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Effects of Woody Debris on Anadromous Salmonid Habitat, Prince of Wales Island, Southeast Alaska

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Abstract.-The effects of woody debris on anadromous salmonid habitat in eight streams on Prince of Wales Island, southeast Alaska, were investigated by comparing low-gradient (1-9%) first- or second-order streams flowing through either spruce-hemlock forests or 6-10-year-old clear-cuts, and by observing changes after debris was selectively removed from clear-cut reaches. Woody debris decreased the rate of shallowing as discharge decreased, thus helping to preserve living space for fish during critical low-flow periods. Debris dams were more frequent in clear-cut streams (14.9/100 m), which contained more debris, than in forested streams (4.2/100 m). As a result, total residual pool length (length when pools are filled with water but there is no flow) and length of channel with residual depth greater than 14 cm-the depth range occupied by 84% of coho salmon *(Oncorhynchus kisutch*)-were greater in clear-cut streams than in forested streams. Greater volumes of woody debris in clear-cut streams produced greater storage of fine sediment (<4-mm diameter) unless the stream gradient was sufficiently high to flush sediment from storage. One-half of the debris dams broke up or were newly formed over a 3-year period, which suggests that they usually released sediment and woody debris before the pools they formed were filled with sediment. Woody debris removal decreased debris-covered area, debris dam frequency, and hydraulic friction in some cases but, in others, these variables were unaffected or recovered within 2 years after erosion and adjustment of the streambed. No consistent differences in pool dimensions were found between treated and untreated clear-cut reaches. Comparisons of habitat in forested and clear-cut streams suggested that removing debris from clear-cut streams reduced salmonid carrying capacity. Retention and natural reformation of debris dams in cleared reaches prevented the expected deterioration of habitat. However, the removal and destabilization of existing woody debris may cause depletion of debris before riparian trees can regrow and furnish new material to the clear-cut streams.

Large woody debris (stems, branches, and roots greater than 10 cm in diameter) is often the most important structural component affecting the behavior and morphology of small forested streams and the physical nature of their ecosystems (Heede 1972; Swanson and Lienkaemper 1978; Keller and Tally 1979; Bilby and Likens 1980; Mosley 1981). More specifically, woody debris in streams improves both the quality and quantity of fish habitat by providing cover and by varying stream velocity and depth. The density of juvenile coho salmon (*Oncorhynchus kisutch*), for example, increases with pool volume up to a point and then depends upon pool quality (Glova 1978). Prey fish can better coexist with predators in the presence of cover in a patchy environment, e.g., where habitable pools are separated by uninhabitable riffles (Fraser and Cerri 1982). Bisson and Sedell (1984) found greater numbers of coho salmon in small unlogged streams in the Cascade Range of Washington than in clear-cut streams where woody debris had been removed and cover and pool volume had subsequently declined. Debris also provides refuge from high-velocity flows during winter (Bustard and Narver 1975; P. A. Bisson and J. L. Nielsen, Weyerhauser Company, unpublished, 1983).

Forest operations in a riparian zone greatly influence the quantity and movement of woody debris in channels and thereby influence the stream's ecosystem and, specifically, the production of fish. Despite its importance, the effects of various volumes and sizes of debris on the stream's carrying capacity for anadromous salmonids in channels of various sizes and characteristics are insufficiently understood.

In this paper, I describe a study of the effects of large woody debris on the low-flow habitat of anadromous salmonids in first- and second-order streams in forested and clear-cut areas in Prince of Wales Island, southeastern Alaska. The paper focuses on water depth, frequencies of pools and debris dams, and substrate composition. The results should be generally useful for predicting the effect of large woody debris on the physical habitat of salmonids in small forested streams.

Woody debris can increase the volume of water held in a small stream channel at a particular discharge. As large roughness elements (individual objects that locally retard the flow), woody debris can reduce mean velocity, increase mean depth, and promote sediment storage. During critical periods of low flow, woody debris can be the major factor in preserving living space in pools ponded behind or scoured below debris dams (Keller and Tally 1979), or in pools scoured around debris projecting partway into the channel (Lisle 1981). For instance, 50-90% of the pools in tributaries of Prairie Creek in northwestern California are formed by large woody debris (Keller and Tally 1979). The greater volumes of water in coastal Oregon and Washington streams before white settlement than exist at present were associated with greater volumes of woody debris then (Sedell and Luchessa 1982).

In 1977, the U.S. Forest Service's Pacific Northwest Forest and Range Experiment Station began a project to study woody debris in streams in controlled experiments on Prince of Wales Island in southeastern Alaska (Bryant 1982; Swanson et al. 1984). Low-gradient first and second-order stream channels provided vital habitat for juvenile coho salmon, Dolly Varden *(Salvelinus malma)*, and steelhead *(Salmo gairdneri)*. After riparian areas were clear-cut during commercial harvesting in the 1960s and early 19 70s, a three-fold greater volume of woody debris was found in small stream channels in clear-cuts than in streams in uncut areas (Swanson et al. 1984). The research project, which includes the following studies as well as the one reported in this paper, was designed to compare debris loading, channel behavior, and fish production of streams in forested areas with those flowing through clear-cuts 6 to 10 years old (in 1978) and to determine the effects of debris removal from clear-cut streams. Swanson et al. (1984) described the channel characteristics and the distribution of woody debris. Bryant (1982) reported preliminary results on methods of measuring debris and the effects of its removal on channels and fish production. Dolloff (1983) reported fish densities and production by age-class and species and related these to differences in woody debris.

This study shows the importance of woody debris to the physical habitat of anadromous salmonids in small streams during low flow. By increasing resistance to flow and ponding water, woody debris significantly increased living space. Increased concentrations of debris from clear-cutting improved habitat for salmonids, and debris removal from clear-cut reaches was ineffective or deleterious over the short term.

Methods

Four forested streams and four clear-cut streams were selected to represent small, low-gradient, fish-bearing streams on Prince of Wales Island. The eight streams are tributaries of Staney or Shaheen creeks and have drainage areas ranging from 0.5 to 2.0 km^2 and active channel widths ranging from 2 to 6 m (Swanson et al. 1984). In each stream, we chose one to six reaches ranging from 55 to 110 m long. Stream gradients surveyed by rod and level range from 1 to 9%. Only streams with moderate gradients were selected because steep channels commonly have fewer anadromous salmonids. Adjacent uncut forests contained mixed-age stands of Sitka spruce *(Picea sitchensis)* and western hemlock (*Tsuga heterophylla)*.

Crews selectively cleared debris from six clear-cut reaches using prescriptions listed by Bryant (1982). They removed accumulations of small debris, but left large stable pieces. In two reaches of Knob Creek, they removed all woody debris from the bed surface-including stable debris, which they cut off at the channel margin. Five reaches of the clear-cut streams served as controls. Debris was removed in the summers of 1978 and 1979. We measured channel condition of clear-cut reaches during the summers of 1978, 1979, and 1981-before and after debris removal, with one or two intervening seasons of high flow. Large stable debris was left in selectively cleared channels as prescribed, but some large debris was also left in totally cleared reaches in Knob Creek. Some of this debris apparently was exhumed by channel scour. Consequently, there was no qualitative difference in the abundance of debris between selectively cleared and totally cleared reaches; therefore, I have lumped the data for the treated reaches for most descriptions of the results. Data were recorded for hydraulic variables, frequency of debris dams and riffle crests, frequency, length, and depth of pools, and surface abundance of woody debris and fine sediment.

Hydraulic variables.-A comparison of discharge-related variations ofwidth, depth, velocity, and friction can reveal some important hydraulic processes affecting physical conditions of the aquatic ecosystem. Mean depth, mean velocity, cross-sectional area, and water surface width were measured from sounded cross sections established every 5 m. Hydraulic variables were measured mostly at low water discharge when fish habitat presumably is most limited. One clear-cut reach

(Knob 1) and one forested reach (Three-Tenths Mile Creek) were measured at higher flows as well to better establish relations between hydraulic variables and discharge.

Because of high spatial variability in velocity and interchange of surface and subsurface discharge, it was considered most accurate to measure velocity and discharge by injecting a concentrated salt solution at the top of a study reach and measuring travel time and dilution of the tracer solution at the bottom of the reach with a conductivity meter (Church 1974). Some of the tracer solution apparently was lost through adherence to sediment particles, storage in backwaters, and exchanges with groundwater. Discharge measured in this manner, therefore, was consistently higher than that measured with a current meter. Day (1977) reported tracer losses as a linear function of distance. Because of these problems, I do not recommend tracer techniques for measuring flow in long reaches of small streams with low to moderate gradients. These effects, however, should not create significant inaccuracies in values of mean velocity, which were computed by dividing channel distance by the time to arrival of the center of mass of the salt solution. Dicharge was computed as the product of mean velocity and mean cross-sectional area.

Hydraulic friction is a ratio of the driving force of gravity, acting on the mean depth of water down the stream gradient, to the square of mean velocity:

$$ff = 8gRS/U^2;$$

ff = friction factor;
g = acceleration of gravity;
R = hydraulic radius (ratio of cross-sectional area to wetted perimeter length, approximately equal to mean depth);
S = channel gradient;
U = mean velocity.

The friction factor is a dimensionless measure of the resistance to flow caused by the roughness of the channel boundary. As long as the relative roughness or ratio of roughness element size (e.g., bed particle diameter) to flow depth does not vary too widely, the friction factor remains approximately constant with increasing discharge.

Values of all hydraulic variables reported here are mean values for the reach. Log-transformed values (base 10) of mean depth, mean velocity, width, and friction were linearly regressed with log-transformed values of discharge according to the "hydraulic geometry" model of Leopold and Maddock (1953).

Frequency of debris dams and riffle crests.-Debris dams (accumulations of woody debris spanning the channel) and riffle crests (or rock steps) impound water in upstream pools and thereby strongly influence the distribution of depth. The frequency of debris dams depends partly upon the frequency of sites preferentially trapping debris. In small streams, where debris is often longer than the channel is wide, debris tends to remain where it falls into the channel (Swanson and Lienkaemper 1978). More transportable, smaller debris often accumulates in existing debris dams, at riffle crests or boulder steps, against protruding rocks (Likens and Bilby 1982), and in channel constrictions. All potential sites for debris dams are difficult to identify. However, rock steps and riffles are easily recognized and create very favorable sites for forming debris dams. Debris dams and riffles were located along tapes strung down channels in the summers of 1978 and 1981. Frequencies are reported as number/ 100 m of channel length.

Pool dimensions and frequency. - Hydraulic conditions important to fish habitat such as depth, velocity, and the relative lengths of riffles and pools depend in part on channel morphology and in part on water discharge at the time of measurement. To compare hydraulic conditions between reaches, it is useful to remove the effects of discharge to cancel its unavoidable spatial and temporal variation. Measuring hydraulic variables over a range of discharges can solve this problem, but this method is time consuming and does not necessarily provide a measure of the frequency of depths preferred by fish. For the latter measure, residual water depth (Bathurst 1981)-the depth that would exist if there were no surface flow and pools were filled only to their lips-is a useful variable. Residual depth can be a standard variable for comparing the distribution ofwater depths between channels at very low flow when habitat is limited. Dolloff (1983) found 84% of coho salmon older than 1 year lived at depths of 14 cm or greater. I used a corresponding residual depth range as an indicator of available fish habitat.

We measured water depth along the thalweg (deepest portion) using tape and rod and recorded locations of end points of local reach types (pool, run, riffle, rock step, debris dam) along each reach. To compute pool dimensions and frequency, depth was plotted against channel distance (depth pro-

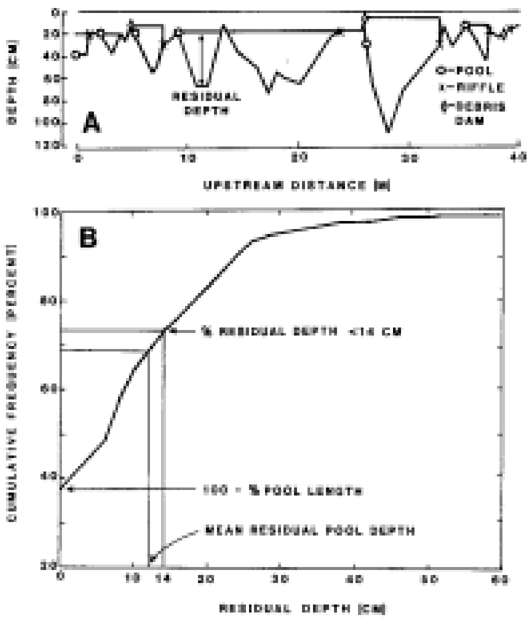

FIGURE 1.- (**A**) Depth profile of 40 m of Knob 1, an untreated reach in a clear-cut stream, Prince of Wales Island, Alaska, showing residual depth frequency for the entire reach-an example illustrating the method of measurement. Residual depths (in pools) are measured from levels set by the water depths over downstream riffles, debris dams, or the downstream lips of pools. (**B**) Residual depth frequency calculated for the entire reach. In this example, 73% of the channel has a residual depth of less than 14 cm, 63% of the channel length consists of pools, and mean residual pool depth equals 12 cm.

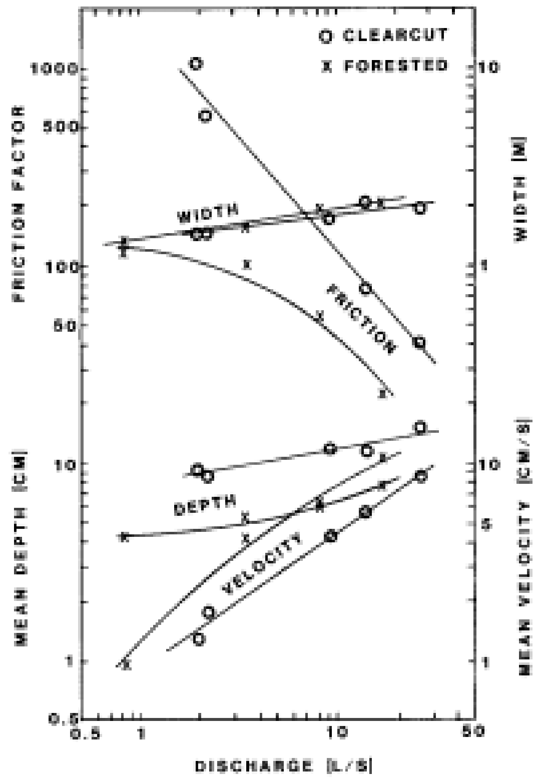

FIGURE 2.- Relationships of water velocity, stream depth and width, and friction factor to stream discharge for a forested reach (Three-Tenths Mile Creek) and an untreated clear-cut reach (Knob Creek, reach 1), Prince of Wales Island, Alaska.

files) and annotations of reach type were entered. The water depth at the lip of each pool was subtracted from depths in the pool to yield values of residual depth at half-meter intervals (Figure 1 A). Residual depths outside of pools are zero by definition. For each reach, the cumulative frequency of 30 residual depth classes was plotted to determine total pool length (PL, percent of channel length) and the percentage of the channel's length with a residual depth greater than 14 cm (PL 14) (Figure 1B). The annotated profiles also yielded values of pool frequency (PF, number/ 100 m) and percent of pools formed by debris dams, whether by ponding water upstream or creating downstream plunge pools.

Abundance of woody debris and fine sediment. - We measured the composition of the bed surface (woody debris, inorganic sediment less than 4 mm in diameter, and inorganic sediment larger than 4 mm) by a method adapted from the "pebble count" of Wolman (1954). We sampled bed composition at three randomly chosen spots every two steps taken up the channel, so that more than 100 points were sampled in each reach. We measured the first object touched (without looking) by a finger extended vertically onto the streambed. Abundance of woody debris and fine sediment covering the bed surface were computed as percentages.

Statistical tests. - Differences within and among the forested and clear-cut streams were tested for statistical significance. Differences tested at the probability level of 0.05 were termed significant. In some cases, I compared variables for the four forested streams with those of three clear-cut streams. When all values of a variable for the forested streams were, for instance, greater than all of those for the clear-cut streams, the minimum significance probability for the Mann-Whitney *U*-test was 0.10. Differences necessarily tested at a probability of 0.10 were termed marginally significant.

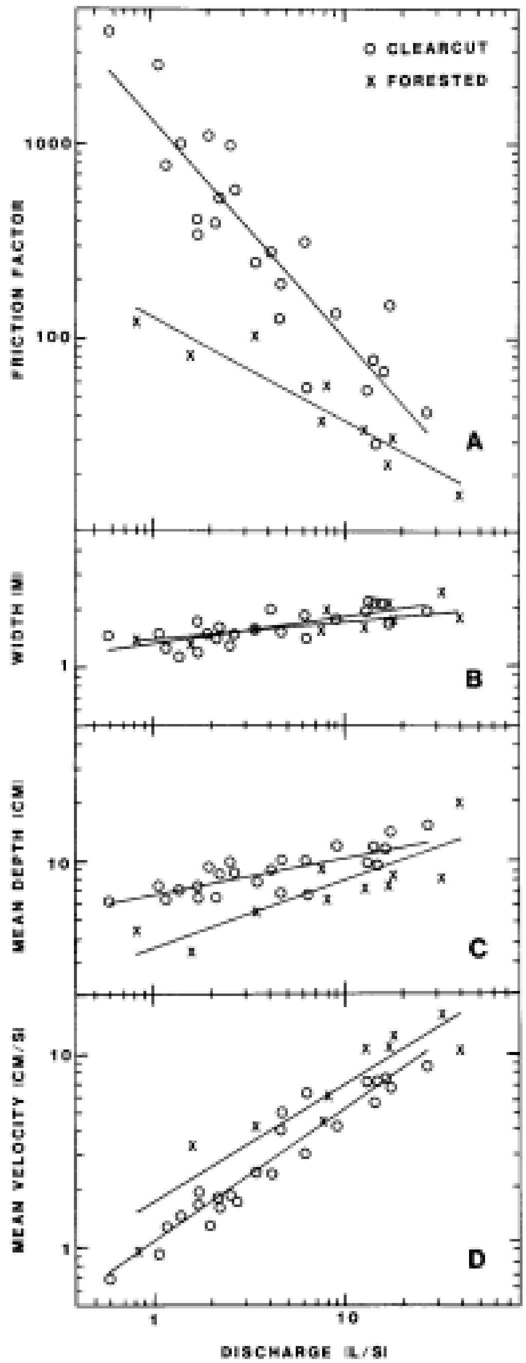

FIGURE 3.- Relationships of water velocity, stream depth and width, and friction factor to stream discharge for four forested reaches and 13 clear-cut reaches of eight streams on Prince of Wales Island, Alaska.

Results

Mean Hydraulic Variables

Variations of mean velocity, mean stream depth and width, and friction factor with discharge were measured at a forested reach (Three-Tenths Mile Creek) and a clear-cut reach (Knob I) (Figure 2). In the forested reach, friction decreased at an increasing rate as discharge increased; in the clear cut reach, friction decreased at a constant rate. Overall, friction was greater, and decreased at a greater rate, with increasing discharge in Knob 1. In both reaches, a decrease of friction with in creasing discharge was accompanied by a rapid increase in mean velocity, averaged over the entire reach, and a slow increase in mean depth. Relationships of width, depth, and velocity to dis charge for the clear-cut Knob 1 and the forested Three-Tenths Mile Creek reaches (Figure 2) were not significantly different from those obtained from all of the points representing the other reaches of each of the two channel types (Figure 3; *F*-test, $P > 0.05$, based on an analysis of covariance). This finding indicated that the variation of hy draulic variables with respect to discharge in a reach was similar to the variation observed downstream along the same stream or between reaches of different channel size but having an equal rate of runoff (discharge per drainage area). If this were not the case, the unavoidable variations in stream size and runoff rate when hydraulic variables were measured would introduce more scatter. The small ranges in sizes and runoff rates of these channels and correspondence of "at-a-reach" and "downstream" relations of hydraulic variables to discharge allowed a comparison of channel types based on relationships of hydraulic variables and discharge taken from all of the reaches and considered at once.

Forested and clear-cut channels were approximately equal in size with respect to width and discharge (Figure 3). There was no significant difference in the relation of width to discharge between forested and clear-cut reaches (*F*-test, $P > 0.05$, based on an analysis of covariance). Discharges measured within a few rain-free days at both types of stream fell within the same range.

Forested reaches differed significantly from clear cut reaches in coefficients or intercepts of regressions of log-transformed values of mean velocity, mean depth, and friction factor with discharge (*F*-test, $P < 0.05$, based on an analysis of covariance). Velocity was greater and depth and friction were less at a particular discharge in forested

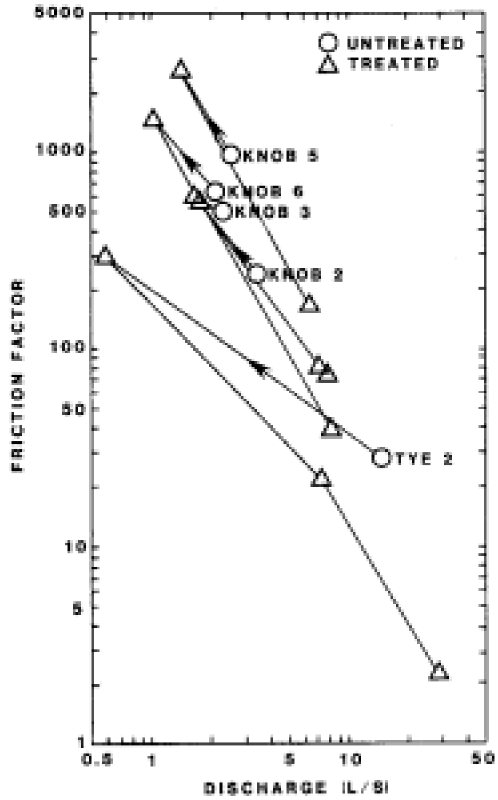

FIGURE 4.- Effects of debris removal on the friction factor in Knob and Tye creeks on Prince of Wales Island, Alaska, in relation to discharge 1978-1981. Arrows show the chronological order of data points for individual reaches; circles represent 1978, before treatment.

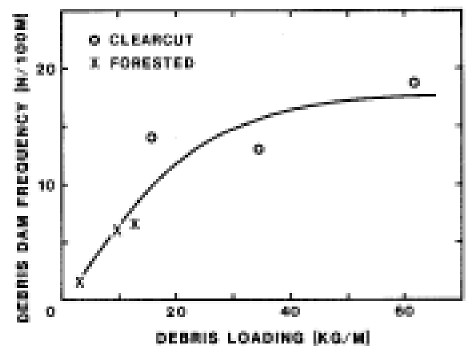

FIGURE 5.- Relationship of debris dam frequency (DDF) to debris loading (DL) in clear-cut and forested streams on Prince of Wales Island, Alaska. $\log_{10}$ DDF = $-0.601(\log_{10}DL)^2 + 2.23 \log_{10}DL - 0.8323$; $r^2 = 0.95$. Measurements from Flat and Aha creeks were excluded because of inadequate data sets.

reaches than in clear-cut reaches (Figure 3). The differences in friction factor and mean depth between the two stream types increased as discharge decreased. Among the forested streams, Holmgren Creek was most similar to clear-cut reaches in terms of its hydraulic geometry, length of pools, and abundance of woody debris.

Because debris removal should most directly affect friction, relations between friction factor and discharge were used to detect effects of debris removal on hydraulic conditions (Figure 4). For each treated reach, there were at least three data sets: one taken at an intermediate discharge before debris removal and ones taken at a larger and at a smaller discharge after removal. For a reach to show change, the initial data point must fall at some distance away from the line joined by the post-removal points. Only reach 2 on Tye Creek showed such a change. Debris removal caused friction to decrease so that the Tye 2 reach came to hydraulically resemble forested streams. For friction to decrease, it follows that depth decreased and velocity increased for a given discharge after debris removal.

Frequency of Debris Dams and Riffle Crests

Debris dam frequency (DDF) depended partly on the supply of debris in the channels. Mean DDF in forested streams (4.2 dams/100 m; Table 1), where debris was less abundant, was less than that of the four untreated clear-cut streams (14.9/100 m; Mann-Whitney *U*-test, $P = 0.10$). Also, DDF was positively correlated with values of debris loading (Figure 5) recorded by Swanson et al. (1984; Student's *t*-test, $P < 0.05$).

The relationship between DDF and debris loading suggests that as debris was added, a greater proportion of it was incorporated into existing debris dams or deposited between dams, instead of forming new dams. Debris dams in forested streams, where debris was relatively scarce, consisted of a few pieces of large debris. In clear-cut streams, debris dams consisting of matrices of small and large debris were commonly more than one channel-width long. From dimensional considerations, DDF (number/m) would vary with the square of debris loading (kg/m^2 or m^3/m^2) if dams were formed of debris accumulations of equal area and thickness. Instead of a linear relationship predicted by this condition, the data better fit a polynomial form that described decreasing rates of increase of DDF with increasing debris loading.

Although DDF was less in forested streams than in untreated clear-cut streams, no difference in the frequency of debris dams plus riffle crests or rock

TABLE 1.-Frequency (number/100 m of channel) of debris dams, exposed riffle crests, and debris dams plus riffle crests in four forested and four clear-cut streams on Prince of Wales Island, Alaska, in 1978 (before treatment), 1979, and 1981.

Stream, reach-treatment[a]	Debris dam frequency			Riffle frequency			Debris dam plus riffle frequency		
	1978	1979	1981	1978	1979	1981	1978	1979	1981
Forested streams									
Aha			3.0			12.0			15.0
Cabbage	1.0		2.0			17.0			19.0
Holmgren	6.0		6.0	4.0		3.0	10.0		9.0
Three-Tenths Mile	3.0		10.0	11.0		4.0	13.0		14.0
Mean (SD)		4.2 (2.4)			10.0 (5.8)			14.2 (3.9)	
Clear-cut streams									
Flat-s		10.9	16.4		18.3	10.9		29.3	27.3
Knob 1-c	21.5	18.5	13.8	3.1	7.7	4.6	24.6	26.2	18.4
2-s		9.5	6.3		7.4	9.5		16.9	15.8
3-t		9.1	9.1		4.5	7.3		13.6	16.4
4-c		10.0	13.0			3.0		10.0	16.0
5-s	11.2	20.0	12.5	2.5	6.2	12.5	13.7	26.2	25.0
6-t	12.0	8.0	7.0	8.0	10.0	16.0	20.0	18.0	23.0
Toad 1-2	16.0		24.0	1.0		6.0	17.0		30.0
2-s			17.5			8.8			26.3
3-c	23.8		26.2	5.0		2.5	28.8		28.7
4-c	16.7		12.2	6.7		10.0	23.4		22.2
Tye 1-c		12.9			2.9			15.8	
2-s		8.6			7.1			15.7	
Mean (SD)[b]		14.9 (3.2)			4.2 (1.2)			18.7 (3.7)	

[a] Treatments: c = control (uncleared); s = selectively cleared; t = totally cleared.
[b] Means are from control reaches.

steps was detected (Mann-Whitney *U*-test; $P = 0.10$). This suggests that favorable sites for debris dams may or may not have contained dams, depending on the abundance of debris.

Repeated formation of debris dams at riffle crests was suggested by the effects of debris removal. The DDF in cleared reaches was not consistently greater or less than that in adjacent control reaches (Table 1), and it was reduced by debris removal in only two of four cases. Apparently, some dams were retained in cleared reaches, new dams were exhumed after clearing, and debris mobilized from the streambed formed new dams. In clear-cut reaches, the direction of change of DDF was opposite to that of riffle frequency (RF) in 10 of 13 cases (Table 1). Consequently, total profile steps (DDF plus RF) varied less than DDF or RF. Small variation in DDF plus RF suggested that some dams formed and broke apart at riffle crests. Riffle frequency decreased as debris collected and formed more dams covering riffle crests.

Although sites for debris dams may be stable,

TABLE 2.- Persistence of debris dams between 1978 and 1981 in five streams on Prince of Wales Island, Alaska.

Stream, reach-treatment[a]	Number of debris dams/ 100 m of channel in 1981 that were: Remaining	Added to: Riffle	Added to: Other	Lost from: Riffle	Lost from: Other	Percent unstable
Forested streams						
Cabbage	1	1	0	0	0	50
Holmgren	5	1	1	1	0	38
Three-Tenths Mile	4	6	1	1	0	67
Clear-cut streams						
Knob 1-c	8	1	2	4	9	68
Toad 4-c	5	1	3	2	5	69
Knob 4-s	6	1	3	3	4	65
Knob 5-t	6	5	1	1	2	60

[a] Treatment: c = control (uncleared); s = selectively cleared; t = totally cleared.

TABLE 3.-Pool frequency, residual depth, and formation by debris dams in eight streams on Prince of Wales Island, Alaska.

Stream, reach-Treatments[a]	Percent of channel length: All pools	Percent of channel length: Pools deeper than 14 cm	Pool frequency (number/ 100 m of channel)	Mean residual pool depth (cm)	Pools formed by debris dams (%)
Forested streams					
Aha	27	6	12	9	33
Cabbage	34	17	13	14	23
Holmgren	76	36	12	14	67
Three-Tenths Mile	38	8	19	9	64
Mean (SD)	33 (5.6)[b]	10 (5.9)[b]	14 (3.4)	12 (2.7)	47 (22)
Clear-cut streams					
Flat-s	54	7	24	6	61
Knob I-c	63	27	18	12	67
2-s	58	29	16	14	62
3-t	49	14	22	11	65
4-c	65	27	18	12	89
5-s	54	17	18	10	79
6-t	37	10	14	8	58
Toad 1-s	55	30	21	17	90
2-s	56	23	24	11	40
3-c	48	17	22	9	100
4-c	53	27	14	14	85
Tye 1-c	50	11	13	9	89
2-s	17	2	11	5	0
Mean (SD)[c]	56 (7.7)	22 (7.4)	17 (3.6)	11 (2.2)	86 (12)

[a] Treatment: *c* = control (uncleared); *s* = selectively cleared; *t* = totally cleared.
[b] Holmgren Creek was excluded from these means.
[c] Means are of the control reaches for each stream.

many debris dams in these streams were short-lived. More than 50% of the debris dams in all but one of seven surveyed reaches were either newly formed or had disappeared over 4 years (1978-1981; Table 2). Dams in the treated reaches showed the greatest instability but, because of the small sample size, it is not known if the untreated clear-cut reaches differed statistically from the forested reaches.

Pool Dimensions and Frequency

Pools were longer but neither more numerous nor deeper in clear-cut streams with more debris dams than in forested streams with fewer dams (Table 3). If Holmgren Creek, which contained two particularly long debris-formed pools, is not included, total pool length (PL) was less in forested streams (mean value, 33%; Table 3) than in uncleared clear-cut streams (meanvalue, 54%; Mann-Whitney *U*-test, $P = 0.10$). Otherwise, there was no significant difference. Although mean total length of pools deeper than 14 cm (PL 14) in forested streams (10%) was about one-half PL 14 in untreated clear-cut streams (19%), the difference was not significant. Pool frequency (PF) averaged 14 pools (100 m of stream in forested streams and 17 pools/100 m in clear-cut streams. Mean pool depths (PD), averaging about 11 cm for both types of streams, were approximately equal for both types. With all streams included, debris dams formed a greater proportion of pools in clear-cut streams (mean value, 86%; Table 3) than in forested streams (mean value, 47%; Mann-Whitney U-test, $P = 0.10$). Dams formed at riffle crests apparently extended pools upstream over shallow water, thus creating longer but not necessarily deeper pools.

An expected result of removing debris was to decrease pool dimensions. However, there were no significant differences in any pool parameters between cleared and untreated clear-cut reaches (Mann-Whitney U-test, $P < 0.10$; Table 2), possibly because DDF was not noticeably affected. However, pool dimensions were not measured be-ore and after clearing.

Abundance of Woody Debris and Fine Sediment

These study reaches varied widely in debris abundance (Swanson et al. 1984). A single tree falling into streams of such small size could dominate woody debris loading measured over 100-m long reaches. Fine debris (< 10 cm in diameter)

TABLE 4.-Concentration of woody debris and fine sediment (< 4 mm) on bed surface before and after debris removal in eight streams on Prince of Wales Island, Alaska.

Stream, reach treatment[a]	Percent covered by woody debris		Percent covered by fine sediment	
	Before	After	Before	After
Forested streams				
Aha	4.8		4.5	
Cabbage	0.0		1.7	
Holmgren	30.0		7.1	
Three-Tenths Mile	0.8		2.5	
Mean (SD)	1.9 (2.6)[b]		4.0 (2.4)	
Clear-cut streams				
Flat-s	11.5	10.8	10.1	13.4
Knob 1-c		9.7	18.0	25.5
2-s	12.5	4.2	37.5	17.9
3-t	12.8	5.8	24.3	25.8
4-c	11.9	36.8	32.6	23.6
5-s	32.3	21.3	13.5	10.3
6-t	10.2	7.8	6.7	13.8
Toad 1-s	19.3	38.7	6.2	0
2-s		27.8		0
3-c	18.4	48.9	10.1	0
4-c	1.81	27.1	8.3	1.0
Tye1-c	11.3	16.3	10.6	22.0
2-s	18.8	25.0	3.5	15.2
Mean (SD)[d]	16.3 (7.2)		11.8 (6.9)	

[a] Treatment: c = control (uncleared); s = selectively cleared; t = totally cleared.
[b] Holmgren Creek was excluded from this mean.
[c] Bedload covered the woody debris.
[d] Averages are from uncleared (control) reaches.

tended to accumulate in frameworks of large debris (Bryant 1982). Some large accumulations in clear-cut streams extended over tens of meters of channel length (Swanson et al. 1984).

If Holmgren Creek, which contained many small waterlogged sticks in long pools, is omitted, the proportion of the bed surface covered by woody debris (BSD) was less (Mann-Whitney *U*-test; P = 0.10) in forested streams (mean, 1.9%) than in uncleared clear-cut streams (mean, 16.3%; Table 4). Also, the mean concentration of fine sediment (<4 mm in diameter) on the bed surface (BSFS) was less in forested streams (4.0%; Table 4) than in clear-cut streams (12%; Mann-Whitney *U*-test, P = 0.10).

Stream gradient apparently influenced BSFS by determining the rate of energy expenditure of the flow and thereby the stream's capacity to flush fine sediment from the bed surface. An inverse relationship between stream gradient and the capacity to store fine sediment is suggested by the declining maximum of the field of values of BSFS with in

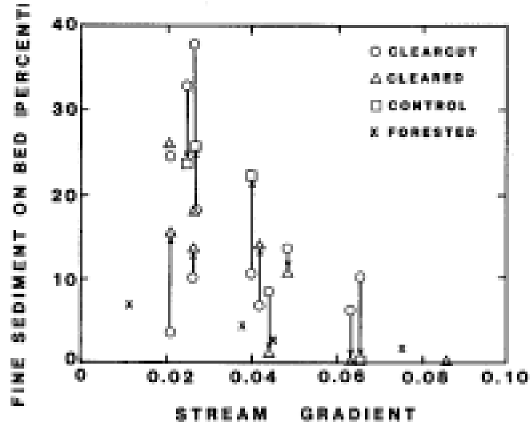

FIGURE 6.-Percentage of the bed surface covered by fine sediment (<4 mm diameter) in relation to stream gradient for eight streams on Prince of Wales Island, Alaska. Arrows show the chronological order of data points for individual reaches; circles represent clear-cut reaches in 1978, before treatment.

creasing stream gradient (Figure 6). At low gradients, BSFS was probably determined by BSD and recent inputs of fine sediment. The flow was able to flush most sediment inputs from storage at high gradients.

Debris removal produced a variety of changes in BSD and BSFS after one or two winters had passed. In Knob Creek, BSD decreased in cleared reaches but increased in control reaches, while changes in BSFS were not consistent with treatment (Table 4). Bed surface debris increased in Toad Creek, while BSFS decreased to a small percentage, at most, in both control and treated reaches after 2 years. In Tye Creek, BSD and BSFS increased in both control and treated reaches after 1 year.

Wide discrepancies in changes in BSD and BSFS after debris removal can be explained by the effects of destabilization and erosion of streambeds. In the clear-cut reaches of this study, debris on bed surfaces overlay buried sediment and debris. In Knob Creek, which has a low gradient, debris removal directly decreased BSD without systematically changing BSFS. This effect suggests that sediment uncovered by debris removal had not been flushed from the streambed during the intervening year. In Toad and Tye creeks, removal of debris led to complex sequences of transport and deposition of debris and sediment and to the eventual exposure of buried debris. Two years after debris removal, BSD increased and BSFS decreased in all reaches of Toad Creek. In that stream, more complete flushing of fine sediment and exposure of underlying debris probably were aided by a greater intervening time period and by a relatively steep gradient. After 2 years, both BSD and BSFS increased in the control and treated reaches of Tye Creek, presumably because of exhumed debris, litterfall, and fluvial deposition of debris and sediment.

Discussion and Conclusions

The important distinction between these study streams on Prince of Wales Island was not between a forested or clear-cut condition per se, but in the abundance of debris. In this study, forested streams contained less debris than clear-cut streams. However, forested streams in Oregon and Washington typically contain more debris than clear-cut streams because post-logging cleanup depletes natural accumulations of debris (Lammel 1972; McGreer 1974; Bisson and Sedell 1984).

Many effects of woody debris on the physical habitat of fishes in small streams are attributed to its function as large roughness elements. On Prince of Wales Island, clear-cut reaches, containing greater volumes of woody debris than forested reaches, had greater depth and friction and lower velocity for a particular discharge. In both types of reach, friction decreased as discharge increased but at a greater rate in clear-cut reaches. Similarly, Heede (1972) found that steep channels with frequent log steps in Rocky Mountains streams had relatively high friction and low velocities.

The small channels on Prince of Wales Island differ fundamentally from channels that do not have large roughness elements such as large rocks and woody debris. In smooth channels (e.g., straight channels with beds of sand and small pebbles), the diameter of roughness elements is much less than water depth. As depth decreases, relative roughness (the ratio of roughness diameter to depth) and friction increase. However, the increase in friction is relatively slight because relative roughness remains small; thus, the flow over the bed remains unperturbed by large-scale eddies and partial blockages that are generated by large roughness elements.

In the streams of this study, cobbles and woody debris protruded into a large proportion of the water depth, and some were emergent. Friction and flow depth are greatly increased by tortuous stream lines over and around rocks and debris, local spills and eddies where flow energy is expended, and ponding of water behind rock steps and debris dams. As discharge and depth decrease and more roughness elements affect the flow as described above, friction can increase greatly (Bathurst 1978). Moreover, when discharge decreases, the quiet deep water ponded behind debris dams undergoes little change in depth. In streams with large accumulations of debris, living space for fish is reduced at a decreasing rate-a much lower rate than if debris or other large roughness elements were absent.

Debris dams are effective in maintaining depth at low flow. Debris dams, particularly those formed of relatively small debris, tend to form in stream shallows and constrictions, thereby ponding water in upstream pools. If dams are high and steep-fronted enough, they also create downstream plunge pools. At low flow, areas of otherwise shallow water are thereby submerged to depths (> 14 cm) favored by pool-dwelling salmonids, such as yearling coho salmon. Comparisons of small streams with few debris dams (DDF = 4.2/ 100 m) with those having numerous dams (DDF = 16/ 100 m) suggest that debris can increase habitable pool length by more than 100% from conditions without debris. Debris does not have to form dams to effectively increase depth. By greatly increasing channel roughness as water discharge drops to extreme low flow in summer, it retards the rate of decrease in depth. Debris and large rocks at the downstream lips of pools are especially effective in increasing overall depth of the stream because they extend the upstream limits of pools.

Debris can create storage not only for water but also for sediment by creating low-energy depositional environments. With time and a source of sediment, debris-created pools can fill with sediment if the stream gradient is sufficiently low. However, sedimentation did not appear to be a problem in the streams of this study 10 years after debris was added during clear-cutting for the following reasons.

(1) Most of these drainages did not show signs of large sediment inputs. However, Aha Creek and Tye Creek contained large volumes of sediment (gravel and finer material). Despite having rather average values of BSD and DDF for their reach types (Tables 1, 4), these two reaches had relatively low values of pool length (Table 3). If large volumes of sediment were added to these streams, therefore, it apparently would limit pool habitat.

(2) Stream gradients in some forested and untreated clear-cut reaches were steep enough to cause BSFS to decrease in successive years without a concurrent change in DDF. Fine sediment apparently could be flushed from storage by high flow

without requiring a reduction in the number of storage sites. In small channels in Idaho with gradients exceeding 15%, sediment stored behind obstructions decreased after a year of high peak flows (Megahan 1982).

(3) Debris dams here were shorter-lived than in other streams, probably because the debris was relatively small. Debris dams have lasted as many as hundreds of years in coniferous forests in the Oregon Cascade Mountains (Swanson and Lienkaemper 1978) and in redwood forests (Keller and Tally 1979), where debris is large. On Prince of Wales Island, debris dams that did not persist beyond a few years did not collect large amounts of sediment. Instead, sediment and debris apparently were transported down channels by intermittent breakup of debris dams as Mosley (1981) also observed. Pool volume was continually renewed by the formation of new debris dams. Thus, living space was maintained during the long-term transport of debris and sediment downstream.

Debris removal had fewer and less persistent effects on debris accumulation, debris dam frequency, pool dimensions, and hydraulic conditions than expected. Clearing crews left most of the large stable debris in place, and debris was replenished after one or two high-flow seasons by material exhumed from the streambed or floated in from adjacent flooded areas. Also, debris dam frequency was largely unaffected by debris removal because a small amount could form a dam. Debris removal reduced depth of flow where changes were detectable, but depth increased the following year after the channels were scoured and new debris dams were formed (Bryant 1982; Dolloff 1983). However, debris removal may have reduced the stability of dams and increased the transport of debris downstream, as has been found elsewhere (Beschta 1979; Likens and Bilby 1982; MacDonald et al. 1982).

According to Dolloff (1983), removing debris from the study reaches reduced carrying capacity for fish by creating larger territories and reducing cover. Thus, uncleared sections contained more fish, average fish size was smaller (because small fish were able to maintain territories), and fish production was greater than in cleared sections.

Positive effects of debris removal could include reduced biological oxygen demand (BOD), improved passage for adult and juvenile fish, and increased living space in debris-choked sections of stream. We did not measure concentrations of oxygen or BOD, but greater populations of fish in untreated clear-cut reaches indicated that this was not a problem. Fish passage also was not a problem because juvenile fish were present in all reaches of the clear-cut channels. Instead of reducing living space by filling available storage, debris in these streams increased carrying capacity by ponding water behind dams, maintaining depth at low flow, and partitioning more territories.

Even unnaturally large accumulations of woody debris can benefit fish production. Debris loading in the clear-cut streams has not surpassed optimum volumes for fish production, despite some reaches that appeared to be choked with debris. Declining increases in debris dam frequency with increased high loadings of debris suggest an overabundance in the supply needed to form debris dams, but debris between dams provides cover and partitions small territories for fish. Therefore, reduction of debris loading in clear-cut streams (16-62 kg/m^2; Swanson et al. 1984) to natural levels (3-13 kg/m^2) probably would reduce present rates of fish production and further deplete debris loading in the future.

The long-term effects of clear-cutting followed by debris removal can be more deleterious than indicated by this short-term study. Clear-cut channels from which debris is removed would not have a source of debris other than material presently in storage in and around the channel until trees grow to a large enough size to furnish important volumes of large debris (Swanson et al. 1976; Likens and Bilby 1982). In the meantime, debris left from logging operations decomposes and is transported downstream. The short lifetimes of many debris dams in the Prince of Wales streams attest to the continued accumulation and breakup of small debris as it is carried downstream. Larger debris can be expected to persist in more stable dams but, with time, much of the storage capacity upstream of stable dams may fill with sediment, especially in low-gradient reaches. Even without stream clearing, in the 50 or more years before new trees replenish large debris in these stream systems, so much of the present debris may be naturally depleted or buried that fish carrying capacity could seriously decline. Likens and Bilby (1982) report a 50% reduction in debris dam frequency 10 years after a drainage basin was clear-cut but otherwise undisturbed.

Moderately steep or gentle small streams containing abundant debris can produce substantial populations of fish. Woody debris demands careful management because the large debris left after clear-cutting constitutes the available supply of wood-created channel structure for several decades. Such management should be planned over a time scale commensurate with the growth cycle of trees that supply large debris (Swanson et al. 1976). Woody debris in large accumulations in upstream reaches can supply enough debris to downstream reaches to satisfy optimum loading for fish habitat. Large local accumulations that bar fish migration, for instance, can be effectively modified on a case-by-case basis without incurring the economic and habitat costs of wholesale debris removal.

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