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physical consequences of large organic debris in pacific northwest streams

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Abstract

Large organic debris in streams controls the distribution of aquatic habitats, the routing of sediment through stream systems, and the stability of streambed and banks. Management activities directly alter debris loading by addition or removal of material and indirectly by increasing the probability of debris torrents and removing standing streamside trees. We propose that by this combination of factors the character of small and intermediate-sized streams in steep forested terrain of the Pacific Northwest is being substantially altered by forest practices.

KEYWORDS: Sedimentation, stream environment, fish habitat, water quality.

This paper was originally presented in the Oregon State University "Logging Debris in Streams Workshop" in March 1977. This paper presents a broader conceptual framework and extends the data base presented in Swanson, et al. 1976. History, physical effects, and management implications of large organic debris in western Oregon streams. 15 p., illus. USDA For. Serv. Gen. Tech. Rep. PNW-56. Pac. Northwest For. and Range Exp. Stn., Portland, Oreg.

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Metric Equivalents

1 meter (m)	=	1.09 yard
1 cubic meter (m^3)	=	1.31 cubic yard
1 hectare (ha)	=	2.47 acre
1 square kilometer (km^2)	=	0.39 square mile
1 event/square kilometer	=	2.59 events/square mile

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Introduction

Large organic debris is such an important part of Northwest forest streams that consideration of stream debris really involves consideration of the entire aquatic ecosystem. The biological and physical characteristics of stream ecosystems in the Pacific Northwest have evolved over thousands of years in response to persistent, heavy loading of organic debris and periodic flushing events, variously termed sluice outs or debris torrents. Forest management activities may significantly alter levels of debris loading and the probability of flushing events. These alterations may have long-term impacts on the entire aquatic ecosystem. Before considering possible impacts of intentional or inadvertent debris management, it is worthwhile reviewing the physical characteristics, history, and effects of natural debris in streams of various sizes.

Physical Characteristics of Debris in Streams

The character of natural debris in Northwest streams was first documented by Froehlich and coworkers (Froehlich 1971, 1973; Froehlich et al. 1972; Lammel 1972) who called attention to and quantified the high natural levels of debris in Coast and Cascade Range streams. They also evaluated the impact of various timber falling and yarding systems on debris loading. Swanson et al. (1976) discussed large organic debris with regard to its history and physical effects. Here we briefly review relevant, published observations and emphasize several additional points concerning management impacts.

Physical characteristics of debris in streams vary systematically through stream systems. Debris loading

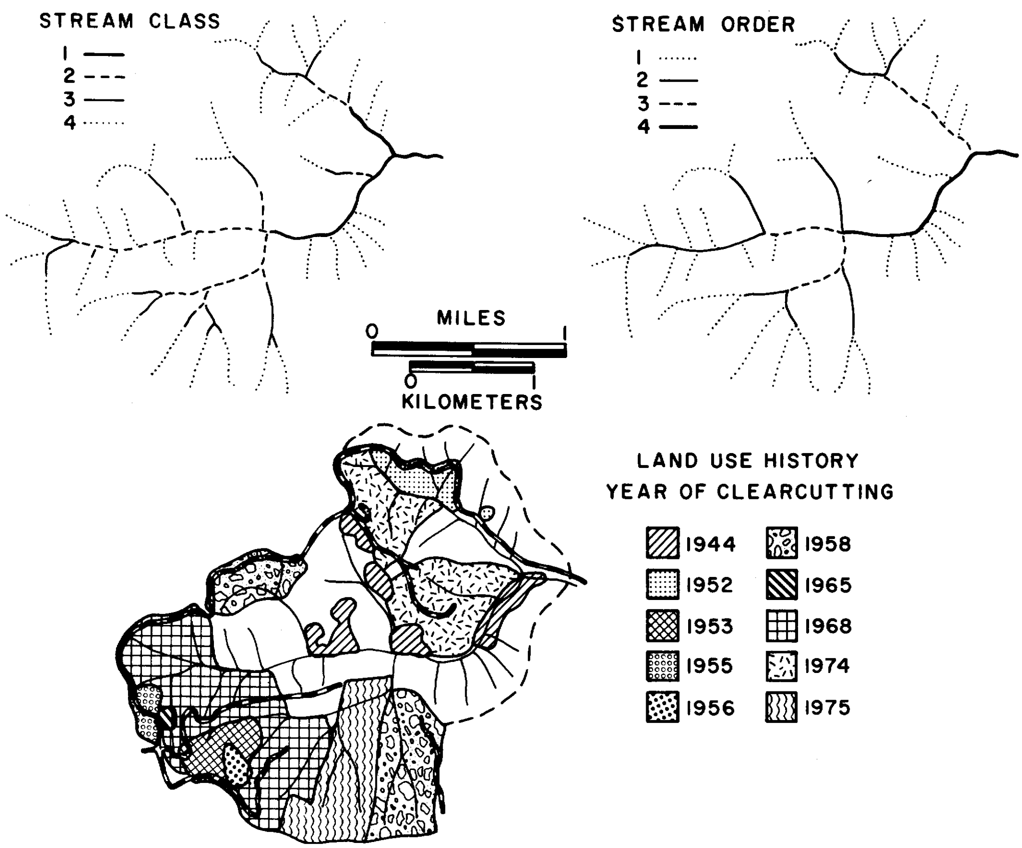

Figure 1.--Drainage network of Cedar Creek, Coast Ranges, in terms of U.S. Forest Service stream class, stream order, and history of timber harvest in the watershed.

is highest in small steep headwater streams and generally decreases downstream. In first- and second-order streams, large debris is randomly located where it inititally fell, because the streams are too small to redistribute it. (Stream order is defined in many geography texts and Harr (1976), and an example is shown in fig. 1). Third- through fifth-order streams are large enough to redistribute debris, forming distinct accumulations which may directly affect the entire channel width. In larger rivers, large debris is generally thrown up on islands or the banks and has little influence on the channel except at high flow conditions.

DEBRIS INPUTS TO STREAMS

Large organic debris enters streams by a variety of mechanisms, some of which are interrelated and act in chain reaction fashion. Principal mechanisms of debris input are blowdown of whole trees or tops and major limbs; debris slides, debris avalanches, and deep seated mass movements from adjacent hillslopes; undercutting of streambanks; and timber falling and yarding operations. Debris also enters stream sections from upstream channel reaches by flotation and debris torrent processes.

DEBRIS MOVEMENT IN STREAMS

Debris is moved through stream channels by flotation at high streamflows or in debris torrents involving rapid movement of a slurry of soil, alluvium, and large organic debris. Debris torrents typically originate in steep (> 50% slope) first- and second-order streams draining areas less than about 20 hectares (ha). Over 80% of 53 debris torrents studied in two areas in the Cascades were triggered by slides from adacent hillslopes (table 1). In these areas, mobilization of debris in channels was not a primary cause of debris torrents. In the steep, highly dissected terrain of the Oregon Coast Ranges, movement of shallow soil and organic debris in steep headwalls of incipient drainage ways commonly results in debris torrents. In these cases, it is difficult to determine (1) whether the initial mass movement should be considered a hillslope or channel event, and (2) if the presence of organic debris played a role in starting the debris torrent.

Table 1--*Land use status of triggering sites of debris torrents in the H. J. Andrews Experimental Forest (Swanston and Swanson 1976) and Alder Creek drainage (Morrison 1975, and pers. comm.)*

Site	Percent of watershed in 1975	Period of record (year)	Torrents triggered by hillslope slide	Torrent initiated in channel	Total number of torrents	Torrents per km² per year	Frequence of torrents relative to forest rate
H. J. Andrews Experimental Forest (6 420 ha)							
Forest	77.5	25	9	1	10	0.008	x 1
Clearcut	19.3	25	5	6	11	1/ .036	x 4.5
Road right-of-way	3.2	25	17	--	17	1/ .33	x 41
Total	100.0		31	7	38		
Alder Creek drainage (1 740 ha)							
Forest	70.5	90	5	1	6	.005	x 1
Clearcut	26.0	15	2	1	3	.004	x 8.8
Road right-of-way	3.5	15	6	--	6	1/ .66	x130
Total	100.0		13	2	15		

1/ Event frequency is significantly different (P <0.01) from forest rate.

Flotation of large organic debris may be a problem in intermediate-sized streams (third- to fifth-order, drainage areas of about 400 to 6 000 ha). These streams are wide enough to float large debris during extreme flood flows. Preexisting debris accumulations may be moved downstream for hundreds of meters, destroying riparian vegetation and rearranging the channel along the way. Several examples of such debris mobilization in the H. J. Andrews Experimental Forest occurred where massive earthflows had constricted the channel of Lookout Creek (Swanson and James 1975). High streamflow resulted in numerous streamside slides and input of abundant large organic debris to the stream. Much of this organic matter and sediment was then flushed downstream 300 to 800 m before setting up in a massive jam. Such earthflow-influenced areas are sites of persistent streamside and channel instability.

Based on reconnaissance studies in the central Cascade and Coast Ranges in Oregon, debris torrents are very common events, particularly following clearcutting and road construction. These events transport large quantities of organic debris and sediment from small streams into intermediate-sized streams. Massive debris export from the intermediate-sized streams occurs under extreme flood conditions as rafts and individual pieces of large debris are floated downstream, damaging riparian vegetation along the channel. At present, there appears to be a general pattern of greatly increased debris and sediment accumulation in many intermediate-sized streams. These considerations are discussed further in the section "Management impacts on stream debris."

Although debris torrents are spectacular events of real management significance, they actually move material relatively short distances (up to several kilometers). The ultimate export of large organic debris occurs in the form of fine particulate and dissolved matter resulting from breakdown of wood by the action of decomposer organisms, invertebrates, and snails. Organic matter in a log in a stream high in the mountains will eventually pass through many organisms' gut tracks in the course of transport down river to the sea.

CHANNEL MORPHOLOGY AND SEDIMENT ROUTING

Large debris in streams controls channel morphology and sediment and water routing. In streams to about third-order size, debris helps form a stepped gradient. The streambed is made up of long, low gradient sections separated by relatively short, steep falls or cascades. Therefore, much of the streambed may have a gradient less than the overall gradient of the valley bottom because much of the stream drop, or decrease in potential energy, takes place in the short, steep reaches. This pattern of energy dissipation in short stream reaches results in less available energy for erosion of bed and banks, more sediment storage in the channel, slower routing of organic detritus, and greater habitat diversity than in straight, even gradient channels.

One way to evaluate the role of debris in sediment routing is to compare the volume of sediment stored behind debris in a channel with annual sediment export from the channel. Megahan and Nowlin (1976) have observed, in several small forested watersheds in central Idaho, that annual sediment yield was only about 10 percent of sediment stored in the channel systems. Woody material made up 75 to 85 percent of the obstructions that trapped sediment. In the case of the 60-ha Watershed 2 in the H. J. Andrews Experimental Forest, average bedload export measured in a sediment basin has been 3.8 m^3 per yr for 1957-1976 (R. L. Fredriksen, pers. comm.). In a 100-m section above the basin, 20.1 m^3 of sediment is stored behind organic debris. The entire length of perennial and intermittent channel is about 1 700 m, so in this watershed annual sediment yield is probably much less than 10 percent of material in storage. Additional, unfilled storage capacity is available within the channel system.

The overall storage capacity serves to buffer the sedimentation impacts on downstream areas when there are pulses of sediment input to channels. Scattered debris in channels reduces the rate of downstream sediment movement and tends to feed sediment through the stream ecosystem in a slow trickle, except in cases of catastrophic flushing events. These flushing events may scour a channel every few centuries, leaving the channel devoid of large organic debris and open to rapid transfer of bedload.

Debris also influences bank stability and the lateral mobility of channels. Debris-related bank stability problems in V-notch, bedrock-controlled streams result from undercutting of the soil mantle on hillslopes by debris torrents. Undercut slopes are subject to progressive failure by surface erosion and small scale (< 100-m^3) mass erosion events over a period of years. Both bank instability and lateral mobility can occur in channels with abundant alluvium and minimal bedrock influence. Changes in channel conditions and position may be greatly influenced by organic debris in the stream. A debris accumulation may cause a stream to by-pass the jam and cut a new channel. Where channels continue to flow through massive depositional areas, streamflow may be subsurface throughout much of the year. In areas of active creep and earthflows, lateral stream cutting may undermine banks and encourage further hillslope failure and accelerated sediment supply to the channel.

DEBRIS AND AQUATIC HABITAT

In small and intermediate-sized mountain streams in the Northwest, large organic debris may be the principal factor determining the characteristics of aquatic habitats. In other geographic areas where streams are characterized by "classic" meandering channel patterns, hydraulic factors are more important in regulating the distribution of aquatic habitats. The role of debris in creating habitat for fish has been reviewed by Narver (1971), Hall and Baker (1975), and others. In addition, the wood itself is a habitat or substrate for a great deal of biological activity by microbial, invertebrate, and other aquatic organisms (Sedell and Triska, 1977).

The influence of wood on aquatic habitats has been measured in several streams in the H. J. Andrews Experimental Forest. In a 245-m section of Mack Creek flowing through an old-growth stand, 11 percent of the stream area is in wood, 16 percent in wood-created habitat (primarily depositional sites) and 73 percent in non-wood habitat, mainly boulder dominated cascades. The studied section occurs on a third-order channel where the stream drains about 600 ha. In Devilsclub Creek, a first-order tributary draining 10 ha, wood comprises 25 percent of the stream area and another 21 percent is habitat influenced by wood. Much of the biological activity by detritus-processing and other consumer organisms is concentrated in the areas of wood and wood-related habitat.

HISTORY OF DEBRIS IN STREAMS

The history of natural debris in streams has been studied in two ways: (1) by using dendrochronologic methods to date the residence time of individual pieces of debris in streams and (2) by examining the debris loading in streams flowing through stands in different stages of recovery following major wildfire. Debris in streams is dated by ring counts on trees growing on down logs and on scars on living trees damaged by debris falling into the stream.

Using these methods, we have commonly observed pieces of debris which have been in channels for 25 to more than 100 years. Western redcedar is particularly longlasting, followed by Douglas-fir, western hemlock, and red alder in order of increasing rate of breakdown.

Debris loading has been studied in streams flowing through 75-, 85-, 90-, and 135-year-old stands. By evaluating debris size, residence time in channel, and other factors, one can determine whether the debris was derived from the pre-fire or post-fire stand. Some of these relationships are evident in figure 2, which shows debris in a stream section in a 75-year-old stand. The large diameter pieces were derived from the pre-fire, old-growth stand, and the small pieces were input from the post-fire stand. Observations in streams such as this indicate that the change in dominance of debris of pre-fire and post-fire origin is gradual, occurring over more than a century when the pre-fire stand was old-growth (figure 3). Of course, the residence time of debris pieces from the pre-fire stand depends on

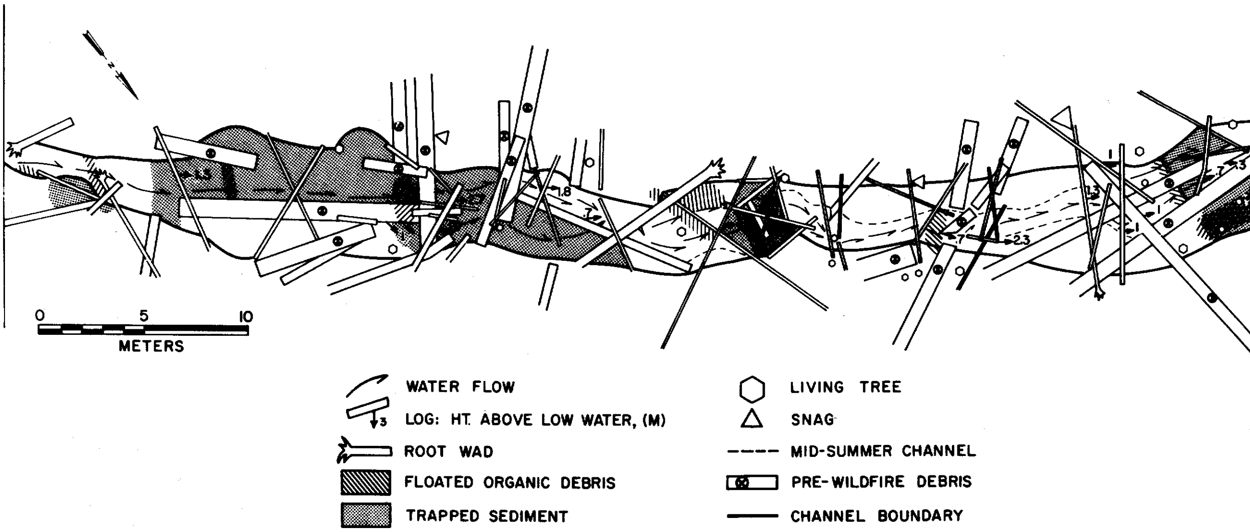

Figure 2.--Map of large organic debris in stream flowing through 75-year-old stand.

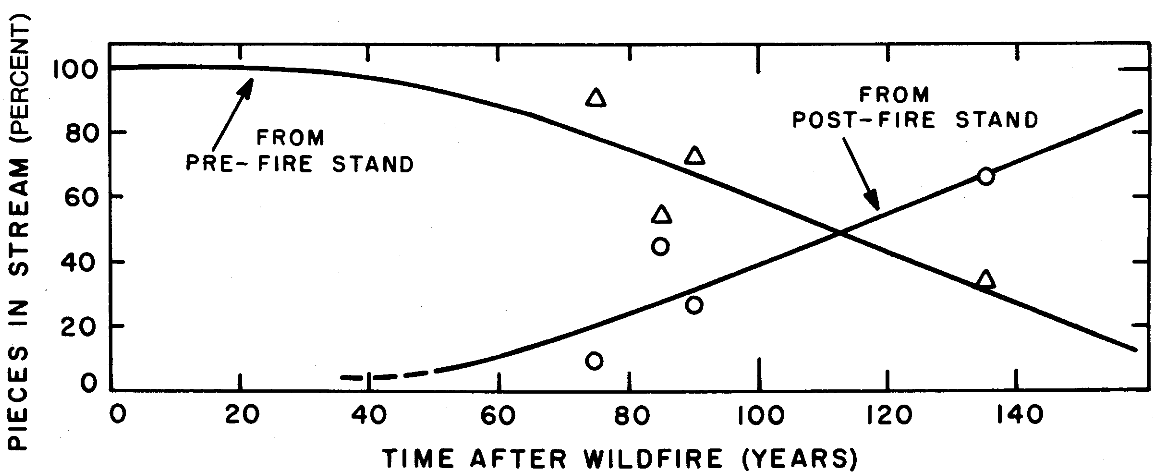

Figure 3.--History of stream debris loading in terms of change in percent of stream debris pieces derived from pre-fire (Δ) and post-fire (O) stands in relation to time after wildfire in three first-order streams in the Cascades.

size distribution and species composition. If the pre-fire stand was young and the stream contained only small diameter material, the debris carried over to post-fire conditions will decompose faster than old-growth sized material. Under these circumstances, total stream debris loading may decline appreciably during stand reestablishment.

Total concentrations of organic debris from the 75-, 85-, 90-, and 135-year-old stands are about 50 percent of values for small streams flowing through old-growth stands (Froehlich 1973). Reduced loading in these second-growth stands is a result of the period of nonproduction of large debris during early stages of stand development. The timing of large debris production varies greatly from stand to stand depending on stocking history and patterns of mortality. Carry over of debris from pre-fire stands is reduced by repeated fires within the period of several decades which may burn up old debris; and delayed establishment of the new stand while debris from the pre-fire stand continues to decompose.

In summary, we have observed that large organic debris in small and intermediate-sized streams may persist for long periods of time and through the period of stand reestablishment following wildfire.

MANAGEMENT IMPACTS ON STREAM DEBRIS

Management activities may have a great variety of impacts on stream debris. For any single action, it is difficult, if not impossible, to sort out near-term and long-term positive and negative impacts. This is in part true because any single action will be viewed differently by foresters, engineers, and stream biologists. The following general statements concerning management impacts may be made, however, based on the assumption that a management goal is to maintain concentrations and size distributions of debris typical of natural stream channels.

Increased debris loading in streams may result either from direct input during logging and road construction operations or by mass movement activity sometime after logging. Extremely high levels of debris loading result in abundant habitat for wood processing organisms but may reduce habitat opportunities for other aquatic life such as fish.

In steep headwater streams, management induced reductions in debris loading relative to typical, natural levels may occur in several ways (fig. 4). Cleanup operations themselves may be "over zealous," removing valuable components of habitat for fish and other organisms (Froehlich 1973, Brown 1974, Bustard and Narver 1975). Management activities also result in increased probability of channel flushing by debris torrents by two mechanisms: (1) by increasing the probability of debris avalanches which trigger debris torrents and (2) possibly, by altering the size distribution of debris in streams.

Impact of management activities on debris torrent occurrence is reflected in terms of high levels of debris torrent activity (torrents/km^2 per yr) in clearcut and road right-of-way areas relative to forested areas (table 1). The management impact has resulted primarily from increased occurrence of debris avalanches from hillslope areas (table 2) which may lead directly to debris torrents down stream channels. Based on the few relevant studies in the Northwest, cutting alone may increase debris avalanche frequency by several times and roads have an even greater impact (table 2). It should be noted, however, that inventories of both debris torrents and avalanches examined roads constructed mainly before 1970, so more modern roading methods have not been evaluated.

In some areas, particularly in the steep, highly dissected terrain of the Oregon Coast Ranges, changes in the size distribution of debris in headwater channels may also result in increased debris torrent activity. One possible mechanism of triggering torrents would involve the following sequence of events: large stable debris is removed, but smaller material which is floatable during extreme flows is left in the channel; unchecked by massive, stable pieces, the floatable material is moved downstream in high flow events; after 10 to 20 m of movement, the debris may have sufficient mass and momentum to move very large pieces of debris, thus initiating a debris torrent. Occurrence of torrents may be less likely where the potential buildup of moving fine and intermediate-sized debris is checked by very large logs every 5 to 10 m along a channel. The potential role of fine and intermediate-sized debris in triggering massive torrents may be analogous to use of the small charge in a blasting cap to ignite large explosive charges.

Management activities also reduce stream debris loading by thinning and harvest operations which remove standing

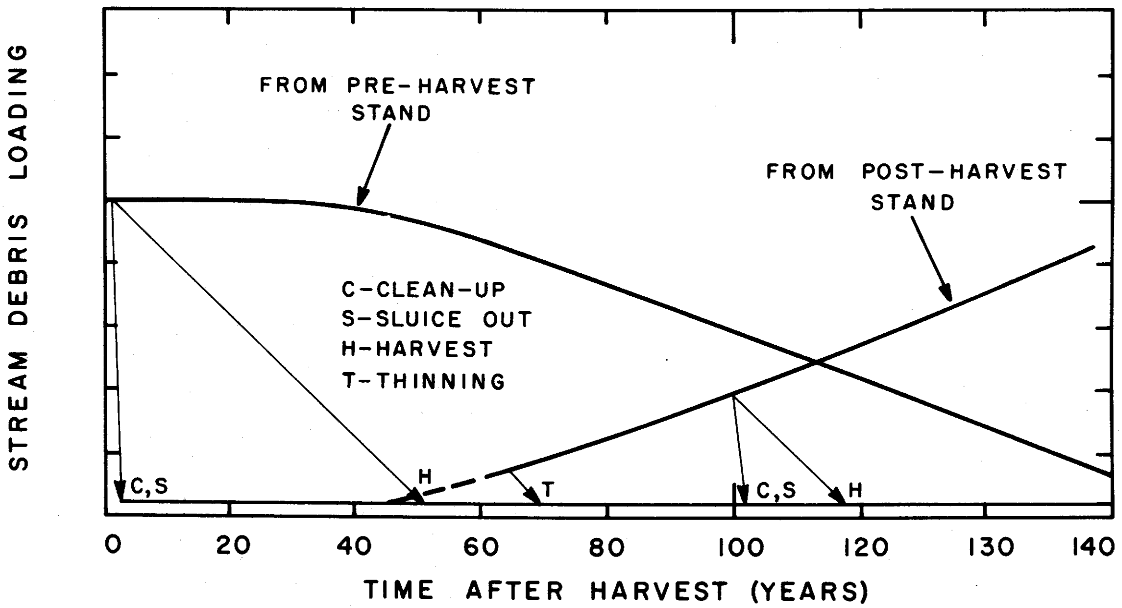

Figure 4.--Hypothetical potential changes in stream debris loading due to management activities in and around steep, headwater streams. Cleanup and sluice out mechanisms involve abrupt removal from the channel. Thinning and harvest remove standing trees that had been the potential source of stream debris.

Table 2--*Debris avalanche activity in forest, clearcut, and road right-of-way areas*

Site	Period of record (year)	Area		Number of avalanches	Avalanches per km^2 per year	Frequency of avalanches relative to forest rate
		Percent	km^2			
Stequaleho Creek, Olympic Peninsula (Fiksdal 1974)						
Forest	84	79	19.3	25	0.02	x 1
Clearcut	6	18	4.4	0	0	0
Road right-of-way	6	3	0.7	83	1/ 20.0	x1000
Alder Creek, western Cascade Range, Oregon (Morrison 1975)						
Forest	25	70.5	12.3	7	.02	x 1
Clearcut	15	26.0	4.5	18	1/ .27	x 14
Road right-of-way	15	3.5	0.6	75	1/ 8.3	x 415
Selected drainages, Coast Range, S.W. British Columbia (O'Loughlin 1972, and pers. comm.)						
Forest	32	88.9	246.1	29	.004	x 1
Clearcut	32	9.5	26.4	18	1/ .02	x 5
Road right-of-way	32	1.5	4.2	11	1/ .08	x 20
H. J. Andrews Experimental Forest, western Cascade Range, Oregon (Swanson and Dyrness 1975)						
Forest	25	77.5	49.8	31	.02	x 1
Clearcut	25	19.3	12.4	30	1/ .10	x 5
Road right-of-way	25	3.2	2.0	69	1/ 1.4	x 70

1/ Event frequency is significantly different ($P < 0.01$) from forest rate.

trees, the future source of large debris for streams. This combination of management impacts directly in a stream and on adjacent forest vegetation is likely to result in marked, long-term reductions in stream debris loading (fig. 4).

Case Study

The characteristics of potential management impacts on the movement of stream debris may be examined in a selected drainage basin. The 700-ha Cedar Creek drainage in the Coast Ranges presents a useful, though perhaps extreme, example. Figure 1 shows the history of timber harvest and the drainage network in terms of U.S. Forest Service stream classification and stream orders in this basin.

Figure 5 shows the history of debris torrents as determined from interviews with knowledgeable people in the area and from field and aerial photograph study. In this 27-year period, there have been 22 inventoried debris torrents: 8 initiated from roads, 8 in clearcuts, 5 in forest, and the point of origin of one was uncertain--either road or forest. Most of the road-and clearcut-related events occurred in the first few years after the management activity. Management impacts appear to be greatest where channels had experienced debris torrents under forest in the previous few decades.

The pattern of debris torrent movement has been from class 3 and 4 or first- and second-order channels to class 1 and 2 or third- and fourth-order channels. From 1950 to 1976, debris torrents in this basin have directly impacted 35 percent of first-order stream length, 61 percent of second order, 40 percent of third order, and 15 percent of fourth order. The small steep streams have been scoured to bedrock (fig. 6), and the transported debris accumulated in the larger, low gradient channels (fig. 7).

The pattern of debris torrent occurrence in the watershed has some

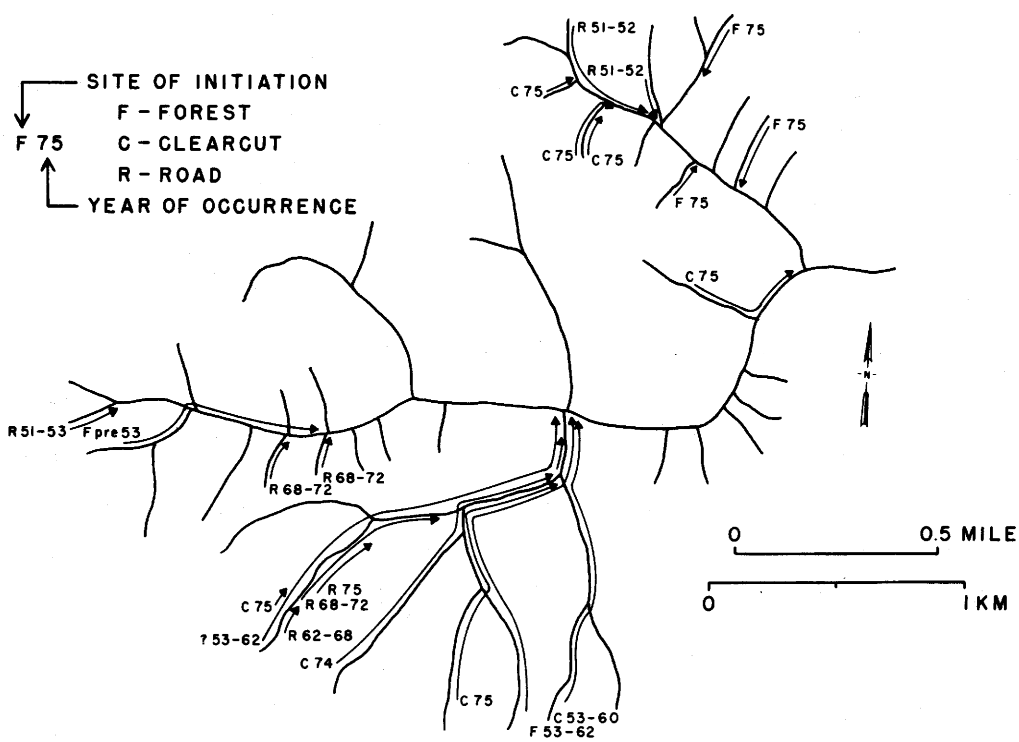

Figure 5.--Debris torrent tracks for 1950-1976 in Cedar Creek.

Figure 6.--Debris torrent scoured channel in South Fork of Cedar Creek.

Figure 7.--Debris jam at end of torrent track in South Fork Cedar Creek. Note figure in upper center of picture.

potentially useful management implications. Figure 8 shows the generalized long profile of the south fork of Cedar Creek and the elevations and channel gradients at the top and bottom of torrent tracks. Events which started above 350-m elevation head in long, straight channels with gradients that may exceed 80 percent. These events ran long distances downstream until setting up at channel gradients of 3 to 11 percent and (or) at abrupt changes in channel direction. The shorter tracks were initiated at lower elevations where debris avalanches entered the channel from short, steep (> 60 percent) tributary draws. These observations suggest that the greatest return on management efforts to minimize stream damage would come from protecting the heads of relatively long, straight, torrent-prone channels.

The general pattern in this watershed has been an increased probability of channel flushing in headwater streams and massive sediment and debris accumulation in intermediate-sized streams. Much of the headwater stream channel length has been cleaned down to bedrock, and timber harvest of surrounding vegetation has removed the source of future large debris for the channel. Repeated timber harvesting will indefinitely prevent the stands from producing large debris for the channel. Therefore, sluiced out or intentionally cleared headwater streams cannot return to levels of debris loading and concentrations of wood and wood-created habitat typical of natural streams.

The massive accumulations of sediment and organic debris at the ends of torrent tracks are probably of greater concern because of their direct impact on fisheries and other resources. Debris jam removal is costly and only minimizes the impact of an event when much of the impact has already occurred. Greater understanding and appreciation of processes of debris jam formation are needed so the occurrence of jams may be minimized.

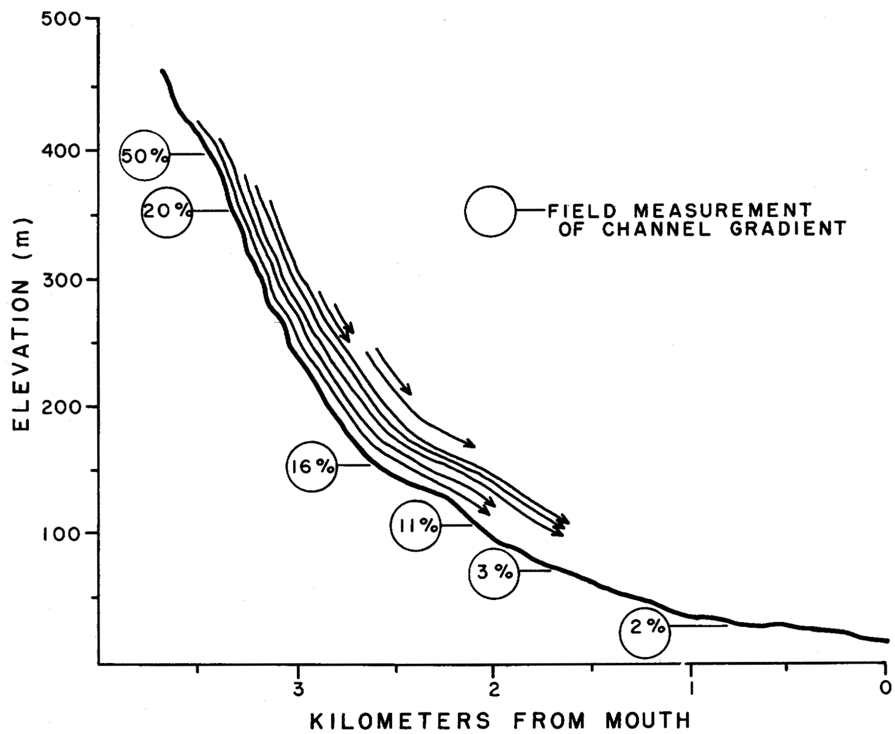

Figure 8.--Generalized long profile of the South Fork and distribution of debris torrent tracks (arrows) with respect to elevation at top and bottom of track.

Summary

Large organic debris is a principal factor determining the biological and physical character of small and intermediate-sized streams in forested landscapes of the Pacific Northwest. Debris enters streams by blowdown, undercutting of streambeds, and mass movement processes on adjacent hillslopes. Debris is moved through channels by flotation at high water, in torrents, and as dissolved and fine particulate matter following breakdown by wood processing organisms.

Water and sediment routing in channels is controlled by large debris which may create a stepped profile. Stream energy is thereby dissipated at the relatively short, steep sections of channel so that much of the stream area may have a gradient less than the overall gradient of the valley bottom.

Debris in streams creates habitat for aquatic organisms both by serving directly as a substrate and by modifying streamflow to form depositional areas. Activity of consumer organisms tends to be concentrated in areas of wood and wood-created habitat. In undisturbed first-order streams, over 50 percent of total stream area may be comprised of wood and wood-created habitat; and in third-order streams, it may exceed 25 percent.

Large pieces of debris reside in streams for decades and even longer than a century. This long residence time results in a continuing concentration of debris in streams during the 100+ years of stand recovery following wildfire, except when debris torrents flush channels.

Management activities directly alter debris loading by addition or removal of material and indirectly by increasing the probability of debris torrents and by removing standing streamside trees. The importance of debris avalanches in triggering debris torrents suggests that torrent prevention is best practiced by minimizing hillslope failures rather than managing stream debris. Of course, debris torrents occur in forested areas, and most steep channels have been repeatedly sluiced out in the past 10,000 years. Clearcutting and road construction, however, may increase the frequency of debris torrents. Inventories of debris torrents in two western Oregon watersheds revealed increases in debris torrent frequency of about 4 and 9 times for clearcuts and 40 and 130 times for road rights-of-way relative to the frequency in forested areas. Most of the roads in these areas were constructed before 1970, so the effects of more modern roading methods has not been evaluated. Repeated logging along headwater streams without buffer strips will prevent small streams from recovering large organic debris loads typical of undisturbed streams.

By this combination of factors, the character of small and intermediate-sized streams over large areas of the Northwest landscape is being substantially altered by forest practices. Neither the extent of these alterations nor the long-term biological consequences are understood. The situation should be examined from a perspective encompassing both general patterns over broad areas as well as the details of site-specific studies.

A program to maximize future options for good stream management would involve: (1) leaving the natural debris in channels and introducing a minimum of additional debris; (2) leaving a buffer strip to help minimize alteration of the stream area and to serve as a source of large debris for the stream in the future; (3) minimizing debris avalanche potential, hence debris torrent potential, by improved unit and road layout, development, and maintenance.

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The mission of the PACIFIC NORTHWEST FOREST AND RANGE EXPERIMENT STATION is to provide the knowledge, technology, and alternatives for present and future protection, management, and use of forest, range, and related environments.

Within this overall mission, the Station conducts and stimulates research to facilitate and to accelerate progress toward the following goals:

1. Providing safe and efficient technology for inventory, protection, and use of resources.
2. Developing and evaluating alternative methods and levels of resource management.
3. Achieving optimum sustained resource productivity consistent with maintaining a high quality forest environment.

The area of research encompasses Oregon, Washington, Alaska, and, in some cases, California, Hawaii, the Western States, and the Nation. Results of the research are made available promptly. Project headquarters are at:

Fairbanks, Alaska
Juneau, Alaska
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Corvallis, Oregon
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P.O. Box 3141
Portland, Oregon 97208

The FOREST SERVICE of the U.S. Department of Agriculture is dedicated to the principle of multiple use management of the Nation's forest resources for sustained yields of wood, water, forage, wildlife, and recreation. Through forestry research, cooperation with the States and private forest owners, and management of the National Forests and National Grasslands, it strives — as directed by Congress — to provide increasingly greater service to a growing Nation.