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Changes in Characteristics and Function of Woody Debris with Increasing Size of Streams in Western Washington

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Abstract. — In second- to fifth-order streams that drain old-growth timber in western Washington, characteristics and function of woody debris changed in relation to stream size. Average diameter, length, and volume of pieces of wood increased as stream size increased, whereas the frequency of occurrence of woody debris decreased. In streams with channel widths less than 7 m, 40% of the pieces of debris were oriented perpendicularly to the axis of flow; in streams with channel widths over 7 m, more than 40% of the pieces were oriented downstream. The types of pools most commonly associated with pieces of wood changed from plunge pools in small streams (42%) to debris scour pools in larger systems (62%). Pool area was correlated with the volume of the piece of wood forming the pool in streams of all sizes. However, this relationship was most evident in larger channels. Nearly 40% of the pieces of wood in channels less than 7 m wide were associated with sediment accumulations. Less than 30% of the pieces retained sediment in channels from 7 to 10 m wide, and less than 20% retained sediment in channels greater than 10 m wide. Surface area of sediment accumulations and the volume of the piece of wood forming the accumulation were related in all streams, but the relationship was clearest in the larger channels. Accumulations of particulate organic matter associated with woody debris were more frequent in small streams but were larger in large streams. No relationship was observed between the volume of fine particulate organic matter accumulated by a piece of wood and the piece of wood's volume.

The role played by large pieces of woody debris in streams has received much attention over the last decade. This material is an integral component of the structure of streams in forested watersheds and profoundly affects the functioning of these systems (Harmon et al. 1986; Bisson et al. 1987). Large pieces of woody debris in streams influence the physical form of the channel, the movement of sediment, the retention of organic matter, and the composition of the biological community.

Channel form may be influenced by woody debris in a number of ways. Debris can be instrumental in forming and stabilizing gravel bars (Lisle 1986) or in accumulating fine sediment (Zimmerman et al. 1967; Megahan 1982). Debris also can form pools by directing or concentrating flow in the stream in such a way that the bank or bed is scoured or by impounding water upstream from the obstruction (Lisle and Kelsey 1982). Woody debris is also responsible for the formation of waterfalls, especially in smaller, steeper streams. The drop in elevation caused by waterfalls formed by woody debris in small streams in New Hampshire was 52% in first-order streams, 46% in second-order streams, and 10% in third-order systems (Bilby 1981).

The formation of waterfalls not only influences the morphology of a channel but also slows the transport of sediment through the system by causing a rapid loss of potential energy from the stream with no consequent erosion of material from the bank or bed (Heede 1972). Debris also slows sediment movement downstream by forming low-energy areas in which this material can be deposited. Debris retained about 49% of the total stored sediment in seven Idaho watersheds (Megahan 1982) and 87% in a New Hampshire watershed (Bilby 1981). Sediment stored by woody debris in an Oregon stream amounted to 1.92 m^2/m (Swanson and Lienkaemper 1978). The cleaning of a 175-m reach of a second-order stream in New Hampshire released stored sediment and resulted in a 500% increase in sediment export the following year (Bilby 1981). Similarly, the removal of several large jams from a 250-m section of stream in the Oregon Coast Range released 5,250 m^3 of sediment (Beschta 1979).

Woody debris also may be responsible for the retention of large amounts of organic matter in streams (Naiman and Sedell 1979). The proportion of the total standing stock of coarse particulate organic matter (material larger than 1 mm) associated with woody debris in some small streams in New Hampshire was found to vary with stream size and declined from 75% in first-order streams to 58% in second-order streams to 20% in third-order systems (Bilby and Likens 1980).

The importance of woody debris as habitat and cover for fish has been documented widely. Certain species and age-groups of fish prefer specific pool types that often are associated with wood in streams (Bisson et al. 1982). Salmonids use wood-associated cover heavily during periods of elevated discharge, when the low-velocity areas created by the debris may offer the only suitable refuge (Bustard and Narver 1975; Tschaplinski and Hartman 1983). The importance of woody debris to fish has been demonstrated by marked decreases in population size after the removal of debris from streams (Lestelle 1978; Bryant 1983; Dolloff 1986; Elliot 1986).

Although the role played by woody debris in streams has been well defined qualitatively, relatively little information is available on the variability in the characteristics, amount, or function of woody debris with changing stream size. Likens and Bilby (1982) found that as stream size increased, the average size of pieces of debris increased, and the frequency of occurrence decreased. Debris function in the accumulation of organic matter also changed. As the frequency of debris-caused waterfalls decreased with increasing stream size, so did the proportion of total coarse, particulate organic matter (>1 mm) associated with woody debris. Thus, a more thorough understanding of the interaction between debris characteristics and stream size may provide some added insight into the influence of system dimensions on ecosystem function of streams. In addition, this information would be valuable for formulating more effective riparian management policies, especially in the Pacific Northwest where many watersheds are managed primarily for timber production, a use that has the potential to substantially alter amounts of woody debris and input rates (Grette 1985; Bisson et al. 1987). Our research examined the influence of stream size on woody debris characteristics, frequency, and function.

Site Description

Sections of 22 streams were surveyed during this study. All were located in areas of undisturbed old-growth forest in southwestern Washington. Restricting the study to old-growth forest helped ensure that the surveyed sites had had a long time period during which debris distribution and debris-associated channel features could develop.

All the study streams were located in either the Willapa Hills or in the foothills of the southern Cascade Mountains of western Washington. Surveyed stream sections were all within 100 km of one another and, thus, likely had a relatively similar history of high discharges, which would have influenced debris distribution. The sites represented a range of stream sizes from second to fifth order (Strahler 1957). Watershed areas ranged from 0.4 km^2 to 68.0 km^2, with average exposed channel widths from 3.6 m to 19.7 m (Table 1). Annual precipitation varied considerably among the study sites and ranged from 180 cm to 280 cm (Sternes 1969), due largely to differences in elevation. Channel gradients of the surveyed stream sections ranged from 1 to 18%. Streambeds were composed predominantly of gravel and cobble. All of the study sites were on volcanic rock (Huntting et al. 1961) to minimize variability caused by geologically controlled morphological features of the channel or characteristics of the stream substrate.

Methods

We selected study sites by locating areas of old-growth forest on aerial photographs and then examining the streams in these areas on the ground to determine if they met the criteria outlined above. Watershed area of each study site was measured on a U.S. Geologic Survey topographic map (scale 1:62,500) by use of a planimeter. The average gradient of each surveyed reach and the stream order were determined from these maps. Bank-full channel widths were measured at 10-m intervals during the surveying procedure, and the length of each study section was measured after the survey of the site was completed (Table 1).

For the purposes of this study, a piece of woody debris was defined as larger than 10 cm in diameter and more than 2 m long. Generally, we measured all pieces of wood meeting these criteria. However, in accumulations of many pieces, only those pieces providing the framework of the accumulation were measured. We limited our inventory to such pieces because they were primarily responsible for the channel features associated with the wood. Identification of the major structural members within an accumulation was usually straightforward. Pieces that were omitted generally were either floating in front of the accumulation or resting on top and easily moved by hand. In those situations where the importance of a piece to the stability of an accumulation was unclear, the piece was included.

The length of a study site was dictated by the distance encompassing 50 pieces of debris. For each piece, we measured the surface area of associated sediment accumulations, the height of

TABLE 1.—Characteristics of stream sections in western Washington and the number of pieces of wood measured at each site.

Stream	Basin area (km^2)	Channel width (m)	Channel gradient (%)	Site length (m)	Pieces measured (*N*)
Skookumchuck River drainage					
Unnamed tributary	0.8	4.2	18	74	50
Unnamed tributary	0.4	4.3	17	82	53
Unnamed tributary	2.3	5.4	10	185	50
Deer Creek	2.9	6.3	11	125	51
South Fork Skookumchuck River	1.7	7.1	12	91	50
Skookumchuck River	26.6	17.0	2	385	50
Tilton River drainage					
Middle Fork Tilton River	1.3	5.9	14	102	50
Otter Creek	3.8	9.7	10	124	51
Newaukum River drainage					
Newaukum River	18.1	8.9	6	312	53
Grays River drainage					
East Fork Grays River	7.5	11.7	2	204	49
North Fork Grays River	21.9	16.1	2	238	50
Deschutes River drainage					
Hard Creek	1.7	5.6	17	77	60
Unnamed stream	1.0	5.8	12	143	50
Mine Creek	2.7	7.5	8	156	50
Thorn Creek	3.6	7.6	14	186	52
West Fork Creek	8.7	9.0	6	204	51
North River drainage					
Unnamed tributary	2.1	3.6	2	143	50
Fall River	30.4	12.4	1	500	50
Lewis River drainage					
Upper Canyon Creek	12.7	10.1	3	417	50
Middle Canyon Creek	33.0	16.1	4	385	50
Fly Creek	50.3	18.9	10	460	46
Lower Canyon Creek	68.0	19.7	2	715	50

debris-formed waterfalls, the surface area of pools influenced by the debris, and the volume of particulate organic matter associated with the wood. For the purposes of this study, particulate organic matter was defined as material less than 10 cm in diameter and less than 2 m long. Sediment was defined as any material smaller in size than the predominant bed material. Thus, an area of gravel associated with a piece of debris in a stream with a bed composed primarily of cobbles would qualify as a sediment accumulation. We measured three widths and the length of each sediment accumulation and pool with a tape or range finder and calculated surface area from the length and mean width. The diameter of each piece of debris was measured with calipers, which also were used to measure the length, width, and height of accumulations of particulate organic matter associated with the woody debris. Heights of debris-caused waterfalls were measured with a meterstick. Debris length in and out of the channel and channel widths were measured with a tape or a range finder. The species of tree that produced the debris also was recorded when possible. Identification was not possible for about 10% of the pieces due to advanced decay.

We assigned pieces to one of four orientation categories (perpendicular, parallel, upstream, and downstream) based on position in the channel with respect to the predominant direction of stream flow at that location. Parallel pieces were positioned with the long axis of the piece oriented in the same direction as the flow. Perpendicular pieces were at right angles to the direction of flow. Downstream pieces were positioned at an angle to the flow with the smaller-diameter end of the piece extending downstream. Upstream pieces also were at an angle to the flow but with the smaller end pointing upstream.

The classification system of Bisson et al. (1982) was used to categorize pools. Four classes of pools were identified according to their presumed origin and general morphology. Debris scour pools were formed by erosion of the bed or bank brought about by deflection and concentration of the streamflow by a piece of debris. Plunge pools were caused by scour of the bed immediately downstream from a debris-caused waterfall. Dammed pools were areas of impounded water caused by obstruction of the flow by debris. Backwater pools were defined as areas of quiet water on the downstream side of a piece of debris and generally near the channel margin.

We determined mean diameter and length of pieces of debris for each of the study sites to examine the relationship between stream size and size of debris. Because the frequency distributions of diameters and lengths of debris were lognormal, a geometric mean was used to calculate average diameter and length of debris for each survey site. The geometric mean for length included the total length of each piece, both in and out of the channel, because the entire piece of wood contributed to its stability. An estimate of the mean volume of a piece of debris for each study site (termed the debris volume index) was determined by calculating the volume of a cylinder having as its dimensions the geometric mean debris diameter and length.

Channel width rather than watershed area was used as an index of relative size of a stream. Channel width was considered to be the best indicator of the magnitude of high flows carried by each channel due to the variation in precipitation among the study systems (Sternes 1969). High discharges were considered to be largely responsible for the observed patterns of debris distribution and debris-associated channel characteristics.

We examined the relationships between debris characteristics and associated channel features and the changes in these relationships with changing stream size by segregating the study systems into three size categories based on channel width: less than 7 m, 7–10 m, and greater than 10 m. There were approximately an equal number of sites in each category. The relationship between debris size and orientation and associated channel features were examined for each category of channel width. Because there was some variability in channel width within these categories, we used a multiple regression to evaluate the relative influence of channel width and woody debris volume on pool surface area and the area of sediment accumulations. Only the portion of a piece of debris within the bank-full channel was considered in these analyses.

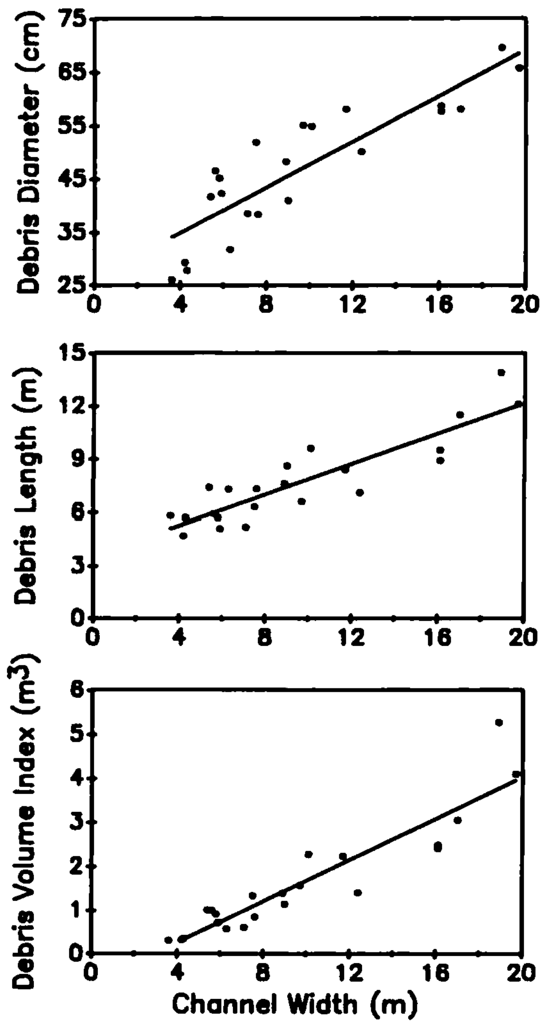

FIGURE 1.—Relationship between mean channel width and geometric mean for debris diameter, geometric mean for debris length, and debris volume index for pieces of debris in streams in western Washington. Mean diameter = 2.14(channel width) + 26.43; r^2 = 0.76; N = 22; mean length = 0.43(channel width) + 3.55; r^2 = 0.79; N = 22; debris volume index = 0.23(channel width) − 0.67; r^2 = 0.85; N = 22.

Results

Debris Characteristics

The mean diameter and length of pieces of debris and the debris volume index increased as channel width increased (Figure 1). The frequency of occurrence of pieces of debris declined as stream size increased (Figure 2) and ranged from nearly 0.8 piece/m in the smallest streams to less than 0.1 piece/m in the largest systems.

We assumed that a piece of wood entering a

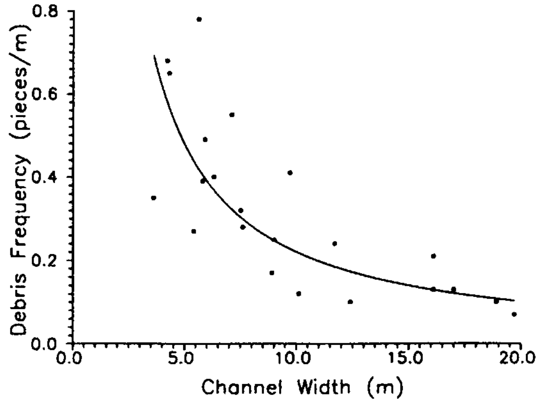

FIGURE 2.—The frequency of pieces of woody debris as a function of mean channel width in streams in western Washington. $\log_{10}$debris frequency = $-1.12 \log_{10}$channel width + 0.46; $r^2 = 0.69$; $N = 22$.

channel had an equal opportunity of orienting upstream, downstream, parallel, or perpendicular relative to the axis of flow. Pieces of debris oriented perpendicular to the flow significantly more frequently than expected in streams less than 7 m wide (chi-square test; $P < 0.05$; Figure 3) but not in the two larger size-classes. In channels from 7 to 10 m wide and those greater than 10 m wide, pieces oriented in a downstream direction were significantly more common than expected (chi-square test, $P < 0.05$; Figure 3). Debris oriented parallel to the flow was approximately equal in occurrence in all three classes of channel width

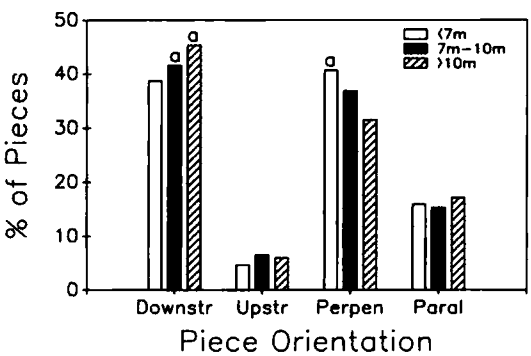

FIGURE 3.—Relationship of channel width (<7 m, 7–10 m, and >10 m) to the frequency of debris oriented downstream (Downstr), upstream (Upstr), perpendicular (Perpen), or parallel (Paral) to the channel in streams in western Washington. The letter a indicates values that are significantly different from expected (i.e., equal probability of each orientation for a piece of woody debris entering the channel; χ^2 test; $P < 0.05$; <7 m stream width, $N = 414$; 7–10 m, $N = 307$; >10 m, $N = 395$).

TABLE 2.—Species of trees producing woody debris in stream sections in western Washington.

	Percent of debris by species of tree[a]				
Stream width (m)	Western red-cedar	Douglas fir	Western hem-lock	Red alder	Miscel-laneous
<7	41.0	39.5	14.3	3.7	1.4
7–10	46.5	33.0	15.3	4.5	0.7
>10	33.9	51.2	7.5	4.8	2.6
All	40.0	41.8	12.2	4.2	1.8

[a] Western redcedar *Thuja plicata*, Douglas fir *Pseudotsuga menziesii*, western hemlock *Tsuga heterophylla*, and red alder *Alnus rubra*.

and was not significantly different in frequency from what would be expected. Debris angled upstream occurred significantly less frequently than would be expected (chi-square test, $P < 0.05$; Figure 3) in all sizes of streams. This indicated that upstream orientation was unstable.

The tree species contributing to woody debris showed no consistent pattern of change with stream size (Table 2). Material from coniferous trees dominated in all three stream size-classes, and Douglas fir and western redcedar contributed about 80% of the pieces. Hardwood debris constituted only about 5% of the pieces in these systems, regardless of stream size.

Debris-Associated Pools

The type of pool most likely to be associated with debris changed as stream size increased (Figure 4). In streams less than 7 m wide, plunge pools were the most common but decreased significantly in frequency as stream size increased (chi-square test, $P < 0.05$) and were relatively rare in streams greater than 10 m wide. Conversely, scour-pool frequency increased significantly as stream size increased (chi-square test, $P < 0.05$), although this type of pool was fairly common even in the smallest category of channel width. Dammed and backwater pools associated with woody debris tended to be rare, and the frequency of occurrence of these pool types was similar in all stream sizes.

Some types of pools were most often associated with a certain debris orientation (Figure 5). In channels less than 7 m and greater than 10 m wide, plunge pools were formed by woody debris perpendicular to the channel significantly more often than would be expected from the frequency of occurrence of such pieces (chi-square test, $P < 0.05$; Figure 3). Debris scour pools and backwater pools were not significantly related to any orientation of debris. Dammed pools were significantly associ-

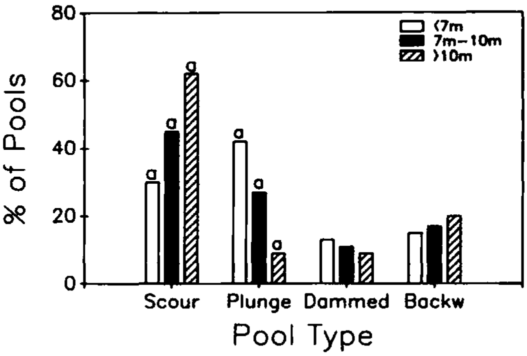

FIGURE 4.—Frequency of debris scour, plunge, dammed, and backwater (Backw) pools associated with woody debris at different stream widths (<7 m, 7–10 m, and >10 m) in western Washington. The letter a above the bar indicates values that are significantly different within a stream width category (χ^2 test; $P < 0.05$; <7 m stream width, $N = 127$; 7–10 m, $N = 96$; >10 m, $N = 102$).

ated with pieces of wood oriented perpendicular to the channel in streams 7–10 m in width (chi-square test, $P < 0.05$).

The volume of a piece of woody debris was significantly related to the surface area of a scour pool produced by that piece in all three categories of stream width (Table 3). However, the degree of influence that the size of a piece had on pool surface area changed with increasing stream size. In streams less than 7 m wide, both channel width and debris volume were about equally important in determining pool surface area; this relationship is indicated by the partial r^2 values for these two variables (analysis of variance [ANOVA], $P < 0.05$; Table 3). However, in larger systems, channel width was poorly related to pool area, whereas the relationship with debris volume improved (Table 3). Thus, within the range of stream sizes represented in this study, the size of a piece of woody debris became progressively more important for determining pool area with increasing stream size.

Changes in the relationship between pool size and debris size as channel width increased were more difficult to discern for other pool types due to their scarcity in at least one category of channel width (Figure 4). The surface area of plunge pools showed little relationship to debris volume in any of the categories of channel width. However, the infrequent occurrence of plunge pools prevented

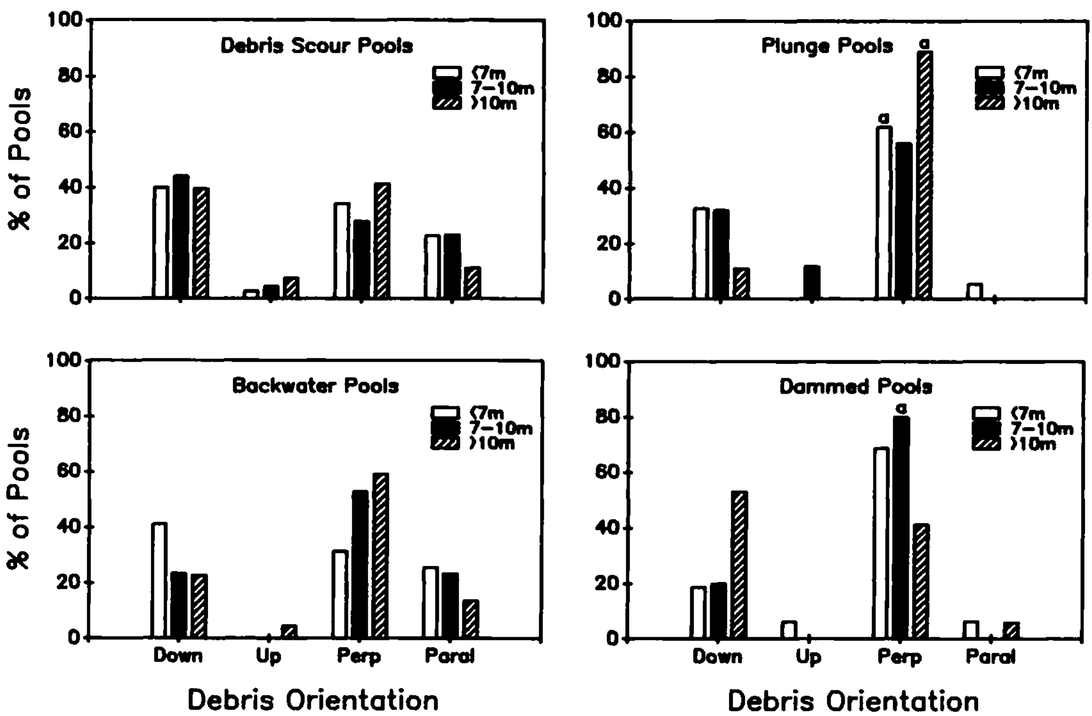

FIGURE 5.—Percentage of different pool types associated with debris oriented downstream (Down), upstream (Up), perpendicular (Perp), or parallel (Paral) to the channel at different stream widths (<7 m, 7–10 m, and >10 m). The letter a indicates values significantly different from expected (i.e., an association between pool type and debris orientation; χ^2 test; $P < 0.05$).

TABLE 3.—Relationship between pool surface area (PA, in m^2) or surface area of sediment accumulations (SA, in m^2) and debris volume (DV, in m^3) and channel width (CW, in m) for streams in western Washington. Regression equations incorporate all variables that have a significant relationship (indicated by asterisk *) with pool area or area of sediment accumulation (analysis of variance; $P < 0.05$).

Channel width (m)	Equation	Partial-regression statistic	
		Debris volume	Channel width
	Pool surface area		
<7	$\log_{10}PA = 0.38 \log_{10}DV - 2.61 \log_{10}CW + 2.24$ ($r^2 = 0.45$; $N = 41$)	$r^2 = 0.18$ $F = 10.15$*	$r^2 = 0.27$ $F = 14.72$*
7–10	$\log_{10}PA = 0.64 \log_{10}DV + 0.49$ ($r^2 = 0.39$; $N = 42$)	$r^2 = 0.39$ $F = 26.01$*	$r^2 = 0$ $F = 0.42$
>10	$\log_{10}PA = 0.64 \log_{10}DV + 1.31 \log_{10}CW - 0.77$ ($r^2 = 0.59$; $N = 33$)	$r^2 = 0.54$ $F = 45.98$*	$r^2 = 0.05$ $F = 4.85$*
	Sediment surface area		
<7	$\log_{10}SA = 0.37 \log_{10}DV + 0.50$ ($r^2 = 0.25$; $N = 149$)	$r^2 = 0.25$ $F = 50.02$*	$r^2 = 0$ $F = 0.45$
7–10	$\log_{10}SA = 0.43 \log_{10}DV + 0.62$ ($r^2 = 0.25$; $N = 81$)	$r^2 = 0.25$ $F = 25.88$*	$r^2 = 0$ $F = 1.70$
>10	$\log_{10}SA = 0.65 \log_{10}DV + 0.53$ ($r^2 = 0.45$; $N = 64$)	$r^2 = 0.45$ $F = 50.12$*	$r^2 = 0$ $F = 0.21$

assessment of the relationship between debris volume and pool area in the larger streams. Backwater and dammed pools were rare in all the streams, so analysis of this relationship was not possible for these pool types.

Debris-Associated Waterfalls

Debris-formed waterfalls decreased in frequency with increasing stream size (Table 4). The likely causes of this decrease were a drop in the channel gradient (Table 1) and a change in the orientation of pieces of debris from perpendicular to downstream (Figure 3). The proportion of drop in streambed elevation caused by debris-formed waterfalls decreased only slightly from the channels less than 7 m wide to those 7–10 m wide (Table 4). However, in streams greater than 10 m wide, debris-caused waterfalls accounted for less than 5% of the total streambed drop over the length of the study sections.

TABLE 4.—Change in the frequency of waterfalls associated with woody debris and in the proportion of channel drop caused by debris-formed waterfalls as a function of stream size in western Washington.

Channel width (m)	Percent of debris pieces forming waterfalls	Percent of total channel drop attributable to debris-formed waterfalls
<7	18.8	18.1
7–10	17.2	15.1
>10	3.1	4.5

Retention of Sediment and Organic Matter

Proportions of debris pieces detaining sediment decreased with increasing stream size from 39% in channels less than 7 m wide to 26% in channels 7–10 m wide to 19% in systems wider than 10 m (chi-square test, $P < 0.05$). Debris orientation had no significant influence on the proportion of pieces retaining sediment in any of the classes of channel width (chi-square test, $P < 0.05$).

In all three categories of channel width, the surface area of sediment accumulations was significantly related to the volume of the piece of wood forming the deposition but not to channel width (ANOVA, $P < 0.05$; Table 3). Debris volume accounted for about the same amount of variability in sediment accumulation in channels less than 7 m wide and in those 7–10 wide. The relationship between debris volume and surface area of sediment improved in channels over 10 m wide.

Some characteristics of accumulations of fine organic matter associated with woody debris changed with stream size (Table 5). No significant change was observed among the size-classes of streams in the proportion of woody debris retaining finer organic matter. However, accumulations of fine organic matter were more common in small streams due to the higher frequency of pieces of wood in these systems. The mean volume of accumulations of fine organic matter exhibited a significant increase (ANOVA, $P < 0.05$) with changing stream size. The increased size of the accumulations did not offset the decrease in their

TABLE 5.—Debris frequency, number of pieces of wood that retained particulate organic matter, average size of accumulations, and volume of particulate organic matter (POM) per unit area for three classes of channel width of streams in western Washington. Particulate organic matter is material less than 2 m long and less than 10 cm in diameter.

Channel width (m)	Debris frequency (pieces/m)	Debris retaining POM		Volume of POM per accumulation (m^3)	Ratio of POM volume to channel area (m^3/m^2)
		Pieces/m	%		
<7	0.50	0.35	69	0.63	0.043
7–10	0.33	0.17	53	1.23	0.025
>10	0.14	0.09	66	2.06	0.012

frequency, however, and the total volume of organic matter associated with woody debris decreased with increasing stream size.

Discussion

We found that the frequency of occurrence of debris decreased and the average size of pieces increased with increasing stream width. These changes were related to the increased capacity of larger streams to move material downstream. Because the composition of the streamside forest was similar at each of the sites, regardless of stream size, and included a wide range of tree sizes, the input of woody debris to the streams likely was similar. However, only the larger pieces of wood that entered the larger streams maintained a stable position in the channel. Progressively smaller pieces of debris and thus a higher proportion of the wood input remained in the channel as stream size decreased.

Pieces of woody debris oriented in an upstream direction were rarely encountered during this study. It is likely that pieces that enter the stream oriented in an upstream direction are moved to more stable positions during periods of elevated discharge or, in the case of pieces too large to be moved by the stream, cause alteration of the channel such that the pieces ultimately assume an orientation other than that originally displayed.

Two factors contributed to the decline in the number of plunge pools with increasing stream size. The streams less than 7 m wide had the steepest gradients and provided the greatest opportunity for the formation of waterfalls and plunge pools, and debris in smaller streams tended to exhibit an orientation perpendicular to the channel, a position related to plunge-pool formation in these systems.

We found that the size of a piece of wood plays less of a role in determining the dimensions of scour pools in small streams than in larger systems. Stream channel width had a major influence on pool area in our systems less than 7 m wide, but these variables were not closely related in larger streams. The formation of scour pools by woody debris results from erosion of the bed or bank due to deflection and concentration of the stream's flow. Because of the relatively small volume of water carried by smaller streams, a wide range of debris sizes may be able to influence flow about equally and result in similar amounts of erosion and pool areas. In larger systems, however, a large piece of debris may be able to influence a greater proportion of the flow and thereby increase erosion of the banks or bed and yield a larger pool. Thus, available flow is the primary determinant of pool surface area in small systems, whereas the capacity of a piece of debris to control flow becomes more important in larger systems. This hypothesis is supported by the relationship we observed between scour-pool area and channel width in streams less than 7 m wide. The change in the relationship between surface area of sediment accumulations and debris volume with increasing stream size also may have been caused by this interaction between available discharge and the capacity for the piece of debris to influence flow.

We found that woody debris played a greater role in routing sediment in small streams than in larger systems. Debris-associated depositional areas occurred more frequently in smaller streams because there were both more pieces of wood and a higher proportion of those pieces that formed sediment accumulations. In addition, because the number and cumulative height of debris-caused waterfalls decreased as stream size increased, these structures were more important agents of energy dissipation in smaller streams than in larger systems. The energy of the stream spent as free-falling water is inefficient in terms of transporting material downstream. Thus, the influence of woody debris on sediment routing changed with increasing stream size because of the decline in frequency of debris-associated depositional areas and a decrease in the importance of woody debris in the dissipation of hydraulic energy through the formation of waterfalls.

The volume of particulate organic material accumulated by woody debris in this study was not related to debris volume. Observations during the survey suggested that the structural complexity of a piece of wood or of an accumulation of debris was more important in determining the likelihood of occurrence and size of a resultant collection of finer organic material than the size of a piece of debris or its position in the channel. Pieces of wood with branches or aggregations of several to many pieces seemed to be associated more often with large volumes of accumulated leaf, needle, and twig material than single, large pieces of wood. It is likely that these structurally complex pieces were more efficient at filtering finer organic materials from the water column. However, we collected no information regarding the relative complexity of pieces of debris during the study.

Influence of Woody Debris on Stream Community Composition

Change in the frequency of different pool types associated with woody debris as stream size increases has the potential to influence the fish assemblage. These pool types exhibit consistent differences in depth and velocity (Sullivan 1986) and use by salmonids (Grette 1985; Bisson et al. 1988). In western Washington, plunge pools and dammed pools are heavily used by juvenile coho salmon *Oncorhynchus kisutch*, age-1 steelhead *O. mykiss* (formerly *Salmo gairdneri*), and all age-classes of cutthroat trout *O. clarki* (formerly *S. clarki*) (Bisson et al. 1982). Lateral scour pools, with their higher current velocities, are used by older trout but not by young-of-the-year salmonids. Backwater pools are favored by nearly all age-0 salmonids, especially coho salmon. Thus, the general pattern of dominance by plunge pools in small streams changing to lateral scour pools in larger systems may influence the species composition and age structure of the salmonid populations. However, factors other than physical habitat, such as competition and food availability, also dictate the composition of salmonid populations.

The information presented in this study also suggests that the change in debris function with stream size may influence stream community structure. Large woody debris is an important retention mechanism for terrestrial organic matter in small streams (Bilby and Likens 1980; Triska and Cromack 1980). Our study indicates that the distribution and size of accumulations of particulate organic matter associated with woody debris changes from frequent, small aggregations in smaller streams to less frequent, larger accumulations in larger systems. A similar pattern of increased debris clumping with increased stream size has been observed in Oregon (Triska and Cromack 1980). The presence of fewer but larger accumulations of organic matter in larger streams could influence the distribution of organisms that process this material. Organisms that feed on allochthonous organic matter typically are found at highest densities in the vicinity of accumulations of this material (Grafius 1976). Thus, a change from many, small accumulations to few, large accumulations could cause a corresponding change in the distribution of invertebrates adapted to this resource.

Woody Debris and Timber Harvest

Many streams in the Pacific Northwest drain watersheds that are managed primarily for timber production. Little regulatory consideration has been given to maintaining woody debris in these channels after timber harvest. Procedures to ensure adequate supplies of woody debris for these streams must address two separate concerns. First, cleaning prescriptions for postharvest stream debris should be designed to leave an appropriate amount of debris of the proper size in streams. Second, the vegetation remaining along the stream after timber harvest should be adequate to meet the long-term debris needs of that stream. Development of management practices that address both of these goals requires knowledge of natural debris input and transport processes in different sizes of streams.

The removal of woody debris from stream channels after timber harvest is a practice that has been used extensively in the Pacific Northwest, especially since the enactment of forest practice laws in the early 1970s. In general, regulations mandate the removal of material entering the channel during logging operations. In practice, however, it is often difficult to discern between old and new debris, and this results in the indiscriminate removal of wood from the channel (Bilby 1984). As a result, cleaning may have detrimental effects on a stream, such as substantial alteration of the morphology of the stream channel, the release of large amounts of stored sediment (Toews and Moore 1982; Bilby 1984), and the reduction of populations of salmonid fishes (House and Boehne 1985; Dolloff 1986; Elliot 1986). Although avoidance of cleaning the channel altogether would be the most desirable way of minimizing this problem, debris removal may be warranted if there is a high probability of obstructing fish or damaging downstream resources. In those rare instances when debris removal from a channel is deemed appropriate, the information presented here could be used as an indication of the size and amount of woody debris typically found in streams of a given size. However, these data can be applied only to streams within the same area and with characteristics similar to those of the study sites.

Data on variations in size and amount of woody debris with changing stream size could also be used to develop prescriptions for the numbers and sizes of trees to be retained along streams during timber harvest. This approach was used to formulate the riparian regulations for Washington state (Bilby and Wasserman, in press). However, little research has addressed the rates and amounts of wood input to streams from riparian areas after timber harvest. Effective management of streamside areas will, ultimately, depend on the development of information that relates the vegetative structure and physical characteristics of riparian areas to the input rate of woody debris to streams.

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