in similar-sized streams flowing through old-growth forests.

Additionally, conifer trees in the Pacific Northwest continue to enlarge substantially in both height and diameter over time (Franklin and Waring, 1979; Franklin et. al., 1982), resulting in taller trees in older stands. Average tree height in mature stands surrounding sampled streams is estimated to be 70% of average tree height in old-growth study areas (J. Franklin, personal communication). Thus, old-growth stands may contribute debris to the channel from greater distances (due to taller trees) than mature stands.

Diameter at breast height and length of piece were obviously larger in old-growth stands due to greater size and height of trees. Although old-growth trees may be less vigorous than younger trees, they are larger in diameter and apparently these larger diameter trees are less likely to break into two or more shorter pieces when toppling. Additionally, smaller diameter pieces in mature stands tend to decompose more quickly (Abbott and Crosley 1982; Graham, 1982), resulting in even smaller pieces which may be more easily transported out of the stream system during high flow periods.

Species

As expected, hardwood species originated closer to the stream and were smaller in length and diameter at breast height than conifer species. Hardwoods are usually found in a riparian border closely adjacent to the stream, often on a gently sloping bench (Swanson et. al., 1982). As distance from the stream increases, the frequency of hardwoods decreases and the proportion of conifers increases. This explains the greater distance from origin to stream channel noted for conifers.

In terms of piece size, hardwood riparian trees are usually smaller and younger than associated conifer species. There are two reasons for this. First, light limitations imposed by upslope conifers may suppress growth of riparian hardwoods (Swanson et. al., 1982). Shade-tolerant conifers may become established along the stream edges, further limiting space and light availability to hardwoods. Second, during high flows, floating organic debris may trim, batter, and destroy existing vegetation along the riparian corridor, thereby initiating sprouting from the remaining damaged trees and shrubs (Swanson et. al., 1982), resulting in smaller debris pieces. When these hardwood species do enter the channel, they are comparatively small in diameter and decompose quickly. These factors, then, account for hardwood pieces which are smaller and shorter than conifer debris pieces.

Stream Order

Several results observed with respect to stream order differ from the expected. For example, it was generally expected that the distance from point-of-origin to channel would be greater in first- and second-order streams as a result of sliding down steep slopes. However, the average distance from the origin to stream channel was greater in third-order streams (although differences were minimal, <2 meters, Table 9). Second, no significant differences in the distance from origin to the end of the piece nearest origin were observed with respect to stream order. Thus, movement from the origin occurs to about the same extent in streams regardless of stream order, an average of 4.10 meters downslope. This is difficult to explain, as third-order streams generally occur in more gentle terrain than that of headwater first- and second-order streams. Third-order streams observed in this study do have significantly more gentle sideslopes than either first- or second-order streams, but this did not result in significantly shorter distances from origin to stream channel. Apparently, the difference in sideslope steepness between the headwater first- and second-order streams and the third-order streams, although statistically significant, does not result in a statistically significant difference in movement of debris from its point-of-origin.

The slightly greater distance from point-of-origin to channel and diameter at breast height in third-order channels may be due to better sites adjacent to some of these streams. Wider benches and more gentle terrain along some third-order streams may result in greater productivity in terms of tree growth (greater height and diameter) due to richer alluvial soils and less moisture stress than in upslope areas. However, bench width adjacent to third-order streams studied is still relatively small in comparison to overall tree height and potential debris source area. Thus, site differences may be present, but minimal, in this study. Such site differences may be more important in larger, lower-gradient channels with wider, more well-developed floodplains.

A second possible explanation for greater distance observed in third-order channels is the conversion of all source area distances to horizontal distances. As discussed previously, this conversion minimizes distances along steep slopes and maximizes distances along gentler slopes. In this case however, the difference in average sideslope steepness is <5 degrees, not nearly as great as that observed for gentle and steep sloped areas. Differences due to a five degree slope difference would probably be quite minimal, and thus would not significantly affect results.

The fact that third-order streams are found in gentler terrain probably does account for the greater length of debris pieces. There is undoubtedly more breakage of debris as pieces fall into the steeper valleys of headwater streams, hence the longer debris pieces in larger, third-order streams.

Management Implications

If a goal of forest management is protection of the stream environment during harvest, including retention of LOD, then the results of this study can assist in developing guidelines for buffer strip design. Several studies have shown that a buffer strip of unlogged timber may reduce alteration of the stream environment. Froehlich (1975a) found that the total increase in coarse and fine organic matter in streams as a result of logging was significantly less when buffer strips were left adjacent to streams. Three different buffer strips were examined : a 20 to 50 foot strip of hardwoods; a 30 to 50 foot strip of hardwoods, large Douglas-fir, and cedar; and a 100 to 130 foot strip of Douglas-fir, cedar, and hemlock. The large buffer strip was clearly the most effective in reducing debris input and the stream remained virtually unchanged. The 20 to 50 foot strip showed an increase in coarse and fine organic matter of 28% and an increase of fine organic matter of 72%; whereas the 30 to 50 foot strip showed an increase in coarse and fine organic matter of 13% and an increase of fine organic matter of 10%. Obviously, even the smallest buffer strip (20 to 50 foot) provided some stream protection. Lammel (1973) noted similar results in comparing debris concentrations in five streams before and after felling and yarding. Three streams had no buffer strips, one had a narrow (5 meter) buffer strip, and one had a wide (50 meter) buffer strip. No change in either total or fine organic debris volume was observed in the channel protected by the wide buffer after falling and yarding. All other streams showed an increase in both total debris volume (1.2 to 3.3 times greater than pre-logging levels) and fine organic debris volume (1.1 to 4.3 times greater than pre-logging levels) following yarding operations. A separate study by Hall and Lantz (1969) found no significant difference in the quality of the stream habitat or the size of fish population between an unlogged stream and a stream where "narrow strips of timber" were left along the channel. However, significant differences in both stream quality and fish population were found between these two streams and a completely clearcut watershed.

It is apparent then that buffer strips can assist in the protection of the stream environment, as well as serve as future sources of LOD. It has been recommended that the riparian zone be left intact primarily for future debris input (Sedell and Triska, 1977). Rainville (1978) suggests buffer strips of at least 100 foot width to provide a suitable stand for log recruitment and to maintain the beneficial influences of temperature insulation and sediment erosion control. Unfortunately, there are no well established guidelines for determining buffer strip widths which consider debris origins, as debris origins have not been previously well documented.

It was not possible to develop a predictive model for determining buffer strip widths (based on sideslope steepness, stand age, stream order, and bench width) in this study. These factors account for only 7% of the total variation observed in distance from point-of-origin to channel. The remaining unexplained variation may be due to a variety of factors, not included in this study, such as prevailing winds, topography, health of forest, soil stability, depth of water table, and site productivity. For example, trees growing on wetter sites are more susceptible to windthrow than those on dry sites due to shallow rooting (Harmon et. al., 1986). Sites which are more favorable to tree growth may produce taller trees than less favorable sites. Thus, these more productive sites may then contribute debris to streams from greater distances than less productive sites.

The study does provide information on the source area of debris for streams, which can then be used in designing streamside buffers. LOD originated as far as 60 meters from the channel. However, most (92%) originated within 30 meters of the stream, and 56% came from within 10 meters of the stream (Figure 3). The manager must remember however, that much of the LOD originating within a few meters of the stream is more likely to be hardwood species which decay relatively rapidly. In fact, well over three-fourths of the hardwood debris originated within 10 meters of the stream, whereas just over half of the conifer species had their origins within this distance (Table 5, Figures 6 and 10). Hardwood debris is generally smaller in both diameter and length of piece than is conifer debris, and several studies have indicated that large debris is needed to maintain the stream's physical and biological environments (Swanson et. al., 1976; Swanson and Lienkaemper, 1978). Larger pieces of debris stabilize smaller pieces which would otherwise be washed out at high flow, or which might trigger a debris torrent. Swanson and Lienkaemper (1978) found that the occurrence of torrents is less likely where the potential buildup of floatable fine and intermediate sized pieces is checked every five to ten meters by very large logs across the channel. In studying logging on Carnation Creek, Toews and Moore (1982) reported that alder trees felled and killed during logging and subsequently entering the stream system did not remain in place within the stream. Because they were generally small and light, the alder pieces were floated away and were found to form a substantial part of downstream debris jams. In view of this, it seems important that the buffer strip extend well beyond the hardwood zone. This suggestion is supported by Froehlich's (1975a) study of differing width buffer strips described previously. The 20- to 50-foot strip consisting primarily of hardwoods showed more than double the increase in coarse and fine debris loading following logging than did the 30- to 50-foot strip of mixed hardwoods and conifers. With the largest buffer strip (100 to 130 foot strip of conifers), the stream remained unchanged.

In developing buffer strip guidelines, it is also important to remember that managed, mature stands are more windfirm and smaller than present old-growth stands, and are thus less desirable as debris sources than old-growth stands (Toews and Moore, 1982). Additionally, a larger proportion of the debris entering the channel from managed, mature stands is hardwood debris (Grette, 1985). In fact, Grette (1985) reported that the frequency of red alder in streams flowing through mature stands was approximately two times the frequency of red alder in old-growth stands. This hardwood debris was generally found to have shorter residence times in streams than pre-harvest coniferous debris, as hardwood debris is smaller, shorter, more rapidly decomposed and more easily transported than larger coniferous debris. The rate of input of larger, more decay resistant conifers may not increase for 60 or more years after harvest (Grette, 1985), resulting in streams with less cover and fewer pools than in unlogged forests (Bisson et. al., 1987).

Other studies have shown that, on the average, debris levels in mature sites are significantly lower than in old-growth areas (Swanson and Lienkaemper, 1978; Grette, 1985; Sedell et. al., 1985). Removal of nearly all large trees during timber harvest results in debris recruitment rates in mature areas which are significantly lower than in old-growth areas (Bisson et. al., 1987). Thus, in order to provide maximum benefits to streams in terms of debris input, it seems desirable that buffer strips of unlogged old-growth timber be left along the stream channel whenever possible.

It is interesting to note that several authors have recommended buffer strip widths of approximately 100 feet (30 meters) or more. In terms of this study on debris origins, 92% of the LOD originated within 30 meters of the channel. With respect to shading of the stream, Brazier and Brown (1973) found that the overstory within 80 feet of the stream normally provides 100% of the shading, although the distance varied according to topography, stream width, overstory height, and orientation to the sun. Benoit (1978) suggested buffer strips of at least 100 feet, and up to 450 feet in width, depending on land slope, to maintain the beneficial influences of sediment erosion control. Finally, Froehlich (1975a) and Lamell (1973) found, in separate studies, that with buffer strips 100 to 130 feet wide and 50 meters wide respectively, the stream remained unchanged after logging, whereas increases in both coarse and fine organic matter were noted with narrower strips.

However, studies on buffer strips reveal that losses may be considerable. Mortality from all causes, including blowdown, ranged from 5 to 55% (Froehlich, 1975b). Franklin et. al. (1982) stated that even a 200 foot wide streamside or roadside strip is not a viable unit in most cases. Buffer strips in areas with significant blowdown before cutting will be subject to large losses. Thus, managers must consider the timber make-up of the stand, as well as previous blowdown history, so that buffer strips can be designed for long term stability and survival.

SUMMARY

It is obvious that LOD is an extremely important component of stream ecosystems. It is also apparent that various management activities can significantly alter the amount, size, and distribution of LOD in streams. A primary goal of management might be to maintain LOD at high, natural pre-management levels, so that it can continue to function as habitat and a long-term nutrient source for stream organisms (Triska and Cromack, 1980). Leaving buffer strips of unlogged timber adjacent to the stream in one way to minimize alteration of the stream environment (Lammel, 1973; Froehlich, 1975a; Swanson and Lienkaemper, 1978), as well as allowing it to serve other important roles, such as shading and allochthonous input into streams. Trees from buffer strips may continue to fall into the stream for many, many years after harvesting, to carry out the important ecological roles of LOD in streams (Swanson and Lienkaemper, 1978). Debris from buffer strips replenishes stream debris as prelogging debris is removed from the stream by decomposition and downstream transport. Although there may be little immediate effect on stream quality or amount of LOD in streams with narrow buffer strips (Hall and Lantz, 1969), habitat degradation could result if the in-stream debris is washed out and there is little or no replenishment. It may take the harvested stand 60 to 100 years or more before it begins contributing debris of sufficient size to avoid wash-out during high flows (Swanson and Lienkaemper, 1978; Bisson et. al., 1987). Thus, effects of streamside logging in the absence of buffer strips or with very narrow buffer strips may be extremely long-term. This paper has provided information on the source area of LOD in streams, so that managers may consider this information when designing streamside buffers to provide for future input of sufficient quantities of LOD into stream systems.

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