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Pool spacing in forest channels

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Abstract. Field surveys of stream channels in forested mountain drainage basins in southeast Alaska and Washington reveal that pool spacing depends on large woody debris (LWD) loading and channel type, slope, and width. Mean pool spacing in pool-riffle, plane-bed, and forced pool-riffle channels systematically decreases from greater than 13 channel widths per pool to less than 1 channel width with increasing LWD loading, whereas pool spacing in generally steeper, step-pool channels is independent of LWD loading. Although plane-bed and pool-riffle channels occur at similar low LWD loading, they exhibit typical pool spacings of greater than 9 and 2–4 channel widths, respectively. Forced pool-riffle channels have high LWD loading, typical pool spacing of <2 channel widths, and slopes that overlap the ranges of free-formed pool-riffle and plane-bed channel types. While a forced pool-riffle morphology may mask either of these low-LWD-loading morphologies, channel slope provides an indicator of probable morphologic response to wood loss in forced pool-riffle reaches. At all study sites, less than 40% of the LWD pieces force the formation of a pool. We also find that channel width strongly influences pool spacing in forest streams with similar debris loading and that reaches flowing through previously clear-cut forests have lower LWD loading and hence fewer pools than reaches in pristine forests.

Introduction

The frequency with which pools occur along a stream is a fundamental aspect of channel morphology. Well-established tenets in fluvial geomorphology hold that pool-to-pool spacing averages 5–7 channel widths in free-formed pool-riffle reaches [*Leopold and Wolman*, 1957; *Leopold et al.*, 1964; *Keller*, 1972; *Keller and Melhorn*, 1978] and 1–4 channel widths in steeper step-pool reaches [*Whittaker*, 1987; *Chin*, 1989; *Grant et al.*, 1990]. Pools, however, may be either freely formed by the interaction of flow and sediment transport or forced by local obstructions (e.g., bedrock, boulders, bank projections, and large woody debris (LWD) consisting of logs, root wads, or debris jams), which cause flow convergence and turbulent velocity fluctuations that scour the channel bed [e.g., *Zimmerman et al.*, 1967; *Swanson et al.*, 1976; *Dolan et al.*, 1978; *Keller and Swanson*, 1979; *Beschta*, 1983; *Lisle*, 1986a; *Smith*, 1990].

An extensive literature documents the influence of LWD on channel morphology in forested mountain drainage basins (see *Maser et al.* [1988] and *Thomson* [1991] for recent reviews). In small channels, individual pieces of LWD trap sediment, cause local bed and bank scour, and create steps in the bed profile [e.g., *Heede*, 1972; *Marston*, 1982; *Beschta and Platts*, 1986; *Lisle*, 1986a, b; *Bilby and Ward*, 1989, 1991; *Robison and Beschta*, 1990]. In larger channels, LWD jams locally influence bed and bank scour, side channel development, bar stability, and island formation [e.g., *Abbe et al.*, 1993; *Gregory et al.*, 1993; *Nakamura and Swanson*, 1993]. While it is widely recognized that flow convergence and bed scour associated with LWD can reduce pool spacing to values less than expected for free-formed pool-riffle channels (see, for example, data presented by *Keller and Tally* [1979], *Sullivan et al.* [1987], *Bilby and Ward* [1991], and *Smith and Buffington* [1994]), there has not been any quantitative analysis of the relation between LWD loading and pool spacing. Here we further examine the influence of LWD on channel morphology and pool spacing across a wide range of LWD loading in forested mountain drainage basins.

Study Areas

We surveyed pool spacing, LWD loading, and the relation of LWD to pools in southeast Alaska and Washington (Figure 1). Reaches surveyed in southeast Alaska were primarily in the Corner Bay and Trap Bay areas of Tenakee Inlet on Chichagof Island. These catchments were glaciated during the Pleistocene and are underlain by limestone, granite, and metasediments [*Gehrles and Berg*, 1992]. Channels surveyed in the central Cascades of Washington were in the Tolt River watershed, which is underlain by Tertiary igneous and sedimentary rocks and pre-Tertiary mélange [*Booth*, 1990]. Valley floors and lower portions of valley walls are covered by Pleistocene recessional outwash and alpine glacial deposits [*Booth*, 1990]. Within each study area, channel reaches were surveyed in both pristine old growth and forests previously clear-cut to the channel margin. The combined data set covers a wide range of channel widths (2.7–38.1 m) and gradients (0.002–0.085) (Table 1).

Methods

Study reaches were selected to represent a range of LWD loading, gradient, and channel morphology. Channel reaches

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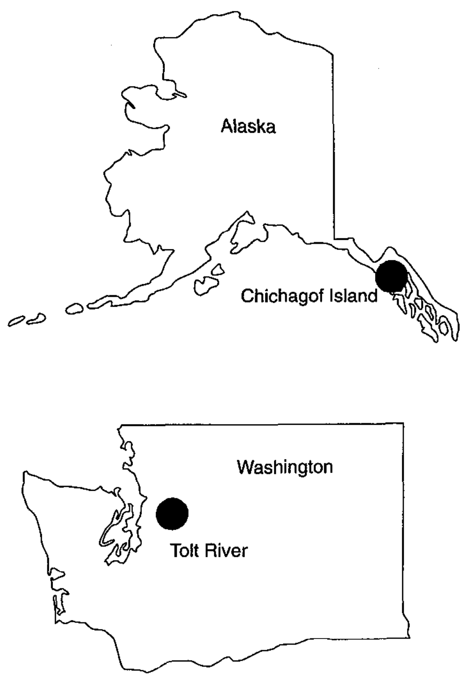

Figure 1. Location maps for the study areas.

surveyed ranged from 8 to 24 channel widths in length. Bank-full channel widths measured at 10 m intervals defined a reach-average channel width. Centerline channel bed profiles were surveyed with either a hand level or engineer's level, tape, and stadia rod.

Each reach was classified as either a pool-riffle, plane-bed, forced pool-riffle, or step-pool channel [*Montgomery and Buffington*, 1993]. Pool-riffle channels exhibit regularly spaced alternate bars and pools that are predominantly free formed; plane-bed channels lack free-formed bars, have subdued cross-channel topography, and consist primarily of riffles; forced pool-riffle channels are those in which more than half of the pool and bar forms are primarily forced by flow convergence, divergence, and turbulent scour associated with in-channel obstructions; and step-pool channels are those exhibiting channel-spanning steps in the low-flow water surface profile (Figure 2). This morphological classification of channel types is not predicated on LWD loading, although in non-step-pool reaches high LWD loading invariably causes a forced pool-riffle morphology.

A variety of criteria have been used to define pools since *Léliavski* [1894] recognized that pools are formed by localized convergent flow within a channel. *Leopold et al.* [1964], for example, used low-flow stages to define pools as areas of relatively deep, slow flow with low water surface slopes distinct from shallower, higher-gradient, faster flowing riffles (see also *Keller* [1971a] and *Lisle* [1979]). Pools and riffles also have been distinguished at low-flow stages on the basis of relative energy gradients [*Leopold et al.*, 1964; *Yang*, 1971]. Several workers proposed using relative topographic deviations from the reach-average bed surface to discriminate pools from riffles [*Richards*, 1976; *O'Neill and Abrahams*, 1984]. *Keller* [1971b] considered a pool to be a closed topographic depression formed by local scour of the channel bed and distinguished by fine grain sizes and slow water at low flow. *Smith and Buffington* [1993, 1995] identified pools based on morphology and a minimum depth criterion expressed as a proportion of the width of the active channel. Fisheries biologists elaborated upon these definitions to recognize as many as 11 distinct types of pools [*Bisson et al.*, 1982; *Hawkins et al.*, 1993]. While some workers require that a pool span the channel, this criterion is not appropriate for channels in forest environments where, in contrast to free-formed pools in alluvial reaches, local scour associated with LWD may force more than one pool to occur in a single cross section.

We counted all morphologically distinct pools in each channel reach surveyed. Features that we identified as pools typically had water depths many times greater than the median bed surface grain size, and we estimate that they had residual depths of at least 25% of the bank-full depth and a length or width of at least 10% of the channel width. Repeat surveys by different personnel found differences of at most one pool per reach. The mean pool spacing for each reach was calculated by dividing the reach length by both the number of pools and the reach-average channel width, yielding a pool-to-pool spacing in units of channel width (i.e., channel widths per pool).

The total number of LWD pieces greater than 10 cm in diameter and 1 m in length [*Swanson et al.*, 1976] within the bank-full channel was counted in each reach. LWD loading was determined by dividing the number of pieces within a reach by both the reach length and width to yield a debris loading per square meter of channel bed. The effect of each piece of LWD on pool morphology was classified by visual assessment as either dominant, secondary, or negligible. Dominant pieces were those interpreted to be the primary cause of the formation and specific geometry of a pool. The geometry and orientation of LWD-forced pools typically mimicked or paralleled that of the dominant obstruction. The deepest scour within a LWD-forced pool was also commonly caused by the dominant piece. Secondary pieces influenced pool morphology by modifying the zone of channel bed scour but were not believed to be responsible for the main geometry of a pool. While there is always the possibility of fortuitous correspondence between log and pool proximity, a number of factors can be used to assess causality. In meandering pool-riffle channels, for example, pools are expected to form on the outside of bends due to flow convergence but are unlikely to form on the inside of bends or in short straight sections between meanders unless forced by an obstruction. While associations of LWD and pools in areas where pool formation is expected are insufficient for determining causal pool-forming mechanisms, the association of LWD and pools in other locations strongly suggests the influence of LWD.

Each pool identified in the surveyed reaches was classified as either self-formed or forced by scour around an obstruction on the basis of criteria similar to those used to assess the morphologic influence of each piece of LWD. At our study sites, pool-forcing obstructions included LWD, bank projections, boulders, and bedrock outcrops. Bank projections were typically caused by tree roots or resistant, on-bank LWD. Self-formed pools are those formed by interactions among shear stress, sediment transport, and bed and bank topography in the absence of other pool-forcing obstructions [*Dietrich and Whiting*, 1989; *Nelson and Smith*, 1989]. Self-formed pools also include those formed by tributary confluences.

Pool-Forming Mechanisms

Scour around LWD was the dominant pool-forming mechanism in the channels that we studied (Table 2); most of the

Table 1. Channel Reach Characteristics

Reach	Channel Type*	Slope, m/m	Length, m	Width, m	LWD/m^2	Channel Widths/Pool
Tolt 1	fPR	0.035	152.5	14.5	0.049	0.81
Tolt 2	fPR	0.034	300.0	24.9	0.050	0.21
Tolt 6	SP	0.040	130.0	16.3	0.013	0.57
Tolt 7	SP	0.029	150.0	12.2	0.011	1.12
Tolt 9	SP	0.054	140.0	15.3	0.021	0.61
Tolt 10	PB	0.029	130.0	12.8	0.008	5.08
Tolt 11	PB	0.040	35.0	2.8	0.010	12.50
Tolt 12	PB	0.030	40.0	3.0	0.033	>13.20
Tolt 13	PR	0.030	40.0	2.7	0.028	3.70
Tolt 14	fPR	0.021	65.0	5.4	0.128	1.34
Tolt 15	fPR	0.007	55.0	4.1	0.062	3.35
Tolt 16	fPR	0.014	50.0	4.4	0.118	1.14
Tolt 17	fPR	0.006	70.0	4.9	0.152	0.75
Tolt 18	fPR	0.012	60.0	4.5	0.189	0.70
Tolt 19	PR	0.010	340.0	35.0	0.005	2.43
Tolt 20	PB	0.013	220.0	23.5	0.004	9.36
Tolt 21	SP	0.085	55.0	4.1	0.160	1.34
Tolt 22	PB	0.023	60.0	4.9	0.010	>12.20
Tolt 23	fPR	0.006	55.0	4.2	0.035	3.27
Tolt 24	fPR	0.002	60.0	4.0	0.108	2.14
Tolt 25	fPR	0.007	65.0	4.4	0.094	1.23
Tolt 26	fPR	0.006	65.0	4.9	0.104	0.95
Tolt 27	fPR	0.005	53.0	4.5	0.092	1.18
Tolt 28	fPR	0.008	379.0	38.1	0.005	1.99
Trap 2	fPR	0.007	225.0	12.5	0.057	0.32
Trap 4	fPR	0.008	112.0	7.0	0.089	0.76
Trap 5	fPR	0.009	104.0	12.0	0.079	0.51
Trap 6	fPR	0.009	102.5	14.0	0.070	0.32
East Fork Trap	fPR	0.009	102.0	7.7	0.104	0.55
Hole in Wall 1	fPR	0.025	106.0	8.2	0.053	0.86
Hole in Wall 2	fPR	0.023	83.0	5.1	0.118	1.08
Hole in Wall 3	fPR	0.023	90.0	6.2	0.122	0.73
Muri 1	PB	0.015	310.0	15.0	0.026	2.30
Muri 2	fPR	0.027	90.0	9.1	0.066	0.82
Corner 1	fPR	0.030	60.0	5.4	0.188	0.79
Corner 2	fPR	0.016	60.0	4.9	0.082	1.36
Corner 4	fPR	0.009	200.0	14.7	0.101	0.26
Bambi 1	fPR	0.006	63.0	4.0	0.056	2.63
Bambi 2	PR	0.016	96.0	4.0	0.021	2.67
Bambi 3	fPR	0.016	55.0	5.3	0.148	0.94
Kook 3	fPR	0.010	100.0	9.7	0.088	0.54
Kook 5	SP	0.027	51.0	5.0	0.169	1.02
Kook 6	SP	0.022	50.0	4.7	0.204	1.18
Buckhorn	fPR	0.005	150.0	11.5	0.060	0.50
Gold	PB	0.025	50.0	4.4	0.027	11.36
Montana	PB	0.003	190.0	18.3	0.010	2.60

*Here, fPR denotes forced pool-riffle; PR, pool-riffle; PB, plane-bed; and SP, step-pool.

reaches surveyed were classified as forced pool-riffle channels (Table 1). Seventy-three percent of the 471 pools surveyed were forced by LWD, while only 18% were self-formed. Boulders and bedrock were minor pool-forming agents in these channels. We observed that 78% of the pools in Alaskan pool-riffle reaches were self-formed, as opposed to 63% of the pools in the Tolt River pool-riffle reaches. There were no self-formed pools in plane-bed channels in the Tolt and only several small self-formed pools associated with channel bends in Alaskan plane-bed reaches. The few pools found in the Tolt plane-bed reaches were primarily forced by bank projections, and the majority of those in Alaskan plane-bed channels were forced by LWD. Pool-forming mechanisms in forced pool-riffle channels in the Tolt and Alaska study areas were more similar; 78% and 87% of the pools were forced by LWD. Most pools in Alaskan step-pool channels were forced by LWD, whereas those in step-pool channels in the Tolt were self-formed, separating steps in the bed profile defined by channel-spanning accumulations of clasts. These results indicate that even though LWD controls the formation of most pools in these channels, the importance of other pool-forming mechanisms depends on local setting and channel type.

The influence of LWD on channel morphology depends on its size relative to channel size, orientation relative to the flow, and height above the bed [e.g., *Beschta*, 1983; *Lisle*, 1986a; *Bilby and Ward*, 1989; *Cherry and Beschta*, 1989; *Robison and Beschta*, 1990; *Richmond*, 1994]. As previously documented by *Lisle* [1986b], *Robison and Beschta* [1990] and *Richmond* [1994], we observed that very large logs oriented either oblique or perpendicular to flow have the greatest influence on pool formation. However, the proportion of in-channel LWD influencing pool formation appears to be independent of wood loading (Figure 3). In general, up to 40% of the in-channel debris exerts a dominant influence on pool formation (Figure 3a). A similar amount provides a secondary influence on pool characteristics (Figure 3b). Typically, 40–80% of the LWD has

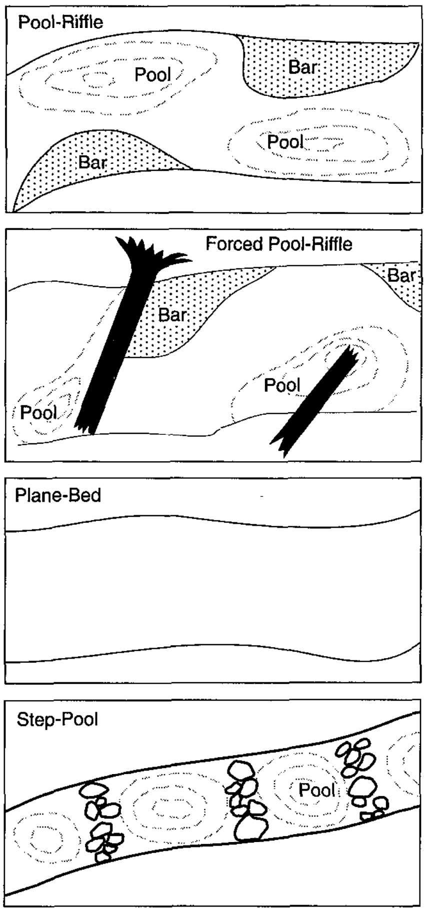

Figure 2. Schematic illustration of low-flow channel bed morphologies used to classify stream channels in this study.

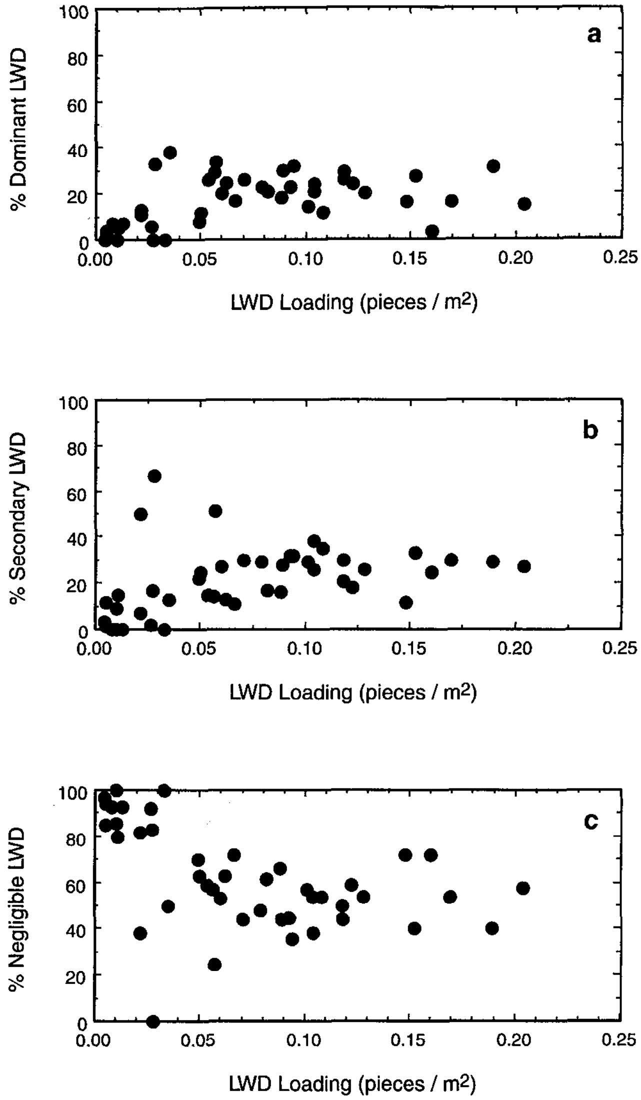

Figure 3. Large woody debris (LWD) loading versus the percentage of pieces that (a) dominate pool formation, (b) modify pool size or shape, and (c) have negligible influence on pool morphology.

no influence on pool formation (Figure 3c), but at very low LWD loading (i.e., <0.03 pieces per square meter) 80–100% of the LWD had negligible influence on pool formation in all but one of the reaches surveyed. The roughly uniform range in the proportion of dominant (i.e., pool-forming) LWD pieces at our study sites (Figure 3a) indicates that increased LWD load-

Table 2. Pool-Forming Mechanisms

Channel Type	Number of Pools	Self-Formed, %	Forced: LWD, %	Forced: Bank Projection, %	Forced: Boulder, %	Forced: Bedrock, %
Pool-riffle	17	70.6	23.5	5.9	0.0	0.0
Tolt	8	62.5	37.5	0.0	0.0	0.0
Alaska	9	77.8	11.1	11.1	0.0	0.0
Plane-bed	19	10.5	47.4	42.1	0.0	0.0
Tolt	5	0.0	20.0	80.0	0.0	0.0
Alaska	14	14.3	57.1	28.6	0.0	0.0
Forced pool-riffle	366	9.3	82.7	6.3	1.4	0.3
Tolt	179	12.3	78.2	6.7	2.8	0.0
Alaska	187	6.4	87.2	5.9	0.0	0.5
Step-pool	69	53.6	39.1	5.8	···	1.4
Tolt	50	74.0	18.0	6.0	···	2.0
Alaska	19	0.0	94.7	5.3	···	0.0
Total	471	18.0	72.8	7.6	1.1	0.4

ing is associated with greater numbers of dominant pieces and hence more LWD-forced pools.

Large Woody Debris (LWD) and Pool Spacing

Our data reveal that mean pool spacing is inversely related to LWD loading in plane-bed, pool-riffle, and forced pool-riffle channels (Figure 4a). In our study areas, pool spacing varied from greater than 13 channel widths per pool at low LWD loading to about 0.2 channel widths per pool at the highest debris loading. While free-formed pool-riffle and plane-bed channels share similarly low LWD loading (i.e., <0.03 pieces per square meter), pool spacing generally differs between the two reach morphologies. Mean pool spacing in five out of eight surveyed plane-bed reaches exceeds 9 channel widths, while pool-riffle channels exhibit a mean pool spacing of only 2–4 channel widths, less than the typical value of 5–7 widths for unobstructed alluvial channels [*Leopold et al.*, 1964]. Reaches classified as forced pool-riffle morphology characteristically have a higher debris loading and lower pool spacing than pool-riffle and plane-bed channels (Figure 4a). Forced pool-riffle channels have pool spacings of 0.2–3 channel widths with pool spacing generally decreasing in range and value with higher wood loading. Pool spacing in step-pool reaches appears to be independent of LWD loading on the basis of our limited data set of six reaches (Figure 4b). In these generally steeper channels, pool spacing ranges from about 0.6 to 1.3 channel widths, whereas pool spacing of 1–4 channel widths characterizes step-pool channels lacking significant LWD [*Whittaker*, 1987; *Chin*, 1989; *Grant et al.*, 1990]. While LWD appears to decrease pool spacing in step-pool channels, there is no clear functional relationship such as observed for plane-bed and pool-riffle channels.

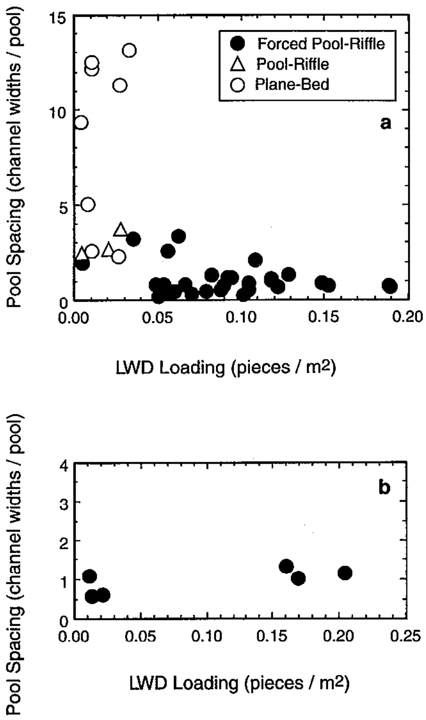

Figure 4. LWD loading versus pool spacing for (a) pool-riffle, plane-bed, and forced pool-riffle reaches and (b) step-pool reaches.

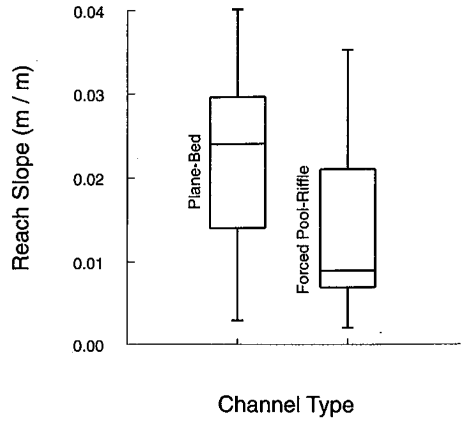

Figure 5. Box and whiskers plots of reach gradient for plane-bed and forced pool-riffle reaches examined in this study. Center bar is sample median, boxes define inner and outer quartiles, and whiskers define range of observations.

Pool-riffle and plane-bed morphologies occur at low LWD loading but over different slope ranges. Although the limited number of pool-riffle channels surveyed in this study precludes direct comparison using our data, previous work indicates that free-formed pool-riffle sequences are rare at channel gradients >0.02 [e.g., *Ikeda*, 1975; *Florsheim*, 1985]. All but one of the plane-bed reaches examined in this study have slopes ≥0.01; the exception (Montana Creek) may have been greatly affected by land use. Other studies in the Pacific Northwest indicate that plane-bed channels tend to occur at gradients of 0.01–0.03 [*Montgomery and Buffington*, 1993]. Slopes of forced pool-riffle channels surveyed in this study range from 0.002 to 0.035 and thus overlap these typical slope ranges for pool-riffle and plane-bed morphologies (Figure 5). Hence a high LWD loading and forced pool-riffle morphology may mask either of these two low-LWD-loading bed morphologies.

The impact of debris loading on pool spacing is additionally influenced by channel width. For a given debris loading, the pool frequency (the number of pools per channel width of stream length; the inverse of pool spacing) increases directly with channel width (Figure 6). This result contrasts with previous studies which indicate that channel width does not influence pool spacing in obstruction-free channels [*Keller and Melhorn*, 1978]. Our data, however, indicate that wider channels have more pools per channel width than narrower channels at similar LWD loading, in part because large pieces of debris may force formation of several pools across a wide channel [*Smith and Buffington*, 1993], whereas only a portion of such pieces would be contained within the banks of a small channel. Figure 6 further illustrates the influence of LWD loading on pool frequency. Narrow channels (i.e., width ≤4 m) share similar low pool frequencies independent of debris loading. With increasing channel width, however, pool frequency rapidly diverges as a function of LWD loading, and for a given width higher debris loading produces a higher pool frequency. In this manner, channel width and LWD loading interact to control pool frequency.

Channel width, however, also influences LWD loading. Our data from both old growth and previously clear-cut forests indicate that LWD loading generally decreases with channel width (Figure 7). Using LWD frequency (i.e., LWD pieces per meter of channel length), *Bilby and Ward* [1989, 1991] found a

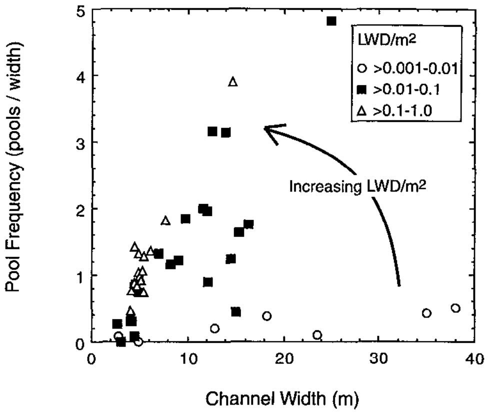

Figure 6. Channel width versus pool frequency stratified by LWD loading.

similar relationship. The inverse relation between LWD loading and channel width presumably results from logs in larger channels being more readily transported by flow because they are more submerged, increasing their buoyancy and exposure to flow. Figure 7 further shows that the variance of LWD loading decreases with increasing channel width. This implies that smaller channels in forested environments should exhibit a wide range of pool spacing, whereas larger channels should more closely conform to expectations for free-formed alluvial channels.

The preceding analyses show that both LWD loading (LWD per square meter) and channel width influence pool spacing in forest channels. LWD frequency (LWD per meter) provides an index of LWD abundance that incorporates both of these influences. For the combined data from pool-riffle, plane-bed, and forced pool-riffle reaches, there is a strong inverse relation between pool spacing and LWD frequency, with pool spacing asymptotically approaching a lower limit of about 0.2 channel widths at the highest LWD frequency (Figure 8). We suspect that interference between zones of forced flow convergence and divergence at high LWD abundance begins to effectively limit the degree to which the channel bed may be divided into morphologically distinct pools.

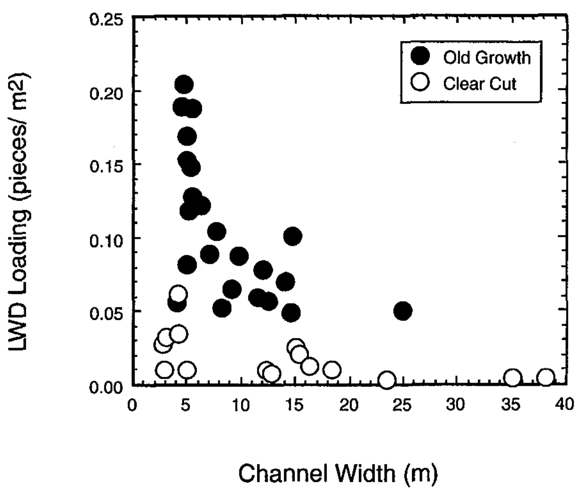

Figure 7. Channel width versus LWD loading for reaches flowing through old growth and clear-cut forests.

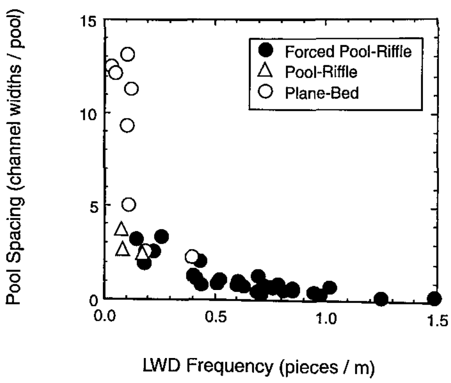

Figure 8. LWD frequency versus pool spacing for pool-riffle, plane-bed, and forced pool-riffle reaches.

A simple stepwise linear regression analysis provides further insight into the controls on pool spacing. On the basis of the above findings we selected three candidate variables for the hypothesized function

$$\log (Y) = \beta_0 + \beta_1 \log (x_1) + \beta_2 \log (x_2) + \beta_3 \log (x_3) \quad (1)$$

where Y is channel widths per pool, β values are coefficients, x_1 is channel width, x_2 is LWD per square meter, and x_3 expresses the interaction of x_1 and x_2 (i.e., $x_3 = x_1 x_2$ is LWD per meter). Analysis of partial F values in a stepwise selection of candidate variables at $P = 0.05$ indicates that only LWD per meter enters (1). This demonstrates that it is not simply LWD loading and channel width that control pool spacing, but rather the interaction between the two. The regression equation from this analysis for the combined plane-bed, pool-riffle, and forced pool-riffle study sites is

$$\text{channel widths per pool} = 0.05\,(\text{LWD/m})^{-1.04} \qquad r^2 = 0.85 \quad (2)$$

indicating a simple inverse proportionality between pool spacing and LWD frequency in the forest channels that we studied.

Land Management and LWD Frequency

Land management history influences LWD frequency and thus pool spacing in our study reaches. Ninety-six percent of the reaches flowing through pristine (old-growth) forests exhibit LWD frequency greater than 0.4 pieces per meter of channel length (Figure 9). In contrast, 73% of the reaches flowing through previously clear-cut forests exhibit LWD loading less than 0.2 pieces per meter of channel length. This lower LWD frequency in previously clear-cut reaches may reflect both direct removal of LWD from within some reaches and decreased recruitment resulting from cutting of channel margin forests. The difference in debris frequency between land use types produces distinct differences in pool spacing (Figure 10). While *Smith and Buffington* [1994] also find that LWD abundance and pool spacing are primary discriminators of land use and channel condition in southeast Alaska, the effect of land management on the size and abundance of in-channel LWD depends on the history of specific management activity, the time since that activity, the species composing the riparian forest, and the natural potential for LWD recruitment.

Discussion

Our results demonstrate that pool spacing in forested mountain drainage basins depends on LWD loading and channel type, slope, and width. We find that the mean pool spacing in pool-riffle reaches is considerably lower than the commonly expected range of 5–7 channel widths [*Leopold et al.*, 1964; *Keller and Melhorn*, 1978], which likely represents an end-member morphology without obstructions such as LWD. Even at very low debris loadings (i.e., <0.03 pieces per square meter), forest pool-riffle channels have pool spacings of 2–4 channel widths, implying that channel morphology in these streams is very sensitive to the presence of LWD and other types of obstructions [*Smith et al.*, 1993]. It follows therefore that free-formed pool-riffle channels are rare in forested environments. Similar low LWD loading in plane-bed reaches results in pool spacings of 2 to more than 13 channel widths, with most above 9 channel widths, and therefore greatly above the expectation for free-formed pool-riffle channels. Channel type, slope, and width, however, are all interrelated; the widest of the study reaches tend to have lower slopes and pool-riffle morphologies, while the narrowest tend to be the steepest and exhibit step-pool morphologies (Table 1).

Pool formation in the forest channels of our study areas is controlled largely by scour around LWD; other pool-forming mechanisms are responsible for only a minority of pools. This finding is similar to that of other studies of alluvial channels in forested mountain drainage basins in the Pacific Northwest [e.g., *Andrus et al.*, 1988], southeast Alaska [*Robison and Beschta*, 1990; *Smith and Buffington*, 1993], and Colorado [*Richmond*, 1994]. Our data, however, also show that the percentage of various pool-forming mechanisms differs among channel types (Table 2), although some of this variation could reflect differences in forest stand characteristics and processes and rates of LWD recruitment to channels, as well as land use history.

Our results indicate that channel type, width, and slope must be considered when assessing channel response to altered LWD loading in forest channels of mountain drainage basins. Pool-riffle and plane-bed reaches typically occur over different slope ranges for comparable low wood loadings, while high-LWD-loading forced pool-riffle reaches overlap the slope ranges characteristic of these two free-formed reach morphologies. Pool-riffle reaches are rare at slopes above 0.02 [*Ikeda*, 1975; *Florsheim*, 1985]; at these slopes plane-bed morphologies are the dominant reach-level morphology at low LWD loading.

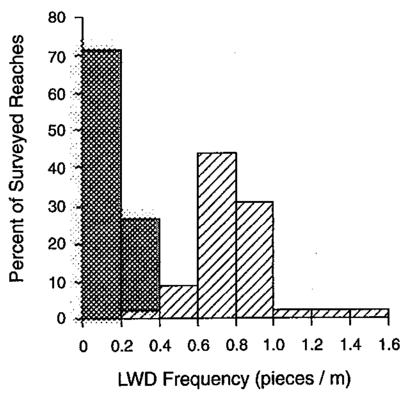

Figure 9. Distributions of LWD frequency for channels in old growth (hatched) and previously clear-cut forests (shaded).

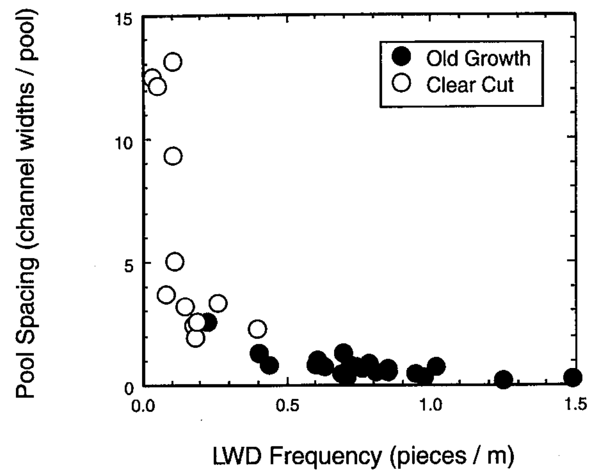

Figure 10. LWD frequency versus pool spacing for channels surveyed in previously clear-cut and old growth forests.

Conversely, plane-bed morphologies are uncommon on slopes less than 0.01; at these slopes pool-riffle morphologies are dominant at low LWD loading. Because slopes of forced pool-riffle reaches overlap slope ranges characteristic of pool-riffle and plane-bed morphologies, channel slope may be a useful indicator of potential morphologic response to reduced debris loading in forced pool-riffle channels. On the basis of these findings, we hypothesize that forced pool-riffle channels with gradients >0.01 are very sensitive to reduced LWD loading, which may transform such reaches into plane-bed channels with few, if any, pools. In contrast, wood loss in forced pool-riffle streams with gradients <0.01 may increase pool spacing, but a pool-riffle morphology will likely be maintained. Other obstructions such as resistant bank projections, however, may compensate for loss of in-channel LWD and maintain pool spacing [*Smith et al.*, 1993].

Pools provide important habitat for fish and other lotic organisms [e.g., *Bisson et al.*, 1982; *Sullivan et al.*, 1987]. As such, channel response to altered wood loading is an important aspect of land management efforts concerned with maintenance and restoration of aquatic habitat. A relatively recent practice in the Pacific Northwest is to leave a riparian buffer strip along channel corridors to maintain aquatic habitat, in part through continued natural recruitment of LWD to channels. Our observation that less than 40% of in-channel LWD dominates pool formation implies that effective riparian zone management must provide a LWD supply that considers the natural inefficiency in recruiting dominant (i.e., pool-forming) LWD. *Richmond* [1994] also finds that only 4–20% of in-channel LWD serves to create pools in small channels in Colorado. While these data imply that on average, natural recruitment of many logs is required to provide a piece situated so as to form a pool, the size and placement of LWD may be engineered to more efficiently catalyze pool formation in channel restoration projects [e.g., *Lisle*, 1986a].

Maintenance and restoration of riverine habitat in the Pacific Northwest are primarily focused on protecting and enhancing salmonid populations. Most salmonids require a diversity of habitat for various life history stages [*Sullivan et al.*, 1987]. Loss of pools likely decreases the variance of channel structure, depth, and velocity, and thus the diversity of habitat available to salmonids. Hence pool loss in managed streams may decrease both the amount and quality of habitat necessary for particular salmonid life history stages. Although our data do not address pool size, we do find that debris loading and pool spacing in channels flowing through previously clear-cut forests essentially lie outside the range of conditions measured for pristine channels. This is significant because it is reasonable to expect a profound biological impact when environmental conditions are altered beyond the range of conditions to which species and communities have adapted [*Ricklefs*, 1979]. While the harvest of streamside forests can in some instances have little immediate impact on pool formation [e.g., *Carlson et al.*, 1990], and may even increase in-channel LWD loading [e.g., *Bryant*, 1980; *Lisle*, 1986b], the number of pools in most low-gradient forest channels will eventually decrease without sustained LWD recruitment. Assuming that natural conditions are desirable for habitat management, Figure 10 could be used to define management objectives regarding pool spacing and LWD frequency in small forest channels of the Pacific Northwest. The foregoing analyses, however, imply that assessment of channel conditions using pool spacing [*Smith and Buffington*, 1995] should consider channel type, the location-specific potential for LWD loading, and availability of other flow obstructions. While such an approach complicates defining desired conditions for land management, it should assist in defining reasonable objectives for aquatic habitat conservation and rehabilitation.

Conclusions

Pool spacing in forest channels of mountain drainage basins is controlled by LWD loading and channel type, slope, and width. The amount of in-channel LWD exerts a systematic influence on pool spacing in pool-riffle, forced pool-riffle and plane-bed morphologies, and LWD also apparently decreases pool spacing in step-pool channels. Mean pool spacing in forest pool-riffle channels is less than expected for free-formed pool-riffle reaches, primarily owing to local flow convergence and bed scour associated with LWD. The traditional concept of a pool-to-pool spacing of 5–7 channel widths likely represents an end-member state for pool-riffle reaches without obstructions. On the basis of both the range of slopes characteristic of forced pool-riffle channels and the observed differences in slope and pool spacing in low debris-loading pool-riffle and plane-bed channels, we propose that channel slope may be a useful indicator of morphologic response to LWD loss in forced pool-riffle channels. Pool spacing may provide a useful means for assessing channel condition in forested mountain drainages if evaluated in relation to the natural potential for LWD loading and channel type, slope, and width.

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