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Relationships between Channel Characteristics, Woody Debris, and Fish Habitat in Northwestern Washington Streams

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Abstract.—Relationships between large woody debris (LWD) and pool area or pool spacing varied with channel slope and channel width for streams in second-growth forests in northwest Washington. Pool spacing (expressed as the number of channel widths between pools) decreased as number of woody debris increased in both moderate-slope (0.02 < slope < 0.05) and low-slope (0.001 < slope ≤ 0.02) channels, but the relationship was stronger in moderate-slope channels. Percent pool was also more strongly correlated with woody debris volume in moderate-slope channels than in low-slope channels. Multiple-regression analyses showed that pool spacing and percent pool were correlated with an interaction term between LWD abundance and channel slope, suggesting that the influence of LWD on pool formation changes with channel slope. Analysis of pool-forming mechanisms indicated that low-slope channels are less sensitive to LWD abundance because pools are formed by mechanisms other than LWD when LWD abundance is low. Size of LWD that formed pools increased with increasing channel width, but was not related to channel slope. Percent gravel (proportion of the bed in patches of gravel 16–64 mm in diameter) was best explained by channel slope and channel width, and there was no significant relationship between woody debris and percent gravel. A regression between median particle size of sediment on the stream bed and basal shear stress showed that the relationships among percent gravel, channel width, and channel slope are adequately explained by the channel's capacity to transport particles of various sizes.

Large woody debris (LWD) in streams forms pools (e.g., review in Bisson et al. 1987; Montgomery et al. 1995) and retains sediment and particulate organic matter (e.g., Bilby 1981; Megahan 1982; Bilby and Ward 1989). Via these physical functions, large woody debris can influence the distribution and abundance of juvenile salmonids in streams. For example, pools that are associated with LWD are preferred habitats for various age-classes of juvenile coho salmon *Oncorhynchus kisutch,* cutthroat trout *O. clarki,* and steelhead *O. mykiss* (Bisson et al. 1988). Higher volumes of LWD have been correlated with higher densities of juvenile salmonids in winter (Murphy et al. 1984), and a greater diversity of pool and riffle types may be associated with a more diverse salmonid community (Lonzarich 1994).

Studies comparing logged and unlogged areas demonstrate that timber harvesting along streams tends to reduce the quantity of woody debris in streams reduces the area and depth of pools (Grette 1985; Bilby and Ward 1991; Ralph et al. 1994). Other studies indicate that woody debris recruitment and in-channel debris in streams with harvested riparian areas will not be sufficient to maintain suitable habitat characteristics for at least 50 years (Grette 1985; Andrus et al. 1988) and that in-channel debris would not reach old-growth levels for about 250 years (Murphy and Koski 1989). Where riparian forests have been removed or altered, these studies taken together describe a scenario of decreased numbers and area of pools, decreased retention of sediment and particulate organic matter, simplification of stream fish communities, and lower survival of juvenile salmonids.

Studies comparing old-growth and clear-cut streams provide a useful description of the effects of riparian logging on woody debris and salmonid habitat. However, most salmonid streams in the Pacific Northwest no longer flow through old-growth forests, and it has become increasingly important that we understand relationships between habitat conditions and riparian management in second-growth forests. As habitat management turns toward the restoration and management of processes that influence habitat conditions (e.g., maintaining or managing riparian buffers), it will be useful to develop empirical relationships between woody debris and pools or spawning gravel areas in channels of a variety of widths and slopes in order to predict the outcome of forest management and restoration activities.

Despite several studies that describe relationships between selected aspects of channel morphology (e.g., channel slope or width), woody debris, and pool sizes or spacing (Andrus et al. 1988; Bilby and Ward 1989; Carlson et al 1990; Montgomery et al. 1995), it is not possible to integrate these into site-specific predictions of stream habitat response in northwest Washington. For example, Bilby and Ward (1989) described a relationship between the size of pool-forming woody debris and the size of the resulting pool. Carlson et al. (1990) found no relationships between pool area and LWD abundance, but they found that "pool volume is greater at lower stream gradients and when there is more woody debris," based on multiple-regression results. By contrast, Andrus et al. (1988) found no correlations between pool area or volume and woody debris volume at their study sites. However, they showed that pools formed by LWD were more numerous in one low-gradient reach than in three others, and they suggested that greater discharge, finer substrate, and the freedom of the channel to meander allowed LWD to form pools more efficiently in that one reach. Because each of these studies addresses selected variables that affect pool size and spacing, we are unable to quantify how the interactions between channel slope, channel size, and the abundance of large woody debris affect pools across a variety of channel widths and slopes. Here we use "interactions" in the statistical sense, meaning that the relationship between one factor and the dependent variable is not wholly independent of the level of another factor (Zar 1984).

In this study we describe the interactive influences of channel slope, channel size, and the abundance of large woody debris on pool formation and sediment retention as indicated by the abundance of gravel-sized sediment (16–64 mm in diameter) in streams in second-growth forests of the North Cascades of Washington State. From these results, we discuss the probable effects of changes in woody debris abundance or size on pools and spawning gravel in small streams.

Study Area

Twenty-eight sample sites were located in four major watersheds of the North Cascades and Puget Sound areas of Washington State (Figure 1). Headwater drainage basins in the eastern part of the study area typically have narrow, steep valleys cut through granite intrusions, andesitic and dacitic volcanics, sandstones, and shales. At lower elevations, rivers flow through wide, glacially carved valleys. The valley bottoms and terraces along the major rivers in the western part of the study area are dominated by Pleistocene lacustrine clays, outwash sands and gravels, and tills associated with the continental glaciers that retreated from northern Washington approximately 14,000 years ago (Crandell 1965). Because this study focuses on relatively low-gradient stream reaches that provide habitat to anadromous salmonids, study reaches tend to be located in the lower elevation glacial deposits or alluvial deposits.

FIGURE 1.—Location of study area.

Two vegetation zones are represented in the study area. The western hemlock *Tsuga heterophylla* zone occurs in most of the lower elevations, and the silver fir *Abies amabilis* zone is found at higher elevations (Franklin and Dyrness 1973). Douglas fir *Pseudotsuga menziesii,* sitka spruce *Picea sitchensis,* and western redcedar *Thuja plicata* also occur throughout the lower elevations. Deciduous species include red alder *Alnus rubra,* bigleaf maple *Acer macrophyllum,* vine maple *Acer circinatum,* cottonwood *Populus trichocarpa,* and willow *Salix* spp.

Anadromous salmonid species in the study area include chinook salmon *Oncorhynchus tsawytscha,* coho salmon, pink salmon *O. gorbuscha,* chum salmon *O. keta,* steelhead, and sea-run cutthroat trout. Resident salmonid species are rainbow trout (nonanadromous *O. mykiss*) and cutthroat trout.

Methods

We focused our field surveys on relatively low-gradient (<0.04) stream reaches in order to assess streams that commonly provide habitat for anadromous salmonids. Sample reaches were in third- and fourth-order streams with channel widths of less than 20 m. We initially grouped sample reaches into four classes based on slope and valley constraint and located sample reaches on 1:24,000 scale U.S. Geological Survey topographic maps. Sample reaches for each group were distributed across the study area to assure that sites with similar slope, valley constraint, and channel width were not grouped into one part of the study area (Beechie and Sibley 1990). Similarly, surveys for each group were temporally interspersed in order to assure that changes in discharge during the survey season would have the smallest possible effect on results.

Channel slopes were surveyed with a hand level and stadia rod over a representative reach of each sample segment (at least 100 m). We located channel cross-sections in straight sections of the stream without woody debris. Hence, the number of cross-sections was limited to one–three riffles in each site. At each cross-section, bank-full width was measured to the nearest 0.1 m, and bank-full depths were measured to the nearest centimeter every 0.5 m along the transect.

Large woody debris pieces included in the survey were at least 10 cm in mean diameter and 2 m in length, and at least partially within the bank-full channel cross-section. Total length, mean diameter, and percentage of the length within the bank-full channel were visually estimated for all single woody debris pieces (less than five clustered pieces). Approximately 10% of the pieces were also measured to check the accuracy of visual estimates. Based on regression analyses of estimated versus measured volumes, the two observers tended to underestimate volumes of single pieces by 5% with high precision (r^2 = 0.98, N = 461). Because debris volume estimates were relatively accurate and consistent, we did not adjust debris volume estimates in this study. For pieces of woody debris in jams (five or more clustered pieces), the total number of pieces in each of three size-classes was tallied. Small pieces were 10–20 cm in diameter and greater than 2 m in length. Medium pieces were 20–50 cm in diameter and greater than 3 m in length. Large pieces were greater than 50 cm in diameter and greater than 5 m in length. We classified woody debris in the smallest size-class for which both diameter and length criteria were met (e.g., a piece 60 cm in diameter and 2.5 m in length was classified as small).

We summarized woody debris sizes by using geometric mean diameter and geometric mean length because distributions of woody debris length and diameter appeared to be log-normal. We summarized woody debris abundance by number of pieces per meter of channel and total woody debris volume per unit area of bank-full stream channel. Only the portions of woody debris within the bank-full channel cross-section were included in volume calculations. Woody debris volume was calculated as the sum of volumes of all single pieces and pieces in jams. The total volume of pieces in jams was estimated by calculating the geometric mean volume of all single pieces in each size-class and multiplying the total number of pieces in jams in each size-class by the geometric mean volume of single pieces in that size-class:

$$V_{\text{jams}} = (v_{\text{ss}} \cdot n_{\text{sj}}) + (v_{\text{ms}} \cdot n_{\text{mj}}) + (v_{\text{ls}} \cdot n_{\text{lj}}),$$

where V_{jams} is the total debris volume in jams, v_{ss} is the geometric mean volume of small single pieces in the reach, n_{sj} is the number of small pieces in jams, v_{ms} is the geometric mean volume of medium single pieces in the reach, n_{mj} is the number of medium pieces in jams, v_{ls} is the geometric mean volume of large single pieces in the reach, and n_{lj} is the number of large pieces in jams.

Each channel unit within sample reaches was classified after Bisson et al. (1982), and pool-forming factors were recorded. Woody debris was classified as pool-forming when it was stable and forced flow in a direction consistent with scour of the pool. Woody debris that was unstable (e.g., floated into a pool) or did not appear to affect flow direction was not considered a pool-forming factor. Other pool-forming mechanisms were boulders, outcrops of bedrock or glacial sediments, and lateral scour at streambanks.

Initially, visual estimation methods were used for estimating channel unit dimensions (approximately half the reaches). However, estimation of channel unit dimensions was more rapid than that of woody debris dimensions, so we elected to measure channel unit dimensions in the remaining reaches. For estimated channel unit dimensions, the length of each unit was estimated by pacing, and the mean width was estimated visually. In a companion study, the observer tended to underestimate individual unit areas by 4–7% with high precision (riffles, r^2 = 0.98; pools, r^2 = 0.93; glides, r^2 = 0.98), and there were no significant differences between the regressions for the three unit types. Hence, errors in the estimates should not affect analyses of the relative proportions of different unit types (Beechie and Sibley 1989). All channel unit surveys were conducted between mid-July and mid-September, when flows are generally low. Surveys were temporarily suspended when flows increased in response to several days of moderate rainfall.

Surface areas of patches of gravel 16–64 mm in diameter were estimated visually in each channel unit. Minimum patch size was 1.5 m^2, and we did not include gravel patches that would probably be outside the wetted perimeter during winter (i.e., gravel patches on bar tops that were unlikely to serve as spawning gravel for salmonids). We assumed that observer bias in identification of gravel patches and in visual estimates of the areas were consistent between reaches. Gravel areas were summarized as a percentage of the total bank-full channel area within a reach (100 × total gravel area/total channel area).

Percent pool for each reach was calculated in a similar fashion (100 × total area of pool units/total wetted area of the reach). We described the number of pools in a reach by the distance between pools normalized to channel width (pool spacing). Pool spacing was calculated by dividing the average distance between pools (reach length divided by number of pools) by the average bank-full channel width (Montgomery et al. 1995).

We used linear regression analyses to evaluate relationships between channel characteristics, woody debris, channel units, and spawning gravel. In most cases, simple linear regressions on untransformed data were used. Log_{10} transformations of the data were used when the pattern of data points indicated that the transformation was appropriate. Regression analyses of relationships between pool spacing and bank-full width or woody debris and between percent pool and bank-full width or woody debris volume were conducted separately for each of two slope classes: slope ≤ 0.02 and 0.02 < slope < 0.05. For analyses of spawning gravel area, three slope classes (slope ≤ 0.005, 0.005 < slope ≤ 0.02, and 0.02 < slope < 0.05) were used because spawning gravel characteristics appeared to change dramatically near the low end of the original smaller range (≤0.02). Slope-class delineations were derived from the characteristics of Rosgen's (1985) stream types. When the results of simple linear regression within slope classes suggested that interactions between variables were important, multiple linear regressions were used to evaluate the significance of interaction terms.

Results and Discussion

Characteristics of Woody Debris

Typical LWD volumes ranged from 0.001 to 0.042 m^3/m^2 in the study area (Table 1). Woody debris volume at one site (0.066 m^3/m^2 at Palmer Creek) deviated from the typical range of woody debris volumes in the study area. The lack of cut stumps in the riparian area suggested that the riparian stand at this one site may not have been harvested previously, even though extensive timber harvest had occurred within the basin.

Neither woody debris frequency (LWD/m) nor mean diameter of woody debris was correlated with channel width. However, both woody debris volume (LWD volume/m^2) and number of pieces of woody debris per unit area (LWD/m^2) were inversely related to channel width (Table 2), and mean LWD length was positively correlated with channel width. There was a stronger correlation between LWD volume/m^2 and channel width when Palmer Creek (the site with high LWD volume/m^2) was omitted (r^2 = 0.32, P = 0.002).

Although LWD length increases as channel width increases, LWD volume/m^2 decreases with increasing channel width because larger piece size is offset by a decrease in number of LWD/m^2. Bilby and Ward (1989) and Montgomery et al. (1995) also found decreasing LWD abundance with increasing channel width in their studies, and both attributed the decrease in LWD abundance to the increased mobility of smaller LWD in larger channels. However, when LWD abundance is expressed as number of LWD/m^2 (e.g., Montgomery et al. 1995), this explanation is partially confounded by the interaction between channel size and number of LWD recruited to a reach. That is, in channels with similar supply of LWD but differing width, one expects a negative correlation between number of LWD/m^2 and channel width simply because channel area increases with increasing channel width.

We found no relationship between number of LWD/m and channel width in our study but found a strong relationship between number of LWD/m^2 and channel width. We therefore conclude that channel width is a dominant influence on number of LWD/m^2 because it is directly related to channel area. Hence, interactions between channel width and LWD abundance should be considered when interpreting relationships between channel characteristics, woody debris abundance, and habitat characteristics such as pool or gravel areas.

Pool-Forming Mechanisms

The percentage of pools in a reach that were formed by LWD ranged from 8% to 84% and averaged 48% over all reaches. Furthermore, the proportion of pools formed by woody debris increased with increasing number of LWD/m (P = 0.02),

TABLE 1.—Selected characteristics of study sites in northwest Washington State.

Stream[a]	River basin[b]	Reach length (m)	Channel gradient (%)	Drainage area (km^2)	Bankfull width (m)	Woody debris (LWD) Number (LWD/m)	Volume (m^3/m^2)	Mean length (m)	Mean diameter (m)	Percent pool	Pool spacing (CW/pool)[c]	Percent gravel
Tokul	Snoqualmie	254	0.2	59.0	12.0	0.18	0.010	4.7	0.29	50	3.5	15.2
Issaquah	Sammamish	545	0.2	118.3	15.6	0.05	0.001	3.8	0.24	62	2.9	16.9
Bear	Sammamish	648	0.3	53.3	9.0	0.16	0.006	2.7	0.29	52	4.2	5.4
W. F. Woods	Skykomish	398	0.4	31.7	7.9	0.23	0.014	3.5	0.28	68	3.2	6.3
E. F. Woods	Skykomish	647	0.4	33.0	9.6	0.32	0.024	3.6	0.30	43	3.8	9.0
Stossel	Snoqualmie	310	0.5	7.4	4.3	0.19	0.026	3.6	0.28	85	2.7	4.7
Elwell	Skykomish	666	0.6	52.3	18.9	0.08	0.002	3.0	0.32	30	5.0	0.7
Ashton	N.F. Stillaguamish	788	0.7	14.4	9.0	0.21	0.013	3.2	0.33	64	3.1	10.5
Boardman	S.F. Stillaguamish	588	1.1	26.0	18.0	0.24	0.007	5.8	0.31	60	3.6	0.9
Dubuque	Pilchuck	277	1.1	18.1	5.7	0.56	0.042	3.0	0.30	79	2.3	31.5
Triple	S.F. Stillaguamish	382	1.2	2.6	6.2	0.40	0.016	3.7	0.22	70	2.4	12.5
Palmer	S.F. Stillaguamish	466	1.3	5.7	9.2	0.66	0.066	4.4	0.35	72	2.0	12.1
Unnamed	Skykomish	240	1.4	8.8	4.4	0.36	0.016	2.9	0.22	61	2.7	30.3
Youngs	Skykomish	358	1.5	34.8	17.6	0.32	0.007	4.3	0.28	20	4.1	1.4
Segelson	N.F. Stillaguamish	390	1.6	10.0	11.3	0.29	0.012	3.1	0.37	44	2.9	4.0
Griffin	Snoqualmie	451	1.7	47.6	10.4	0.14	0.002	3.3	0.23	25	5.5	2.7
Wilson	Skykomish	386	1.8	13.1	22.1	0.56	0.015	4.1	0.33	30	2.2	0.8
French	N.F. Stillaguamish	618	2.1	19.2	11.4	0.28	0.018	4.8	0.29	17	5.4	0.8
Worthy	Pilchuck	801	2.4	17.8	10.2	0.30	0.017	4.0	0.25	25	4.9	1.6
Deer	N.F. Stillaguamish	620	2.6	20.2	15.2	0.41	0.019	3.9	0.38	18	5.1	0.3
Benson	S.F. Stillaguamish	328	2.8	4.3	6.5	0.52	0.022	2.8	0.30	13	7.2	0.1
Roesiger	Skykomish	338	2.8	9.2	5.9	0.67	0.032	3.6	0.26	49	1.9	3.1
Brooks	N.F. Stillaguamish	209	2.9	11.6	11.9	0.27	0.021	5.5	0.35	30	3.5	0.7
Cherry	Snoqualmie	280	3.0	6.5	5.3	0.34	0.032	4.0	0.29	29	5.9	3.6
Schweitzer	S.F. Stillaguamish	668	3.0	4.3	8.2	0.47	0.038	4.2	0.25	59	1.7	1.3
Blackjack	S.F. Stillaguamish	557	3.5	9.1	10.2	0.29	0.022	3.6	0.36	20	4.2	1.4
Montegue	N.F. Stillaguamish	346	4.2	10.9	11.7	0.74	0.025	3.3	0.25	29	2.7	0.8
Maiden	S.F. Stillaguamish	315	4.8	3.2	8.9	0.85	0.024	3.3	0.26	27	2.2	1.0

[a] W.F. = West Fork; E.F. = East Fork.
[b] N.F. = North Fork; S.F. = South Fork.
[c] CW = channel width.

and the number of pools formed by LWD (which includes only those pools where LWD forced flow convergence and scour of the pool) increased as LWD abundance increased in both slope classes. Thus, LWD is a dominant pool-forming mechanism in these channels, and there is an apparent cause and effect relationship between LWD abundance and pool abundance.

The geometric mean diameter of single LWD pieces that formed pools was equal to or larger than the overall geometric mean diameter in all reaches, and geometric mean length of single LWD pieces that formed pools was larger than the overall geometric mean length in all but two reaches. The smallest single piece that formed a pool increased from 0.12 m in diameter in the smallest channels to 0.75 m in the largest channels (Figure 2; Table 2). Because the smallest piece that formed a pool is correlated with channel width but mean diameter of pieces in the reach was independent of channel width, it follows that a smaller proportion of available LWD will form pools in larger channels.

Free-formed pools (those not formed by woody debris or boulders) accounted for an average of 23% of the stream area in low-slope channels ($0.001 < \text{slope} \leq 0.02$) and an average of 9% of stream area in moderate-slope channels ($0.02 < \text{slope} < 0.05$). A t-test indicated that the means were significantly different ($P = 0.02$, $\alpha = 0.05$). A second t-test showed that the number of free-formed pools per channel width was higher in low-slope channels than in moderate-slope channels (0.15 versus 0.08 pools per channel width; $P = 0.01$). Both results indicate that free-formed pools are more readily formed in low-slope channels than in moderate-slope channels.

Pool Spacing

Pool spacing (channel widths per pool) was not correlated with channel slope or channel width. However, pool spacing was correlated with number

TABLE 2.—Summary of selected regression analyses. All variables are mean values for the study reaches, except for debris diameter and length which are geometric mean values. The sample size (N) is the number of study reaches included in the regression analysis; W_{bf} is average bank-full channel width; LWD volume/m^2 is total woody debris volume per unit channel area; LWD/m^2 is number of pieces of woody debris per unit area of channel; LWD/m is number of pieces of large woody debris per unit length of channel; pool spacing is the average distance between main channel pools divided by average bank-full channel width; minimum LWD diameter$_{pf}$ is the minimum diameter of single LWD that formed a pool.

Gradient class	Regression equation	N	r^2	P
	Woody debris			
All	LWD volume/m^2 = $-0.0014(W_{bf}) + 0.034$	28	0.22	0.01
All	LWD/m^2 = $-0.0045(W_{bf}) + 0.091$	28	0.43	<0.001
All	Mean debris length = $0.07(W_{bf}) + 3.1$	28	0.15	0.04
All	Minimum LWD diameter$_{pf}$ = $0.028(W_{bf}) + 0.0057$	26[a]	0.65	<0.001
	Percent gravel			
0.2–0.5%	Percent gravel = $1.2(W_{bf}) - 2.5$	6	0.83	0.01
0.6–2%	Log$_{10}$(percent gravel) = $-2.6(\log_{10}W_{bf}) + 3.3$	11	0.93	<0.001
2.1–4.8%	Percent gravel = $-0.2(W_{bf}) + 3.6$	11	0.41	0.03
	Percent pool			
0.2–2%	Percent pool = $-2.4(W_{bf}) + 81.1$	17	0.46	0.003
0.2–2%	Percent pool = 1,050(LWD volume/m^2) + 39	16[b]	0.32	0.02
2.1–4.8%	Percent pool = 1,720(LWD volume/m^2) − 13.7	11	0.70	0.001
	Pool spacing			
0.2–2%	Pool spacing = −6.2(LWD/m) + 4.3	17	0.41	0.006
2.1–4.8%	Pool spacing = −14.7(LWD/m) + 7.9	11	0.52	0.01

[a] Two reaches had no pools formed by single LWD.
[b] Palmer Creek omitted.

of LWD/m (LWD > 20 cm in diameter and > 3 m in length) in both low-slope and moderate-slope reaches (Figure 3). At a similar number of LWD/m, pool spacing was shorter in low-slope channels than in moderate-slope channels, with a decreasing difference as number of LWD/m increased. That is, pool spacing declined more rapidly with increasing number of LWD/m in moderate-slope channels than in low-slope channels. Pool spacing was approximately two channel widths per pool in both low-slope and moderate-slope reaches when debris frequency was 0.4 LWD/m.

Our results suggest that pool spacing is more

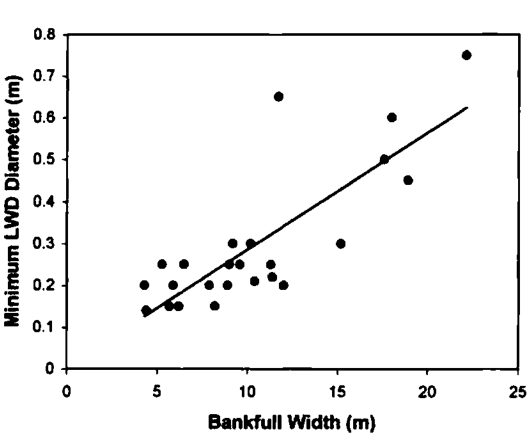

FIGURE 2.—Relationship between diameter of smallest LWD that formed a pool (diameter$_{pf}$) and bankfull channel width (W_{bf}). Two reaches did not have any pools formed by single pieces of LWD. Regression equation is diameter$_{pf}$ = $0.028(W_{bf}) + 0.0057$ ($r^2 = 0.65$, $P < 0.001$).

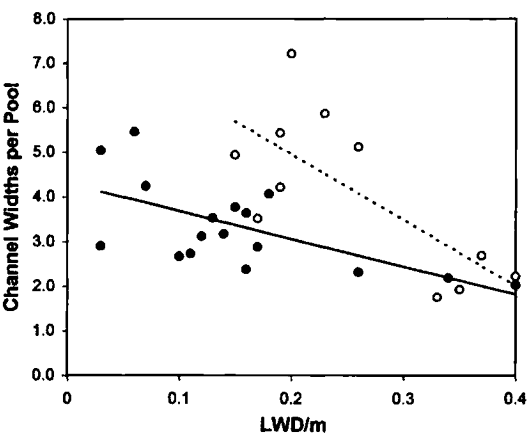

FIGURE 3.—Pool spacing relative to number of LWD per meter (includes LWD ≥0.2 m in diameter and ≥3 m in length). Both regressions are significant (Table 2). Filled circles and solid line are for reaches with low slopes (0.002–0.02). Open circles and dashed line are for reaches with moderate slopes (0.02–0.05).

sensitive to number of LWD/m in moderate-slope channels than in low-slope channels. Furthermore, the difference in regression slopes for the two stream slope classes suggests that pool spacing is not only a function of number of LWD/m and slope but a function of the interaction between number of LWD/m and slope. That is, the relationship between pool spacing and number of LWD/m changes depending on the slope of the channel. If slope and number of LWD/m were each individually significant but there was no interaction between slope and number of LWD/m, we would expect the regression lines for the two slope classes to be parallel and have different intercepts.

To evaluate the interaction between number of LWD/m and slope, we ran a multiple regression with pool spacing as the dependent variable and three independent variables: slope, LWD/m, and the interaction term slope × LWD/m. We found that only slope × LWD/m and slope were significant variables, yielding the equation

$$\text{pool spacing} = 2.7 - 4.6(\text{slope} \times \text{LWD/m}) + 1.6(\text{slope})$$

($r^2 = 0.42$, $P = 0.001$). This equation supports our contention that pool spacing is a function of the interaction between slope and number of LWD/m. The interaction term predicts the differing regression slopes for low-slope and moderate-slope channels because it predicts wider pool spacing in steeper channels at similar numbers of LWD/m. Additionally, the variable, slope, is significant in the regression. Slope alone predicts closer pool spacing in low-slope channels when number of LWD/m is low, suggesting that pool formation by mechanisms other than LWD is more important in low-slope channels.

Our earlier result showed that number and area of free-formed pools are greater in low-slope channels than in moderate-slope channels. In low-slope channels, pool formation is less sensitive to the presence of LWD or boulders because pools are more readily formed by other mechanisms, such as lateral scour at banks. Hence, as number of LWD/m in low-slope channels decreases, the change in pool spacing is relatively small because pools formed by other mechanisms compensate for the loss of LWD-formed pools. By contrast, free-formed pools are rare in moderate-slope channels when LWD/m is low. This suggests that woody debris or other obstructions to flow may be required to force flow convergence and initiate scour of a pool and that the change in pool spacing is relatively large as number of LWD/m decreases because other pool-forming mechanisms do not compensate for the loss of LWD-formed pools.

The results of Montgomery et al. (1995) are also consistent with these conclusions. They found that pool spacing is greater in moderate-slope channels (0.01–0.03) than in low-slope channels (<0.01) when LWD abundance is low and that channels in either slope range exhibit similarly low pool spacing when LWD abundance is high. They also suggested that pool spacing in moderate-slope channels is more sensitive to reduced LWD loading than in low-slope channels, primarily because a pool–riffle morphology is maintained in low-slope channels despite loss of LWD.

We caution that regression equations presented in this paper are only appropriate for the ranges of channel slope and woody debris abundance represented by our study sites. This caution is especially important because of the interactions between slope and number of LWD/m. Pool spacing converges at about two channel widths per pool when number of LWD/m reaches 0.4, leading us to believe that channels of all slopes between 0.002 and 0.05 will be equally sensitive to further increases in number of LWD/m (i.e., LWD/m >0.4). Hence, one might reasonably suspect that there is no interaction between slope and number of LWD/m when the number of LWD/m is higher than 0.4. Furthermore, there is no reason to suspect that channels with slope greater than 0.05 are more sensitive to LWD/m than are moderate-slope channels. The results of Montgomery et al. (1995) support both of the preceding cautions. They found that pool spacing is not sensitive to channel slope when LWD/m exceeds about 0.3 and also that pool spacing appears to be independent of LWD loading in step-pool channels. Furthermore, our data indicate that the relationship between pool spacing and LWD/m can be reasonably approximated by a linear function over the range of LWD abundance in our study sites. However, the results of Montgomery et al. (1995) indicate that over a wider range of LWD loadings, the relationship is best represented by an exponential function.

Percent Pool

The percentage of total wetted area classified as pools (percent pool) was inversely related to slope ($r^2 = 0.33$, $P = 0.01$). Percent pool was also correlated with woody debris volume (LWD volume/m^2) in both low-slope and moderate-slope channels (Figure 4A; Table 2), but percent pool was correlated with bank-full width only in low-slope channels (Figure 4B; Table 2). In low-slope

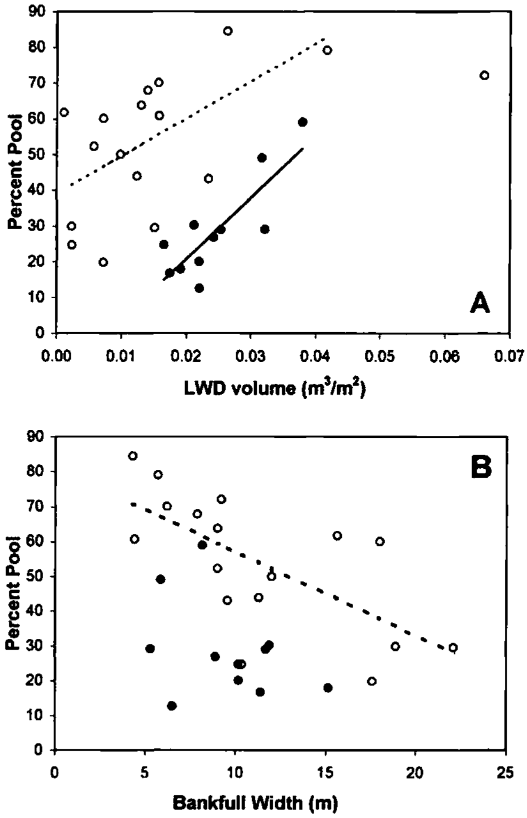

FIGURE 4.—(A) Relationship between percent pool and LWD volume/m^2. (B) Relationship between percent pool and bankfull channel width. Lines indicate significant linear regressions (Table 2). Regression between percent pool and bankfull width was not significant for slopes >0.02. Open circles and dashed lines are for reaches with low slopes (0.002–0.02). Filled circles and solid line are for reaches with moderate slopes (0.02–0.05).

channels, LWD volume/m^2 explained 32% of the variation in percent pool, whereas channel width explained 46%. However, the opposite was true in moderate-slope channels where LWD volume/m^2 explained 70% and channel width explained only 14% of the variation in percent pool.

The fact that percent pool is to varying degrees correlated with channel slope, channel width, and LWD volume/m^2 indicates that interactions between these variables may be important influences on percent pool. The LWD volume/m^2 expresses the interaction between channel width and LWD volume/m. Its significance in both slope classes suggests that the relationship between LWD volume/m and percent pool is partially dependent on channel width in either slope class. However, the stronger correlation between LWD volume/m^2 and percent pool in moderate-slope channels suggests that moderate-slope channels are more sensitive to LWD volume/m^2 than are low-slope channels. This is consistent with the preceding result for pool-spacing. By contrast, the stronger correlation between percent pool and channel width in low-slope channels suggests that LWD volume is less important to pool area in low-slope channels. Again, the most likely explanation for the weak relationship between percent pool and LWD volume/m^2 in low-slope channels is that free-formed pools are more common in low-slope channels with low LWD volume, thereby masking the lack of LWD-formed pools.

In Figure 4a, the regression intercepts are dramatically different for different slope classes, indicating that slope is a significant independent variable. However, the regression slope for low-slope channels is only slightly different from that for moderate-slope channels. This suggests that percent pool may not be related to an interaction between channel slope and LWD volume/m^2. However, two of our preceding results indicate that an interaction should occur. First, we found that the interaction between channel slope and number of LWD/m is a significant predictor of pool spacing. Second, we found that LWD volume/m^2 is a poor predictor of percent pool in low-slope channels, but a good predictor of percent pool in moderate-slope channels.

A multiple regression including the variables slope and LWD volume/m^2 yields the regression equation

$$\text{percent pool} = 48.4 - 14.1(\text{slope}) + 1{,}100(\text{LWD volume/m}^2)$$

($r^2 = 0.57$, $P < .001$). However, a similar correlation was obtained with slope and slope × LWD volume/m^2 in the regression equation

$$\text{percent pool} = 67.3 - 28.2(\text{slope}) + 681(\text{slope} \times \text{LWD volume/m}^2)$$

($r^2 = 0.60$, $P < .001$). The residual plots for the two regressions were similar and provided no indication that one regression was preferable to the other. Additionally, both equations tended to overpredict when percent pool was low and underpredict when percent pool was high, suggesting that another unmeasured factor is also related to percent pool.

Both equations indicate that slope and LWD volume/m^2 are significant predictors of percent pool. Slope alone predicts that percent pool is greater in low-slope channels than in moderate-slope channels at low LWD volume/m^2. As stated earlier, we attribute this to the greater area of free-formed pools in low-slope channels than moderate-slope channels, especially when LWD volume is low. The term LWD volume/m^2 shows that percent pool increases with increasing LWD volume/m and decreases with increasing channel width.

Our data provide no conclusive evidence that the interaction term slope × LWD volume/m^2 is a better predictor of percent pool than LWD volume/m^2. Nor did we find evidence for or against a slope–LWD interaction in other research. None of the studies that we reviewed specifically addressed relationships between pool area and a slope–LWD interaction. In view of the ambiguous regression results, we based our preference for one equation over the other on its consistency with our earlier results. Thus, we concluded that the equation with the slope–LWD interaction term is a more appropriate representation of the relationships between channel slope and width, LWD abundance, and pool area.

The interaction term slope × LWD volume/m^2 indicates that the correlation between LWD volume/m^2 and percent pool increases as channel slope increases. This result is consistent with the relationship between pool spacing and the slope–LWD/m interaction, as well as with the decreasing correlation between percent pool and LWD volume/m^2 as channel slope decreases. All of these relationships support the interpretation that numbers and area of pools are more sensitive to LWD abundance in moderate-slope channels than in low-slope channels.

Percent Gravel

One of our objectives in this study was to identify relationships between woody debris abundance and spawning gravel area, excluding those parts of the bed, such as tops of bars, that are dewatered for most of the year. (Gravel is defined here as particles 16–64 mm in diameter.) We expected to find reach-scale correlations between LWD abundance and gravel area because other researchers have found that the surface area of individual sediment accumulations was correlated with the volume of individual LWD pieces (e.g., Bilby and Ward 1989). However, we found no correlations between percent gravel (100 × gravel area/channel area) and number of LWD/m, LWD volume/m, or LWD volume/m^2 in any slope class, despite the fact that woody debris can store sediment and locally increase spawning gravel area (e.g., House and Boehne 1985).

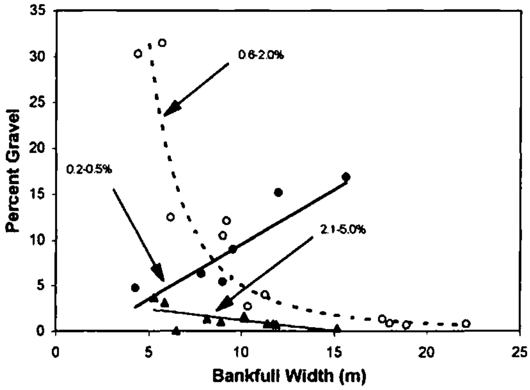

FIGURE 5.—Percent gravel relative to channel width and slope. All regressions are significant (Table 2). Filled circles and heavy solid line are for reaches with slopes between 0.002 and 0.005. Open circles and dashed line are for reaches with slopes between 0.005 and 0.02. Filled triangles and light solid line are for reaches with slopes between 0.02 and 0.05.

An average of 6% of all LWD in a reach trapped sediment in our study sites (range, 0–38%). Nevertheless, LWD was not significantly correlated with percent gravel, presumably because much of the stored gravel did not meet our criteria of remaining within the wetted perimeter during winter. Debris volumes in our study sites may also have been too low to see a correlation between percent gravel and debris abundance because volumes of individual debris pieces were too small to trap large areas of gravel.

Although percent gravel was not correlated with LWD frequency or volume, percent gravel increased with increasing channel width when slope was 0.005 or less (Figure 5; Table 2). Percent gravel decreased logarithmically with increasing channel width when channel slope was between 0.005 and 0.02 and decreased linearly with increasing channel width when slope was between 0.02 and 0.05. Because percent gravel was not correlated with any of our LWD measures (including independent terms and terms expressing interactions with channel width), we hypothesized that the relationships between percent gravel and channel width differ among slope classes because bed shear stress increases as water surface slope or channel depth increase (Richards 1982). Channel depth is typically correlated with channel width, so wider channels (of similar slope) have higher shear stresses and can transport larger particle sizes. Similarly, steeper channels (of similar width) have higher shear stress and can transport larger particles. Hence, median particle size on the surface of

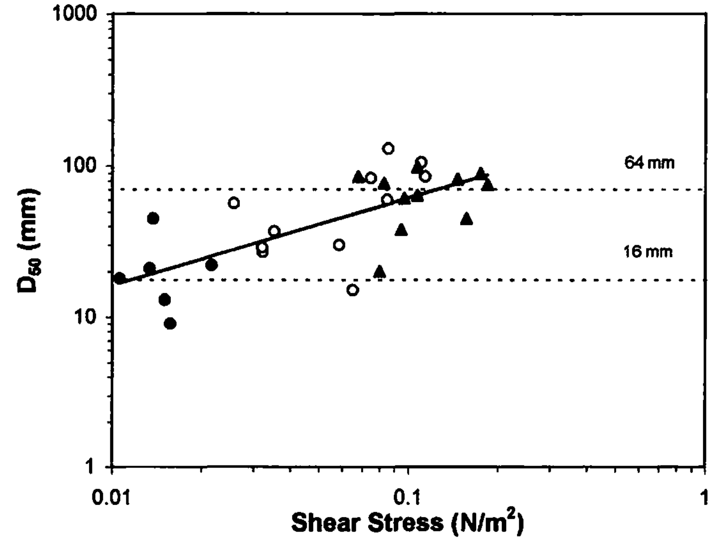

FIGURE 6.—Relationship between median particle size (D_{50}) on the streambed and basal shear stress (τ). Regression equation is $D_{50} = 231\tau^{0.581}$ ($r^2 = 0.49$, $P < 0.001$). Filled circles indicate reaches with slopes between 0.002 and 0.005. Open circles indicate reaches with slopes between 0.005 and 0.02. Filled triangles indicate reaches with slopes between 0.02 and 0.05.

the bed should increase as channel slope or width increase.

To test this hypothesis, we regressed median particle size of the bed surface (D_{50}) on mean basal shear stress (τ). We calculated mean basal shear stress for each reach as $\tau = \rho ghs$, where ρ is the density of water, g is acceleration due to gravity, h is the mean depth of cross-sections, and s is reach slope (Richards 1982). This estimate of shear stress represents only those parts of the channel where slope and depth are equal to mean slope and mean depth. Shear stress at other points in the reach will be higher or lower than the mean value due to local variations in depth or slope. However, we expected variability between reaches to be larger than within reaches because the range of channel slopes in the study is approximately one order of magnitude, and channel widths vary by up to a factor of five. Hence, mean shear stress can vary by more than an order of magnitude among reaches. We expected this to be sufficient range to detect relationships between shear stress and median particle size among reaches despite within-reach variation.

We found that D_{50} was positively correlated with mean shear stress and that mean basal shear stress explained about 50% of the variability in D_{50} ($P < 0.001$; Figure 6). The regression between D_{50} and shear stress indicates that D_{50} tends to be smaller than 16 mm when shear stress is less than about 0.01 N/m^2 and that D_{50} increases to greater than 16 mm as shear stress increases. Low shear stress tends to occur in low-slope channels (0.001 $<$ slope $\leq$ 0.005), especially in smaller channels that tend to be shallow. Larger particles are not easily transported in small low-slope channels, and most particles on the bed are less than 16 mm in diameter. Shear stress increases as channel width and depth increase, so larger low-slope channels can transport larger particles. Hence, the proportion of the particle size distribution that is between 16 and 64 mm also increases, and we observe a positive correlation between channel width and percent gravel for low-slope channels.

The regression between D_{50} and shear stress also shows that D_{50} tends to be between 16 and 64 mm when shear stress is between about 0.01 and 0.1 N/m^2. When reach slope is between 0.005 and 0.02, smaller channels typically have shear stresses in the range of 0.02–0.08 N/m^2 and a relatively high proportion of particles between 16 and 64 mm. As channel size increases, shear stress increases and the proportion of the particle size distribution that is greater than 64 mm increases. Therefore, we see a negative relationship between percent gravel and channel width when slope is between 0.005 and 0.02 (Figure 5). In the steepest channels of our study (slope between 0.02 and 0.05), D_{50} is near 64 mm even in smaller channels, resulting in consistently low percent gravel.

Management Implications

Typically, logging of a riparian forest reduces the rate of LWD recruitment to a stream for several decades (Grette 1985; Murphy and Koski 1989; Bilby and Ward 1991). Depletion of instream LWD continues during the period of little or no recruitment, resulting in a net decline in LWD abundance for several decades (Grette 1985) and sustained low amounts of LWD between 50 and 100 years after logging (Murphy and Koski 1989). If we were to apply this general scenario to both moderate-slope and low-slope channels, we would predict declines in number and area of pools in channels of both slope classes (based on the inference of a cause and effect relationship between LWD abundance and pool abundance). However, given the same decrease in LWD abundance, we would predict greater decreases in number and area of pools in moderate-slope channels than in low-slope channels.

Other studies have shown that some juvenile salmonid species preferentially select pools as rearing habitat (Bisson et al. 1988) and that increased pool area can result in larger populations of single species (e.g., Fausch et al. 1988), in shifts in species or age-class composition, or in changes in species diversity (Gorman and Karr 1978; Angermeier and Schlosser 1989). For example, as pool size decreases, one typically finds higher densities of juvenile coho salmon in individual pools (Hankin 1984), which may occur because distances to available cover are shorter or because food availability increases as drift is transported near low velocity resting stations (Ruggles 1966; Mundie 1969). Increased cover complexity from greater amounts of LWD and pockets of slow-water refugia behind LWD may also contribute to greater abundance of coho salmon during winter (McMahon and Hartman 1989).

These studies indicate that the preceding scenario of logging, decreased LWD abundance, and reduction in number and area of pools may affect juvenile salmonid abundance or species age-class distribution. In general, we expect decreases in abundance of species that show strong preferences for pools as rearing locations (e.g., coho salmon), and we may also find increases in abundance of other species that are better suited to rearing in riffle environments (e.g., steelhead). Adjustments in relative abundance of various species are expected to be more pronounced in moderate-slope channels because pool abundance is more sensitive to reduced LWD abundance in moderate-slope channels.

After logging of a riparian forest, recruitment of LWD from deciduous second-growth stands can begin within 25 years, and recruitment from conifer stands can begin within 50 years (Grette 1985). Recruitment of larger woody debris (>60 cm in diameter) does not begin until about 75 years after clear-cutting (Murphy and Koski 1989). Assuming that the rate of increase in LWD abundance after logging (e.g., Grette 1985; Bilby and Ward 1991) is the same for both moderate-slope and low-slope channels, we would then expect increases in number and area of pools to be more rapid in moderate slope-channels than in low-slope channels. However, when the number of LWD/m (>20 cm in diameter) reaches about 0.4, pool spacing in both slope classes should have similarly low sensitivity to further increases in number of LWD/m. Percent pool should also increase in both low-slope and moderate-slope channels, with percent pool increasing more rapidly in moderate-slope channels. The response of salmonids to this postlogging scenario should be an increased abundance of pool-rearing species and a reduction in riffle-rearing species, and moderate-slope channels should undergo a slightly greater rate of change.

Logging practices today often leave riparian buffers along streams, which would present a different scenario for LWD recruitment after logging in a second-growth forest. In such cases, LWD recruitment rates can increase for several years after logging of the stand outside the buffer. This is primarily a result of windthrow, which occurs when the buffer stand is exposed to strong winds by removal of the surrounding forest. As with the preceding changes in LWD recruitment, we would expect a similar level of windthrow recruitment to have a greater effect on pool abundance in moderate-slope channels than in low-slope channels. In other words, we can expect increases in abundance of pools and pool-rearing species after logging where riparian buffer strips are left, provided LWD abundance is not already greater than 0.4 LWD/m. Furthermore, such increases would be more pronounced in moderate-slope channels than in low-slope channels.

The only relationship between LWD and pool formation that appeared to be independent of channel slope (over the slope range 0.002–0.048) was that between channel width and the minimum size of LWD that formed a pool. This relationship indicates that LWD recruited from a second-growth stand should begin to form pools sooner in small channels than in large channels. In channels less than 10 m wide where LWD as small 20 cm in diameter can potentially form a pool, we anticipate that pool abundance may begin increasing as soon as deciduous LWD begins to enter the channel after 25 years. By contrast, in channels 20 m wide where pools do not form until debris of about 60 cm in diameter enters the stream, significant increases in number or area of pools may not begin until 75 years after logging when larger conifer debris is recruited.

Where streams have low LWD and pool abundance because of previous logging, it may be possible to accelerate recovery to prelogging conditions by management of the riparian forest (Berg 1990). For example, thinning of a riparian forest to increase conifer growth rates may benefit larger streams which require larger woody debris to form pools. For a stream 20 m wide where LWD that is 60 cm in diameter forms pools, it may take as much as 75 years to begin recruiting LWD of pool-forming size. Thinning may allow remaining trees to grow faster, thereby decreasing the time required for recruited LWD to reach pool-forming size. However, on smaller streams, thinning may provide little benefit because relatively small woody debris is sufficient to form pools.

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