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Woody debris and channel morphology in first- and second-order forested channels in Washington's coast ranges

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[1] While there are conceptual and theoretical reasons to believe small streams behave differently than larger streams, the lack of information on small streams has lead land managers to rely on data from larger streams to guide management decisions. In response to the need for descriptive information on habitat and channel morphology specific to small, non-fish-bearing streams in the Pacific Northwest, morphologies and wood frequencies in 42 first- and second-order forested streams <4 m wide were surveyed. Frequencies and size distributions of woody debris were compared between small streams and larger fish-bearing streams as well as between second-growth and virgin timber streams. Statistical models were developed to explore dominant factors affecting channel morphology and habitat. Findings suggest geomorphological relationships, specifically the role of woody debris in habitat formation, documented for larger streams do not apply to headwater streams. Relatively small wood (diameters between 10 and 40 cm), inorganic material, and organic debris (diameters <10 cm) were major step-forming agents while big woody debris pieces (>40 cm diameter) created <10% of steps. Streams in virgin and managed stands did not differ in relative importance of very large woody debris. Because of low fluvial power, pool habitat was rare. These streams featured mostly step-riffle morphology, not step-pool, indicating insufficient both flow for pool-scour. Stream power and unit stream power were dominant channel shaping factors. *INDEX TERMS:* 1803 Hydrology: Anthropogenic effects; 1815 Hydrology: Erosion and sedimentation; 1824 Hydrology: Geomorphology (1625); 1845 Hydrology: Limnology; *KEYWORDS:* headwaters, large woody debris, geomorphology, small streams

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1. Introduction

[2] Basic information is needed about the geomorphology and ecology of small headwater streams to guide management of these streams and to inform the development of geomorphological theory encompassing these streams. For the purposes of this paper, small headwater streams are defined as first- and second-order streams (determined in almost all cases by field inspection) with active channel widths <4 m (active channel widths of 41 of the 42 streams analyzed are <3 m). Because of the lack of scientific information on small headwater streams, management decisions for these streams have been based on information gathered in larger fish-bearing streams, yet basic differences in the type and routing of physical inputs to these channels strongly suggests they should not behave similarly. This paper focuses on timbered, non-fish-bearing streams below 1250 m elevation, because these are the streams where management information is most needed. Nontimbered, higher elevation streams are of less concern because human management is minimal or nonexistent. This study has four purposes: to compare small stream wood frequencies to larger streams; to provide descriptive information on small streams; to evaluate effects of large woody debris (LWD) frequency and size on small stream morphology; and to explore relationships between landscape variables and channel habitat variables in small streams.

2. Role of Woody Debris in Fish-Bearing Pacific Northwest Streams

[3] There is a large and growing body of literature on the role of wood in streams, but nearly all of this literature is based on fish-bearing streams with channel widths >4 m. Consequently, land managers have assumed the role of wood in small streams is equivalent to its role in larger streams. A summary of the literature on LWD in larger PNW streams is provided to illustrate the relationships assumed to hold in small streams and to set a baseline for evaluating the function of woody debris in small streams. The literature review focuses on data from fish-bearing PNW headwater streams most similar to the small streams studied in this project.

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[4] Studies of forested channels between 4 and 30 m in width have shown that large woody debris (usually defined as wood larger than 10 cm diameter and 1 m length) (1) increases frequency and volume of pools, (2) traps organic material and slowly releases nutrients to the stream, (3) provides substrate and food for aquatic invertebrates, (4) traps sediments, and (5) increases hydraulic roughness and habitat complexity (in the sense of *Independent Multidisciplinary Science Team* [1999] and *Bilby and Bisson* [1998]). Furthermore, land managers assume that larger wood provides better function than smaller wood because of positive relationships between residual pool depth and woody debris size shown for alluvial pool-riffle streams [*Bilby and Ward*, 1989; *Keller and Swanson*, 1979]. Through fluvial and catastrophic transport, smaller streams serve as sources of wood to larger channels.

[5] Wood is an important determinant of habitat structure. An increase in LWD can be associated with an increase in pool formation [*Montgomery et al.*, 1995]. *Andrus et al.* [1988] discovered that nearly three-fourths of all pools present in a small Oregon watershed were associated with LWD or organic debris dams. Such pools are formed during high discharge flood events capable of scouring holes or reorienting LWD [*Whittaker and Jaeggi*, 1982]. Both *Bilby and Ward* [1989] and *Keller and Swanson* [1979] found pool volumes were positively correlated to the size of the pool-forming LWD element. Pool frequency and gravel size distributions are a function of LWD abundance, channel slope, and channel size, and pool frequency is more sensitive to LWD abundance in moderate slope channels than in low slope channels [*Beechie and Sibley*, 1997; *Keller and Tally*, 1979; *Montgomery et al.*, 1995].

[6] LWD plays important roles in shaping aquatic communities and routing sediment [*Swanson and Lienkaemper*, 1978]. *Scarlett and Cederholm* [1996] found that cutthroat trout populations in the state of Washington were greatly diminished after debris flows scoured sample streams. Wood steps that create pools are eliminated during these mass wasting events. Removal of woody debris has been related to a decrease in fish and invertebrate density and diversity [*Piegay and Gurnell*, 1997] because resultant channelization decreased viable habitats [*Keller and Swanson*, 1979]. The channelization process leads to rapid removal of stored sediment and exposes bedrock [*Montgomery et al.*, 1996; *Keller and Swanson*, 1979]. In steep headwater channels, LWD retains colluvial material in the valley floor that would otherwise be occupied by bedrock [*Montgomery et al.*, 1996; *Heede*, 1972]. LWD and colluvial material are episodically flushed from these channels by debris flows [*Benda and Dunne*, 1987]. *Marston* [1982] indicated that sediment stored behind LWD in third to fifth-order streams is 123% of the total annual sediment yield. The removal of LWD from headwater streams can temporarily increase basin sediment yield by an order of magnitude which affects downstream river geomorphology by increasing deposition in sink sites [*Piegay and Gurnell*, 1997; *Smith et al.*, 1993].

[7] Large woody debris creates areas of low energy on smaller streams that slow the transport of sediment and organic material [*Bilby and Ward*, 1989; *Marston*, 1982; *Heede*, 1972; *Montgomery et al.*, 1996]. LWD aligned perpendicular to the channel create steps where, in smaller streams, waterfalls form, and these sites can account for thirty to eighty percent of the overall channel drop [*Keller and Swanson*, 1979]. The area occupied by steps is low compared to overall reach length; however, much of the stream's energy is dissipated where steps are located [*Keller and Swanson*, 1979; *Abrahams et al.*, 1995]. Stream energy is also reduced as LWD increases channel roughness [*Smith et al*, 1993], and the depletion of energy reduces bed and bank erosion potential [*Froehlich*, 1973].

[8] Steps and scour pools in steep streams dissipate fluvial kinetic energy and thereby reduce the transport capacity. *Abrahams et al.* [1995] postulated that "step pool streams evolve toward an arrangement of steps that maximizes resistance to flow," reasoning that such an arrangement of steps would constitute a stable equilibrium morphology. Using laboratory flumes, they discovered that flow resistance was maximized when the ratio of the average step steepness (H/L) to the average channel slope, s, lies between one and two. They surveyed eighteen Adirondack mountain streams with step pool morphology and found the ratio of H/L/s to range from 1.18 to 1.85, indicating that these channels indeed featured a morphology that maximized flow resistance. Since Abraham et al.'s field surveys only included streams with step-pool morphology, it is unclear how steep step-pool streams differ from other steep streams in terms of fluvial resistance and whether sample bias influenced the field results.

[9] Some researchers have indicated that densities of LWD and organic debris dams decrease as the order of a stream increases [*Bilby and Ward*, 1989, 1991; *Swanson and Lienkaemper*, 1978]. Larger streams have higher discharges capable of transporting LWD, whereas smaller streams may not reach flows capable of transporting this material [*Piegay and Gurnell*, 1997]. The distribution of LWD and organic debris dams in smaller streams is often independent of stream hydraulics [*Heede*, 1972], and thus results in a randomly distributed pattern [*Froehlich*, 1973; *Swanson and Lienkaemper*, 1978]. Some of the larger first and second-order streams may be capable of transporting the smallest of LWD pieces; however, it is likely that these pieces will be retained in organic debris dams until a debris flow evacuates the channel and sweeps all woody debris downstream.

3. Conceptual Framework for Assessing Small Stream Morphology

[10] The mechanical roles of woody debris in streams can be broadly categorized as hydraulic alteration, which will affect both flow and sediment routing, and habitat formation, which results from the scour and sediment deposition caused by hydraulic alteration. Wood transport is a function of piece size relative to channel width and to the amount of flow in a channel. Small streams have little ability to move wood, so relatively small woody debris can form jams, and very large wood tends to move the channel so that it flows around the wood or it buries the valley in accumulated sediment and the stream flows subsurface. Because of the limited fluvial power of small streams and because of colluvial inputs of large cobbles and boulders, the role of large woody debris in creating habitat complexity and shaping channel structure in small streams should be much less than in larger streams which have the power to flush

smaller wood or which have relatively smaller frequencies of large inorganic structures.

[11] Export of gravel and larger particles from small steep streams is driven by rare catastrophic events (debris flows) and not frequent fluvial events. After debris flows, streams are usually scoured to bedrock, and the stream goes through a process of recovering a colluvial/alluvial valley floor. This process may take 60-100 years before the stream appears “recovered”, and big woody debris (>40 cm diameter) may be necessary to help store sediments in the valley [*May and Greswell*, 2001]. Recurrence intervals of scour events in first-order debris flow prone streams are around 600 years [*Benda and Dunne*, 1997] so there are long between-disturbance periods where channel and valley structure is relatively stable [*May and Greswell*, 2001]. During these periods of stability, export of wood and coarse sediments from small headwater streams should be minimal.

[12] Ideas about what is “quality” habitat in small streams cannot borrow from knowledge of fish-bearing streams, but should be driven by habitat needs and preferences of amphibians and macroinvertebrates which comprise top trophic levels in headwater streams. Structural habitat “quality” in PNW non-fish-bearing streams is best evaluated against the known habitat preferences of stream-dwelling amphibians such as the Tailed frog (Ascaphus *truei*), Pacific Giant salamander (*Dicamptodon tenebrosus*), and the Torrent salamander (*Rhyacotriton* spp.). These creatures are most prolific in streams with large amounts of interstitial spaces (steps and clean coarse sediment) and cool water temperatures. Step habitat contributes to low water temperatures due to hyporheic exchange that occurs in steps. Therefore small non-fish-bearing streams should be managed to maximize steps, minimize fine sediments, and maintain cool water temperatures.

[13] Since typical periods of small stream channel stability are long enough to grow several rotations of commercial timber, timber managers need information on basic habitat relationships in these streams to infer how management might affect habitat and to guide road, harvest, and buffer policies. Timber management activities affect the structural habitat quality in four principal ways: routing road runoff to streams [e.g., *Reid and Dunne*, 1984; *Megahan et al.*, 1983; *Swift*, 1984], altering wood loading through harvest practices, altering long term wood loading by changing riparian stands [e.g., *Ralph et al.*, 1994], and increasing the probability of landslides from hillslopes and of debris flows in channels [e.g., *Swanson and Dyrness*, 1975; *Ziemer and Swanston*, 1977; *Ziemer*, 1981]. Road runoff delivered to these streams increases fine sediment loads and thus the percentage of fine sediments. Harvest practices and riparian buffer policies can alter the timing, type, and amounts of woody debris recruitment to streams [e.g., *Jackson et al.*, 2001]. Reducing root strength and evapotranspiration on hillsides after harvest increases the incidence of landslides which deliver sediment and wood to channels. The data and analysis presented in this paper are intended to provide a better understanding of habitat structure in small streams. The analysis will explore the relative role of wood in creating desired habitat in non-fish-bearing streams, not on the role wood plays in long-term valley aggradation after disturbance. Habitat and woody debris characteristics are compared between managed and unmanaged streams to yield inferences on management effects on small streams.

4. Study Design and Methods

[14] This study uses two roughly comparable sets of data collected on small streams in the Coast Ranges of Washington State, mostly in landscapes managed for commercial timber production. Each of the two sets contains some streams located in virgin timber. Some of these virgin timber stands have not experienced large-scale disturbance in over 250 years and some experienced a large windstorm in 1921 and are described locally as “21 Blow”. The 21 Blow stands feature mixed canopies with some very large trees that survived the storm and many 80-year old trees. Streams in the 21 Blow stands would have received large inputs of woody debris in the 1921 storm. The 1921 windstorm affected large areas of the west slope of the Olympic lowlands and foothills, and “21 Blow” stands comprise a large portion of virgin timber in this area. The virgin timber streams from both data sets comprise a third data set for comparison of managed versus old growth streams. There are a total of 42 streams, 31 in managed landscapes and 11 in virgin timber, in the two data sets (Figure 1). All of the streams have bank-full channel widths of <4 m (all but one less than 3 m). Channel gradients range from five to 32% (average 18%), and basin areas range from 0.011 to 0.458 km^2 (average 0.118 km^2). All of the streams are located either in the Willapa Hills in southwestern Washington, in the western and northern foothills of the Olympic Mountains, or on the southern margins of Grays Harbor. The lead author helped plan the surveys on all 42 streams. Most of the channel measurements in the two data sets are identical, but some measurements differed between the two sets, and this affects how the data were treated. Basic descriptive data on all 42 streams are presented in Appendix A.

[15] The first data set includes 23 streams that were monitored to provide baseline data for a study evaluating the effects of logging on the morphology and ecology of small streams. Fifteen of these 23 streams were located in second-growth western hemlock approximately 50 to 65 years in age. The remaining eight streams were located in old-growth timber. This data set is referred to as the IHSR data (for integrated headwater stream riparian study). The second data set includes nineteen streams that were surveyed by Rayonier Northwest Forest Resources and Merrill and Ring Timber Company to provide basic data on non-fish-bearing streams in their managed landscapes. Sixteen of these streams were located in second growth varying in age from young plantations to sixty-year old trees, and the other three streams were located in virgin timber. This second data set is referred to as the RMR data (for Rayonier and Merrill and Ring).

[16] Methods for determining particle size distributions varied between the IHSR and RMR data sets. In the IHSR streams, zigzag pebble counts (N = 200) [*Bevenger and King*, 1995] were used to compare reach scale differences in surface particle size distributions, while surface particle size distributions in the RMR streams were determined from Wolman pebble counts conducted on five separate riffles

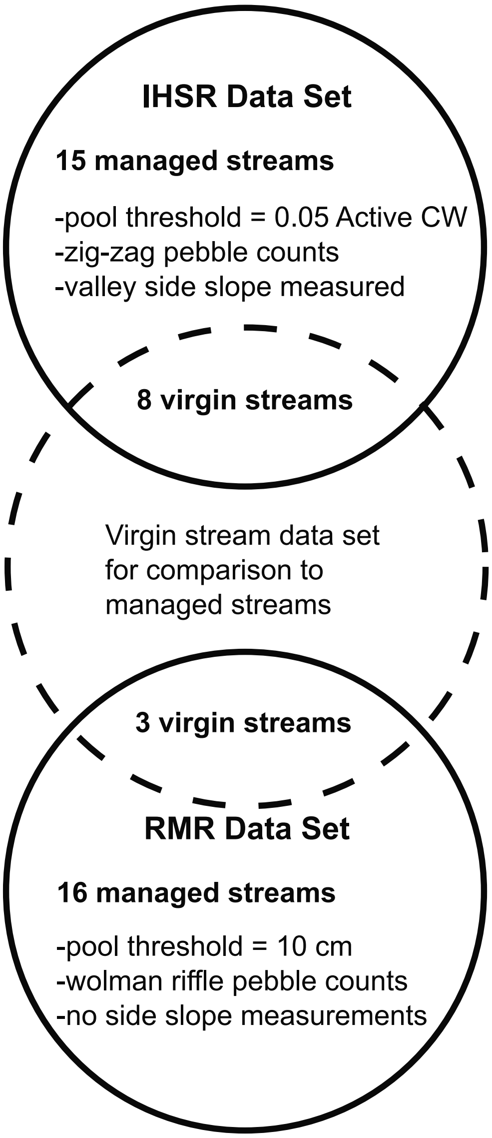


Figure 1. Venn diagram illustrating the relationship of the sources of data used in the analysis and the differences in data collection methods.

(N = 50 in each riffle). Valley side slopes were measured in the IHSR streams, but not in the RMR streams.

4.1. Channel Survey Methods

[17] A reach of each stream was surveyed to determine overall change in elevation, reach gradient, overall length, individual habitat unit drop, individual habitat unit length, residual depth for pool habitat, dominant and subdominant particle class in each habitat unit, bank-full width, amount of functional LWD, amount of nonfunctional LWD, and substrate characteristics, including fine organic debris and small wood. Functional LWD was any piece that contributed to a step or jam, caused scour, trapped or sorted sediment, or protected the bank from erosion. LWD pieces within the bank-full channel that did not serve any of the above functions were classified as nonfunctional. The length of the reach surveyed was approximately equal to twenty times its channel width, with a minimum survey each length of 20 m. Habitat units were classified as one of the following: riffle, step, pool, bedrock cascade, subsurface (where the channel flows in a tunnel below a vegetated ground surface), and run. Steps were subdivided into LWD steps (keyed by a piece of LWD), organic debris dams (all wood less than 10 cm diameter), inorganic steps (composed of boulders and cobbles), and mixed jams (keyed by inorganic material but including LWD).

[18] Because relatively small wood functions well to alter hydraulics and habitat in these small streams, our definition of LWD was more liberal than has been used in most LWD literature. A minimum diameter of 10 cm and a minimum length of 50 cm (as opposed to 1 or 2 m length used in most studies) were defined for LWD. Woody debris was classified by diameter and functionality. Although the functionality of woody debris is considered to increase, or at least change, with wood size, there have been no defined terms to distinguish between size classes of wood. For the purposes of this paper, the term big wood applies to 40–80 cm diameter debris, and the term very large wood applies to wood larger than 80 cm diameter.

[19] The accepted definition of a pool in Pacific Northwest streams surveys requires a minimum residual pool depth of 10 cm [*Washington Forest Practices Board*, 1996]. This definition is based upon habitat requirements for salmonids and was used in the habitat surveys for the 19 Rayonier streams analyzed in this study. In non-fish-bearing headwater streams, home to amphibians and macroinvertebrates, this definition is probably too restrictive. The IHSR stream surveys used a more liberal (and also more subjective) definition of a pool. At the beginning of the survey, average active width of the channel from ordinary high water mark to ordinary high water mark was estimated, and the minimum criteria for residual pool depth was set at 5% of the estimated active channel width, or 10 cm, whichever was less.

[20] Habitat and wood frequency was reported in terms of number of units per length of stream equivalent to the channel's width. For example, a 10 m length of a 2 m wide channel encompasses five channel widths, and if there are two pools in this segment, pool frequency is 0.2 pools/cw. In this example, the metric has dimensions of pools. In streams of this size, most habitat units span the entire channel, and the scale of habitat units is on the order of the stream width. Bigger channels tend to have longer habitat units, so habitat frequency expressed as number per meter necessarily decreases as channel width increases. Expressing habitat frequency in terms of a variable length unit equal to each channel's width allows direct comparison of frequencies between channels of different size. Woody debris was also quantified in the same way because the wood data was analyzed primarily in terms of its role in habitat formation. The "correct" reporting of woody debris frequency depends on the analysis. For example, LWD/m^2 is appropriate for assessing macroinvertebrate density relationships, and LWD/m is appropriate for conducting wood budgets.

[21] The drainage area for each stream was determined from USGS 1:24,000 scale maps. Mean annual flow was estimated using Weather Bureau isopluvial maps and assuming a uniform annual evapotranspiration of twenty inches. A stream power index was calculated as the mean annual flow multiplied by the field-measured reach-averaged channel gradient, and a unit stream power index was

Table 1. Summary and Definition of Variables Used in the Statistical Analysis

Variable	Definition
%fines$_{zz}$	% of particles less than or equal to 2mm dia. based on zig-zag pebble count
%fines$_{Wo}$	% of particles less than or equal to 2mm dia. based on Wolman pebble count
D50$_{zz}$	median particle size (mm) based on zig-zag pebble count
D50$_{Wo}$	median particle size (mm) based on Wolman pebble count
%BR$_{zz}$	% of channel bottom composed of exposed bedrock based on zig-zag count
Cw	bankfull channel width (m)
Pools/cw	pool frequency, pools per channel length expressed in channel widths
% pools	% of channel length composed of pool habitat units
TS/cw	total step frequency, steps per channel length expressed in channel widths
LWDS/cw	LWD step frequency, LWD steps per channel length expressed in channel widths
LWDS/TS	ratio of LWD steps to total steps
ODD/cw	organic debris dam frequency, dams per channel length expressed in channel widths
FLWD/cw	functional LWD frequency, pieces per channel length expressed in channel widths
TLWD/cw	total LWD frequency, pieces per channel length expressed in channel widths
Sideslope	average valley side slope (%)
% drop steps	ratio of total drop in steps to the total channel drop, expressed as a percentage
LWDS%drop	ratio of total drop in LWD steps to the total channel drop, expressed as a percentage
Power	stream power index, defined as (MAF x gradient). This has units of liters/s
unit power	unit stream power index, defined as (MAF x gradient / cw). This has units of liters/s/m
Runoff	estimated average rainfall minus estimated evapotranspiration (m)
DA	drainage area, km^2
MAF	estimated mean annual flow (liters/second)
Gradient	channel gradient (%)

calculated as stream power index divided by channel width. These indices are equivalent to stream power and unit stream power divided by the specific weight of water.

4.2. Statistical Analysis

[22] These streams are important habitat for stream-dwelling and riparian-associated amphibians including *Dicamptodon* spp., *Rhyacotriton* spp., *Ascaphus truei*, *Plethodonvehiculum*, and *Plethodon vandykei*, and obviously these streams support aquatic macroinvertebrate communities. Based on Pacific Northwest amphibian literature and basic stream ecology concepts, the following habitat and geomorphic variables were deemed of ecological interest: percentage of fines (<2 mm), median particle diameter, percentage of bedrock exposed in channel, channel width, pool frequency, percent pool area, total step frequency, LWD step frequency, and percent of channel drop in steps. Variables used in the statistical analysis, and their definitions, are summarized in Table 1.

[23] The relative importance of different factors influencing these habitat variables was explored using forward stepwise linear regression (SigmaStat). For each variable of interest, a set of predictive channel or landscape variables were hypothesized and forward stepwise regression was used to select the most important explanatory variables. In all cases, F to enter was 4.00 and F to remove was 3.90. All accepted p values were less than 0.055. If two or more variables known to be structurally auto-correlated entered the regression, the regression was repeated with each of the auto-correlated variables individually, and the best resulting regression was chosen. Because of the large number of variables in the analysis and because of known collinearity between "independent" variables, no attempt was made to transform variables for better linear regression. Fitting of nonlinear relationships was done on a case-by-case basis after linear model selection. Any regression with an adjusted R^2 less than 0.4 was rejected. In some cases, relatively strong relationships yielded poor R^2 values because the relationship was not linear. Because streams were not controlled for geology, topography, time since last disturbance, or climate, geomorphic relationships in these channels should exhibit high variability, and high R^2 values were not expected for regression relationships.

5. Results

5.1. Descriptive Channel Data

5.1.1. Large Woody Debris

[24] The frequency of total large woody debris (functional and nonfunctional) in these streams averaged 1.06 pieces/cw or 0.62 pieces/m, but was highly variable with a standard deviation of 0.95 pieces/cw or 0.36 pieces/m. Fifty-three percent of the total LWD in these channels was functional, but this number is almost meaningless as an average since the percentage of functional LWD in each stream was highly variable (median 60%; standard deviation 23%; maximum 100%; minimum 11%).

[25] LWD frequencies were plotted against channel width along with other published data from PNW fish-bearing streams to see how small stream LWD frequencies compared to those in larger streams (Figure 2). *Martin* [2001] showed that valley cross section was an important control on wood loading, and only his floodplain and mixed valley data were used, since his confined valley segments had very low wood frequencies. When analyzed as pieces/m, total wood frequencies in these small streams are higher than for PNW fish-bearing streams between 4 and 40 m wide (average of 0.62 pieces/m versus 0.34 pieces/m; significance determined by *t* test $p < 0.001$). For several reasons, such comparisons must be made with caution. Because relatively small wood was observed to create habitat in the small non-fish-bearing streams, our definition of LWD used a minimum size of 0.1 m diameter and 0.5 m length, while the other studies used either 1.5 m or 2.0 m minimum length. Therefore, this comparison can be used to compare relative availability of wood for habitat creation, but it cannot be used for wood budgets or wood-routing models,

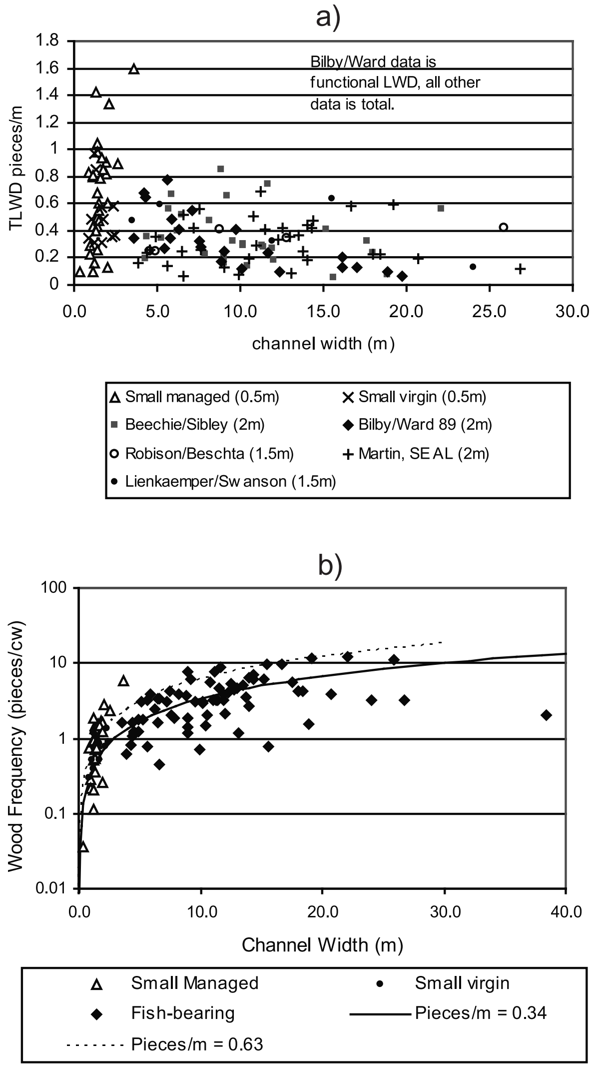


Figure 2. Relationship between LWD frequency and channel width determined in this study and some similar studies. Graphs include data from all 42 streams surveyed in this study along with data from *Beechie and Sibley* [1997], *Bilby and Ward* [1989], *Robison and Beschta* [1990], *Martin* [2001], and *Lienkaemper and Swanson* [1987]. Numbers in parentheses in the legend refer to the minimum wood length used in each study. (a) LWD frequency expressed as pieces per meter. In small channels, the longitudinal frequency of LWD is highly variable but shows no discernible trend with channel width. Small stream LWD frequencies are greater than larger stream frequencies, but this is probably an artifact of different definitions based on differing functionality. Only the *Bilby and Ward* [1989] data show a negative relationship with channel size, reflecting the fluvial sorting of functional wood relative to total wood. (b) LWD frequency calculated as total pieces per channel length expressed in channel widths without the *Bilby and Ward* [1989] data which reports functional rather than total wood. When expressed as pieces/cw, total LWD frequency is nearly constant in channels >5 m in width, but LWD frequency is much lower in small channels. In small channels, pieces/cw increases linearly with channel width due to auto-correlation between this metric and the channel width.

because many of the pieces measured in the small streams would not serve as LWD in larger streams. Using consistent minimum size definitions, Liquori is finding much lower total wood frequencies in small non-fish-bearing streams [*Liquori*, 2001]. According to *Benda et al.* [2002], the stand-averaged fraction of fallen trees that become in-channel woody debris drops off with increasing channel width, other things being equal.

[26] Frequencies of LWD in these small streams were generally lower than hypothesized by *Keller and Swanson* [1979], and also lower than would be expected by extrapolating *Bilby and Ward*'s [1989] relationship between wood frequency and channel width. Figure 2a shows that only Bilby and Ward's data show a negative relationship with channel size. This is probably due to the fact that Bilby and Ward counted only functional wood, whereas the other data sets present total wood. Since larger channels need larger wood to store sediment, scour pools, and create habitat, the negative relationship with channel size shown by Bilby and Ward's functional wood data probably reflects fluvial sorting and flushing of smaller wood from larger channels and the fact that smaller wood is less likely to be functional in large channels. The proportions of transportable and mobile wood increases with channel width [*Martin and Benda*, 2001]. The other data sets of frequency of total wood per meter show no trends with respect to channel width.

[27] When evaluating pieces/cw, the average total LWD frequency in our small streams (1.06 pieces/cw) was less than in the compilation of PNW fish-bearing stream total wood frequency (3.43 pieces/cw), reflecting the auto-correlation between this metric and channel width (Figure 2b). Since pieces/m is invariant with channel width across the small stream data set, the pieces/cw metric necessarily increases as channel width increases. Therefore, if LWD were the dominant driver of habitat complexity in small streams, greater wood loading in pieces/m would be required to generate the same relative habitat unit frequency in small streams as in fish-bearing streams.

[28] The high variability in LWD was not surprising given that the stands varied in side slope and management status and history, and the channels varied in gradient and flow. Although no attempt was made to estimate time since last disturbance, less than five of these streams appear to have experienced a debris flow in the last century. Only a few of these streams were set in inner gorges, and there was evidence of recent landslides and debris flows only in a small number of these streams. Bank erosion was inconsequential due to the low fluvial power of these streams. Most wood recruitment therefore appeared to come from limb senescence, blow down, and chronic mortality.

[29] Total LWD frequency in pieces/m was positively related to valley side slope in the 23 IHSR streams (Figure 3). It appears that steeper valley side slopes increase LWD recruitment distances. This observation is consistent with *Fetherston et al.* [1995] and *Froehlich* [1973]. Apparently, broken limbs and trees are more likely to fall downslope and to bounce or slide toward the stream when the side slopes are steeper. Also, landslide contributions are likely to be greater as side slopes increase beyond 45%.

5.1.2. Step Types and Frequencies

[30] Steps in these channels were formed by large woody debris (>10 cm in diameter), organic debris dams (no key

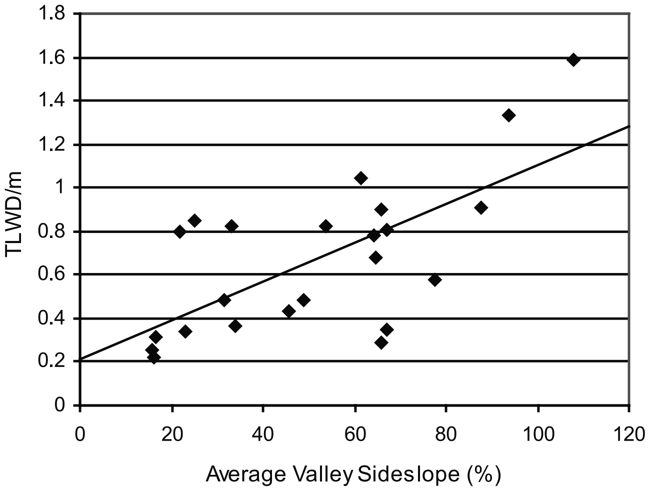


Figure 3. Relationship between total LWD frequency (pieces/m) and average valley side slope (%) in the 23 IHSR streams. The regression $y = 0.21 + 0.0089x$ was fitted with an R^2 value of 0.45 ($p < 0.001$). Data indicate that increasing valley side slopes increases the recruitment area for woody debris.

piece greater than 10 cm), mixed jams (cobble or boulders are the dominant step-forming agent, but wood or organic debris significantly adds to the jam), and by inorganic agents (cobbles and boulders). The distribution of step forming agents in all 42 streams is shown in Figure 4a. Fifty-five percent of the steps in these streams are formed by something other than large woody debris (LWD). Organic debris dams (all wood less than 10 cm diameter) comprised seventeen percent of steps, and organic debris was an important contributor to many steps. *Chesney* [2000] also found that wood less than 10 cm diameter was an important contributor to small stream morphology in eastern Cascade streams.

5.1.3. Comparisons of Virgin and Managed Streams

[31] The distributions of step types and wood frequencies varied little between the virgin timber and managed streams. The percentage of wood steps was actually lower and the percentage of inorganic steps was greater in the eleven virgin timber streams (Figure 4b). Average total LWD frequency in 11 virgin timber streams was 0.80 pieces/cw or 0.51 pieces/m as compared to 1.15 pieces/cw or 0.67 pieces/m in managed streams, although this difference was not statistically significant. As shown in Figure 5, size distributions of woody debris in the virgin timber and managed streams were not different.

5.1.4. Relationships Between Wood Size and Habitat Formation

[32] Eighty-one percent of functional LWD in these channels had a diameter between 10 and 40 cm (Figure 6). As discussed above, a principal effect of woody debris in these streams is to create steps. Since only 45% of steps are formed by LWD, and since only nineteen percent of the functional LWD has a diameter exceeding 40 cm, it can be inferred that about 8.6% of steps should be created by wood larger than 40 cm in diameter. The actual percentage of steps created by wood larger than 40 cm in diameter was precisely 8.6%. The data on functional woody debris and step-forming agents strongly suggest that relatively small woody debris effectively functions in these streams to form steps and trap sediments. Larger wood is likely more effective in storing valley sediments [*May and Griswell*, 2001], but this role was not evaluated in this project. Comparing the distributions of functional and nonfunctional large woody debris (Figure 6) shows little relationship between the fraction of functional wood and the size class. The histograms suggest that small wood is not preferentially flushed from these streams.

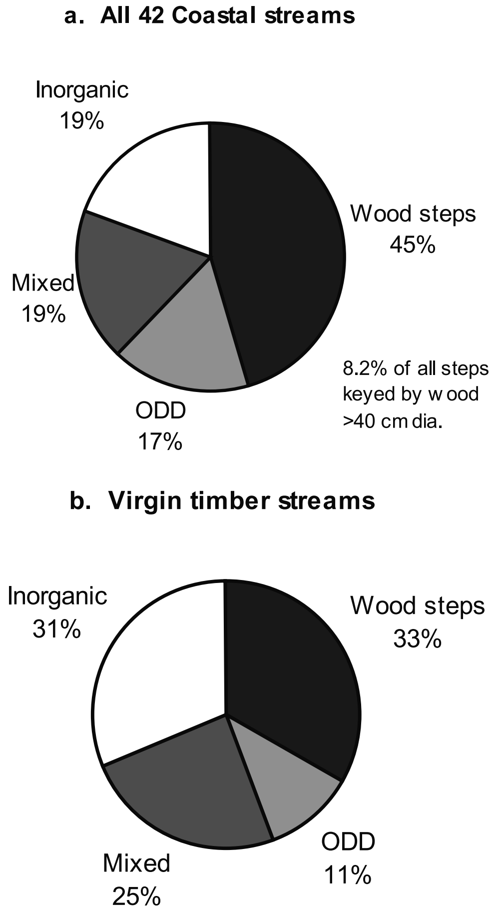


Figure 4. Distribution of steps by type. (a) Data from all 42 streams (31 managed and 11 old growth). (b) Data from only the 11 virgin timber streams.

[33] In the 23 IHSR streams, there were 12 subsurface habitat units where woody debris in excess of 40 cm diameter had stabilized so much sediment on the valley

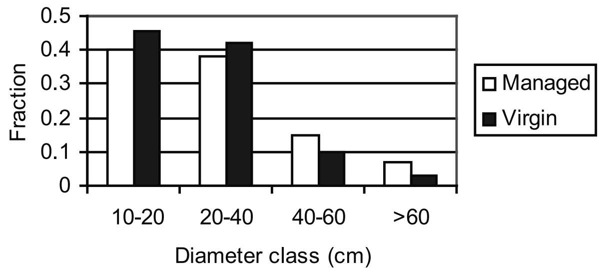
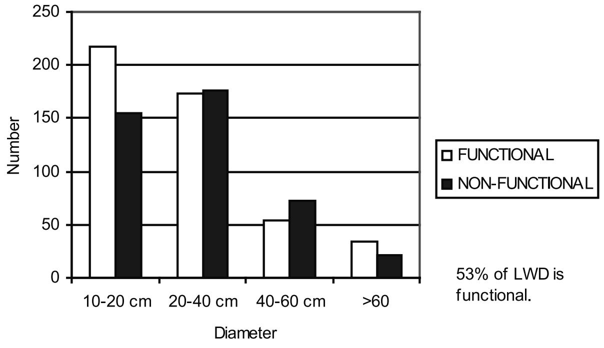


Figure 5. Histograms comparing total LWD by diameter class between streams draining managed forests (N = 31 streams) and streams draining virgin timber (N = 11).



53% of LWD is functional.

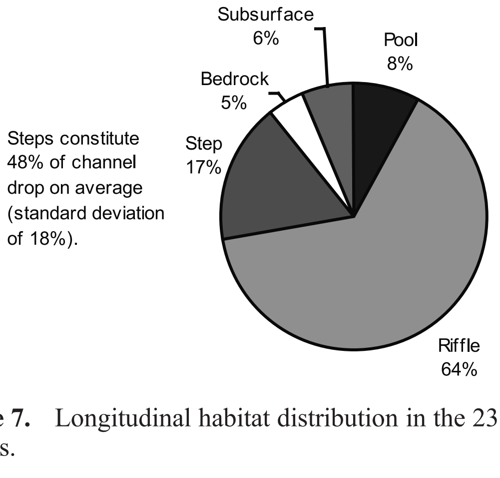
Figure 6. Histogram of functional and nonfunctional LWD by diameter class in all 42 streams.

floor that the channel flowed essentially in tunnels beneath a vegetated ground surface. Of these 12 subsurface habitat units, four were keyed by wood 40–59 cm diameter, four were keyed by wood 60–79 cm diameter, and four were keyed by wood larger than 80 cm diameter. The biological value of these subsurface habitat units is unknown because we were physically unable to survey these channel units for amphibians or macroinvertebrates.

5.1.5. Gross Reach-Scale Morphology

[34] Most of these streams featured what we called step-riffle morphology. While steps constituted 17% of channel length and 48% of channel drop on average, plunge pools were rare because these small streams lacked sufficient fluvial power to carve pools. Therefore, these streams do not fit into the Montgomery-Buffington classification system for mountain streams [*Montgomery and Buffington*, 1997]. With the 10 cm residual pool depth threshold used in the 19 RMR streams, no pools were identified in 18 of these streams. With the more liberal pool definition used for the 23 IHSR streams, pools constituted about 8% of the channel length on average. The cumulative distribution of habitat types over the 23 IHSR streams is illustrated in Figure 7.

[35] The ratio of average step steepness (H/L) to channel slope, s, in 22 of the IHSR streams was analyzed, and only 12 streams featured H/L/s ratios in the range of 1 to 2, which is the range *Abrahams et al.* [1991] found to maximize flow resistance (Figure 8). H/L/s was less than one in 9 of the 22 streams and was 3.47 in another. Even among the 12 streams within the range of 1 to 2, five of the streams featured H/L/s ratios less than 1.18, which was the lowest ratio found in Abraham et al.'s 18 step-pool streams. This discrepancy with Abraham's findings cannot be explained by differences in channel gradients in the data sets. This illustrates that these streams lack sufficient flow to carve scour pools and create step-pool morphology.



Steps constitute 48% of channel drop on average (standard deviation of 18%).

Figure 7. Longitudinal habitat distribution in the 23 IHSR streams.

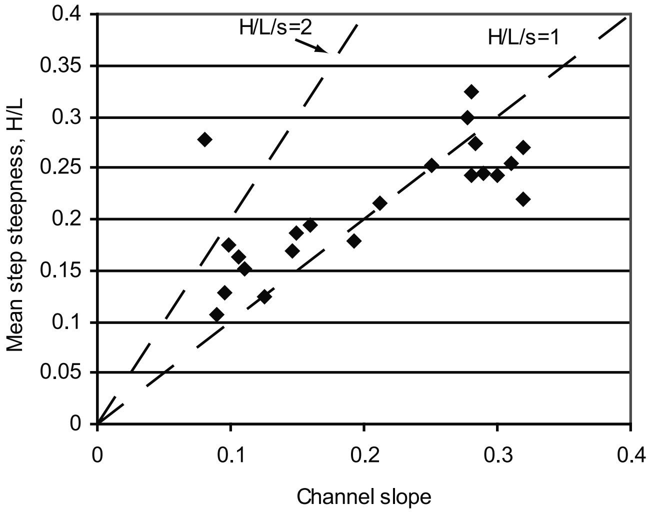


Figure 8. Relationship of average step steepness, H/L, to channel gradient *s* in the 23 IHSR streams. According to *Abrahams et al.* [1995], step-pool streams should fall within the dashed lines. Although the IHSR streams featured channel gradients with which step-pool streams are usually associated, many of the streams lacked sufficient fluvial power to carve pools. Typical morphologies were best described as step-riffle. Therefore many of these streams do not fall within Abrahams et al.'s prediction. Mean step steepness is well correlated with channel slope.

5.2. Regression Results

5.2.1. Particle Size Statistics

[36] The regressions for particle size statistics differed drastically between the zigzag pebble counts and the Wolman pebble counts. Particle size metrics from the zigzag counts were explained by landscape-level variables while metrics from the Wolman counts were explained by the dominance of LWD in creating steps. All regression models are summarized in Table 2.

[37] The percentage of fines determined from zigzag pebble counts (%fines$_{zz}$) was negatively related to total step frequency and the unit stream power index. The R^2 value was low (0.45) but this is mostly due to the nonlinear relationship of %fines$_{zz}$ to unit stream power as shown in Figure 9a. At low unit stream powers, %fines$_{zz}$ in the channel are quite variable, but at high unit stream powers, %fines$_{zz}$ are uniformly low. The same basic relationship holds true for the stream power index in this data set, but there is not a lot of practical difference in these two statistics in this analysis because our data set features little variability in channel width. Actually, it appears that the power index is a better predictor of %fines$_{zz}$ than is the unit power index, but the relationship is more nonlinear (Figure 9b). Because of the obvious shape of the relationship between %fines$_{zz}$ and the power index, an exponential relationship was fitted

Table 2. Summary of Forward Stepwise Linear Regressions

	Coefficient	Variable	p Value	Standard Error
	IHSR Data[a]			
%fines$_{zz}$	+30.394	constant		4.793
	−21.733	TS/cw	0.035	9.623
	−12.579	unit power	0.019	4.918
	N = 23	$R^2 = 0.450$	Adj. $R^2 = 0.395$	Std. Error = 11.067
	variables not included in the model: LWDS/cw, LWDS/TS, ODD/cw, FLWD/cw, TLWD/cw, sideslope, cw, %drop steps, %drop LWD steps, power, runoff, DA, MAF, gradient.			
D50$_{zz}$	+11.779	constant		3.674
	+20.817	power	<0.001	2.294
	N = 23	$R^2 = 0.797$	Adj. $R^2 = 0.787$	Std. Error = 13.258
	variables not included in the model: TS/cw, LWDS/cw, LWDS/TS, ODD/cw, FLWD/cw, TLWD/cw, sideslope, cw, %drop steps, %drop LWD steps, unit power, runoff, DA, MAF, gradient.			
%BR$_{zz}$	−3.858	constant		1.795
	+0.171	sideslope	<0.001	0.0311
	N = 23	$R^2 = 0.589$	Adj. $R^2 = 0.570$	Std. Error = 3.868
	variables not included in the model: TS/cw, LWDS/cw, LWDS/TS, ODD/cw, FLWD/cw, TLWD/cw, cw, %drop steps, %drop LWD steps, power, unit power, runoff, DA, MAF, gradient.			
pools/cw	−0.167	constant		0.0397
	+0.124	cw	<0.001	0.0281
	+0.00278	LWDS%drop	0.027	5.759
	+0.816	DA	<0.001	0.174
	N = 23	$R^2 = 0.853$	Adj. $R^2 = 0.829$	Std. Error = 0.0687
	variables not included in the model: TS/cw, LWDS/cw, LWDS/TS, ODD/cw, FLWD/cw, TLWD/cw, sideslope, %drop steps, power, unit power, runoff, MAF, gradient.			
%pools	−4.484	constant		2.412
	+1.920	TLWD/cw	0.025	0.792
	+0.016	%dropsteps	0.051	0.0512
	+4.765	power	<0.001	0.768
	N = 23	$R^2 = 0.792$	Adj. $R^2 = 0.759$	Std. Error = 4.206
	variables not included in the model: TS/cw, LWDS/cw, LWDS/TS, ODD/cw, FLWD/cw, sideslope, cw, %drop LWD steps, unit power, runoff, DA, MAF, gradient.			
	RMR Data[b]			
%fines$_{Wo}$	+1.296	constant		2.827
	+57.228	LWDS/TS	<0.001	9.808
	−0.414	LWDS%drop	<0.001	0.102
	N = 18	$R^2 = 0.713$	Adj. $R^2 = 0.675$	Std. Error = 5.473
	variables not included in model: TS/cw, LWDS/cw, ODD/cw, FLWD/cw, TLWD/cw, cw, %drop steps, power, unit power, DA, MAF, gradient.			
D50$_{Wo}$	+21.9114	constant		3.451
	−25.555	LWDS/TS	<0.001	5.384
	−48.834	ODD/cw	<0.001	8.649
	+4.452	cw	0.061	2.173
	+0.149	LWDS%drop	0.022	0.0572
	N = 18	$R^2 = 0.824$	Adj. $R^2 = 0.770$	Std. Error = 3.001
	variables not included in model: TS/cw, LWDS/cw, FLWD/cw, TLWD/cw, %drop steps, power, unit power, DA, MAF, gradient.			
	Merged Data[c]			
cw	+1.169	constant		0.155
	+1.079	TS/cw	<0.001	0.292
	+0.435	FLWD/cw	<0.001	0.0698
	−0.00440	%dropsteps	0.003	0.00138
	+1.480	DA	0.001	0.429
	−0.0139	gradient	0.033	0.000627
	N = 42	$R^2 = 0.792$	Adj. $R^2 = 0.764$	Std. Error = 0.764
	variables not included in model: LWDS/cw, LWDS/TS, ODD/cw, TLWD/cw, LWD step %drop, power, unit power, MAF.			
TS/cw	−0.063	constant		0.0827
	+0.240	cw	<0.001	0.0444
	+0.00639	gradient	0.040	0.00300
	N = 42	$R^2 = 0.507$	Adj. $R^2 = 0.481$	Std. Error = 0.156
	variables not included in model: FLWD/cw, TLWD/cw, power, unit power, DA, MAF.			

[a] Particle size distributions based on zig-zag pebble counts; 23 streams.

[b] Particle size distributions based on modified Wolman counts in five riffles; no pools due to strict pool definition; 19 streams.

[c] Sideslope and particle size metrics not used in regressions; 42 streams.

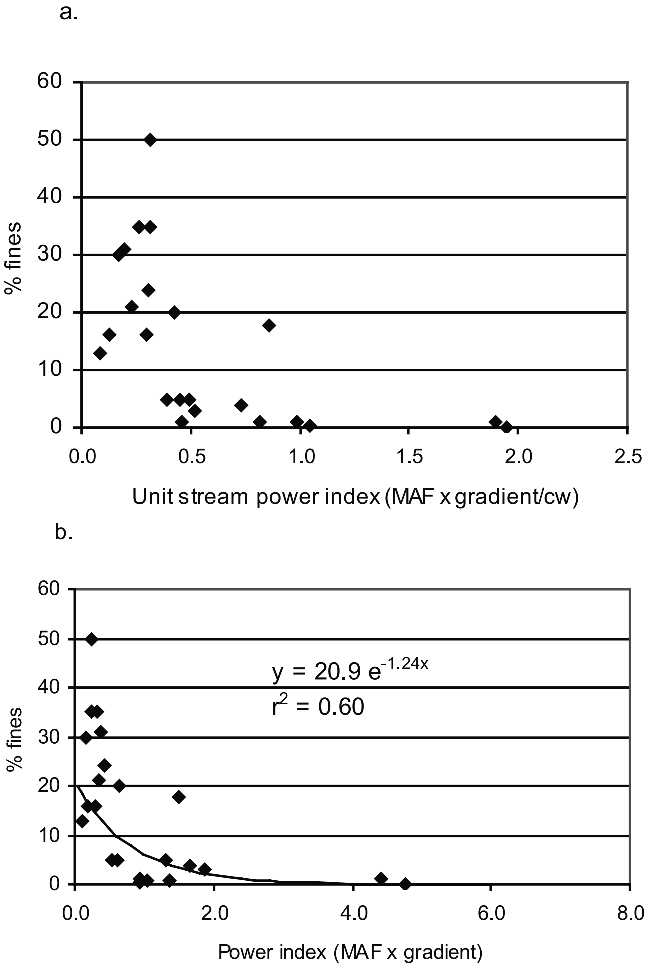


Figure 9. Relationship between percent fines determined from zigzag pebble counts in the 23 IHSR streams and (a) the unit stream power index and (b) the power index with a fitted exponential model.

as shown in Figure 9b. In some sense, the negative relationship between %fines$_{zz}$ and total step frequency is counterintuitive, because steps increase the amount of sediment trapped in the channel. Apparently the surface shear stresses are higher in channels with high step frequency and thus fines sediments are flushed from these channels.

[38] The median particle size determined from the zigzag pebble counts (D50$_{zz}$) was explained by only one variable, the stream power index, and Figure 10 shows a strong relationship between these two variables. Basically, these regressions indicate that fines are flushed from streams with greater fluvial power. These streams therefore have a higher median particle size. Wood frequency did not help explain particle size metrics determined at the reach scale.

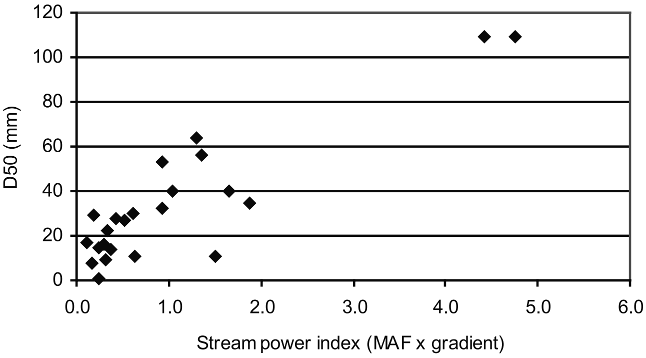


Figure 10. Relationship between median particle size (mm), known as D50, determined from zigzag pebble counts in the 23 ISHR streams and the stream power index.

[39] Conversely, the percentage of fines and the median particle diameter determined from Wolman pebble counts in the 19 RMR streams show no relationship to either the stream power or unit stream power indices. Rather, %fines$_{Wo}$ was positively related to the ratio of LWD steps to total steps and negatively related to the % drop in LWD steps. This suggests that the proportion of LWD steps somehow influences the retention of fines in riffles. Conversely, D50$_{Wo}$ was negatively related to the ratio of LWD steps to total steps and positively related to the % drop in LWD steps. D50$_{Wo}$ also was negatively related to the frequency of organic debris dams. Again, the type of steps in the channel appeared to affect riffle particle size distributions. D50$_{Wo}$ was positively related to channel width, indicating that larger channels have more fluvial power to flush fines from the riffles. While two of the same variables are predicted to affect %fines$_{Wo}$ and D50$_{Wo}$, and while these two independent variables have the expected opposite effects on %fines$_{Wo}$ and D50$_{Wo}$, the physical reasons for why the ratio of LWD steps to total steps and the percent drop in LWD steps would affect particle size distributions are difficult to fathom. It is possible that wood steps concentrate flow better than other steps, thus directing more fluvial power to the riffles where the Wolman pebble counts are conducted. These hard-to-explain relationships also feature relatively good R^2 values (0.713 and 0.767) for channel geomorphic relationships. Landscape-scale variables played little role in predicting riffle particle size distributions. Rather, riffle particle size distributions were best explained by the types and frequencies of in-channel obstructions.

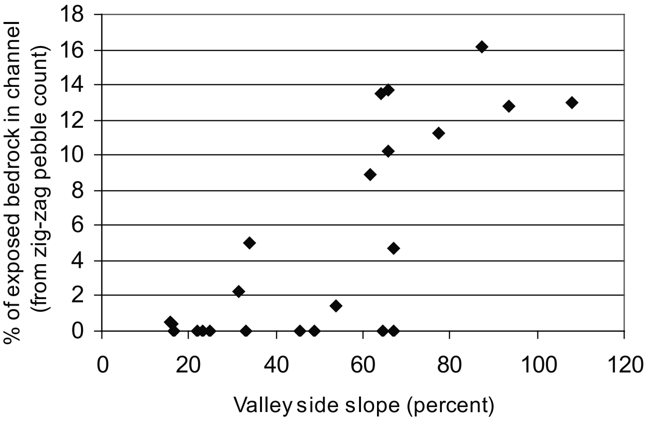


Figure 11. Relationship between the percent of bedrock exposure in the channel and the average valley side slope in the 23 IHSR streams. Bedrock percentage was determined from zigzag pebble counts. Data indicate that landscape-scale topography is a dominant determinant of bedrock exposures in channels.

[40] The percent of bedrock determined from the zigzag pebble count (%BR_{zz}) was explained only by side slope. As valley side slopes increase, so does the amount of exposed bedrock in the channel (Figure 11). In debris flow channels, bedrock exposure is a function of time since last disturbance, and disturbance is more likely in steeper topography, so this result may reflect a partial auto-correlation between side slope and time since last disturbance. Some streams are not going to feature bedrock, regardless of slope, because the parent material does not include bedrock or bedrock is far below the equilibrium channel. This would be the case for a first-order stream that is founded in unconsolidated deposits. It would also be true of a channel founded on a debris fan (just a special case of alluvial deposits). Such streams generally do not evacuate by debris flow. None of the metrics of wood or step frequency entered the regression to explain bedrock exposure in the channel.

[41] These regression models cannot explain a large amount of variability in particle size distributions because the models do not incorporate basin geology which varies within each data set. Essentially this analysis assessed how well particle size distributions could be explained without accounting for geology.

5.2.2. Channel Width

[42] Five variables entered the forward-stepwise regression for channel width, and all five variables and their coefficients match intuitive expectations. Channel width increased in response to higher step frequency, higher functional large woody debris frequency, and larger drainage area. Basically, the channels become wider as flow increases and as the frequency of flow obstructions increases. Channel width decreased as the channel gradient and the percent drop in steps increased.

5.2.3. Pools

[43] The frequency of pools, expressed as pools/cw, was positively related to channel width, drainage area, and the percentage of drop in LWD steps. The dependence of pool frequency on channel width and drainage area shows that pool formation is more likely in streams with more flow and thus more fluvial power. Pool frequency also increases when a greater percentage of the channel drop occurs in LWD steps. It makes intuitive sense that the amount of drop in steps would influence pool formation, since a step allows the fluvial power to be concentrated at the base of the step. However, it is not clear why LWD steps would be more important than other steps. Wood steps may concentrate fluvial energy better than other steps with allow more flow to move through the step matrix itself.

[44] The percent of the channel surface in pool habitat was positively related to TLWD/cw, the percent drop in steps, and the stream power index. Again, the dependence of percent pool habitat on power indicates that pool formation in these small channels is limited by fluvial power. In this case, pool habitat increases with the percentage of channel drop in all steps, but LWD steps are not singled out.

5.2.4. Step Frequency

[45] Total step frequency in these channels increases as the channels become steeper and as the channels become wider. Width and gradient were the only variables that entered the regression for total step frequency. Given the high proportion of non-LWD steps, it is not surprising that wood frequency did not enter the regression for total step frequency. Again, it appears that fluvial power dominates the morphology of small streams.

6. Discussion

[46] The low fluvial power of these streams, even with very high channel slopes, dominates all aspects of the geomorphology of these small streams. These streams do not behave as step-pool streams because they do not have sufficient fluvial power to carve scour pools below the steps. As a result, they do not maximize flow resistance according to the analysis of *Abrahams et al.* [1995]. Most of these streams are well described as exhibiting step-riffle morphology, and so they do not fit into the Montgomery and Buffington classification system for mountain streams (1997) which assumes that channel gradient (and indirectly landscape position) will control the overall morphology of mountain streams. This points out some of the problems of a channel classification system based on a single controlling variable. Step-riffle and step-pool streams exist in the same gradient range, but are differentiated by the volume of flow. The Montgomery-Buffington classification system basically assumes steady state conditions, and it ignores the dependence of reach-scale morphology on the temporal and spatial relationship to previous disturbances.

[47] The relative unimportance of LWD exceeding 40 cm diameter also results from the low fluvial power of these streams. If very large wood or large amounts of sediment block these streams, the streams cannot excavate this material. Instead, the stream will carve a subsurface channel below what becomes a stable vegetated surface. In reaches where this occurs, surface expressions of the streams appear and disappear. Our data set is actually biased against subsurface habitat, because we explicitly avoided surveying streams with large amounts of subsurface habitat because we were unsure how to characterize this habitat. The ecology of these subsurface channels may be an interesting topic for investigation.

[48] The low fluvial power of these streams allows organic debris and relatively small LWD to play important roles in creating steps and affecting the morphology and habitat. If fluvial transport of LWD were an important part of wood mechanics in these streams, the size distribution of functional wood should be skewed to the right of the distribution for nonfunctional wood, but that is not the case. In fact, the distributions suggest that wood between 10 and 20 cm diameter is more likely to function than is larger wood. Organic debris dams, which lack any LWD, comprise seventeen percent of the steps in these streams. The low fluvial power also means that bank erosion is an inconsequential component of wood recruitment. We hypothesize that the major sources of wood to these streams are chronic mortality, limb senescence, and wind throw.

[49] While obviously important, the role of big and very large woody debris in small stream morphology may have been overstated in recent decades, partly because LWD is one of the few controlling geomorphic variables that land managers can manipulate. Consequently, the role of other landscape variables and the natural variability in habitat quality may have been undervalued. The morphology and behavior of any channel is affected by seven inter-related major factors: (1) climate, (2) soils and geology, (3) topography

Table A1. Summary of Stream Characteristics

Stream	Forest	Percent Fines	D_{50}, mm	Percent BR	Percent Pool	Pools/ cw	TS/cw	LWDS /cw	ODD /cw	FLWD /cw	NFLW /cw	TLWD /cw	Sideslope, %	cw, m	Percent Dropsteps	LWDS Percent Drop	Drainage Area, km^2	Est. MAF, L/s	Gradient, %
								IHSR Streams (N = 23)											
12R	50–65 yr hemlock	3.0	35	13.0	22.8	0.509	1.02	0.85	0.17	4.58	1.19	5.77	108.0	3.63	55.1	51.6	0.081	5.88	32
12E	50–65 yr hemlock	1.0	53	12.8	10.2	0.317	0.51	0.13	0.06	2.47	0.32	2.79	93.6	2.09	46.3	19.5	0.046	3.34	28
12W	50–65 yr hemlock	5.0	64	13.7	8.2	0.243	0.89	0.32	0.08	1.78	0.57	2.35	65.7	2.62	54.5	19.8	0.101	7.33	28.4
17R	50–65 yr hemlock	35.0	9	0.0	0.0	0.000	0.03	0.00	0.00	0.16	0.35	0.51	45.6	1.18	7.1	0.0	0.081	3.90	8
17W	50–65 yr hemlock	16.0	16	10.2	0.0	0.000	0.19	0.09	0.09	0.14	0.14	0.28	65.9	0.96	27.6	13.5	0.022	1.06	27.8
17M	50–65 yr hemlock	50.0	1	1.44	0.0	0.000	0.20	0.08	0.08	0.39	0.36	0.75	53.8	0.91	34.2	18.4	0.027	1.30	19.2
17E	50–65 yr hemlock	31.0	14	16.2	0.0	0.000	0.32	0.13	0.06	1.01	0.70	1.71	87.5	1.89	60.5	13.2	0.039	1.88	19.6
21R	50–65 yr hemlock	5.0	30	0.0	2.7	0.055	0.33	0.05	0.00	0.39	0.50	0.88	21.8	1.10	61.6	19.6	0.057	5.51	11
21M	50–65 yr hemlock	20.0	11	0.0	8.6	0.227	0.40	0.28	0.11	1.02	0.57	1.59	33.1	1.93	65.2	50.6	0.069	6.67	9.6
21E	50–65 yr hemlock	30.0	8	0.46	0.0	0.000	0.25	0.00	0.19	0.16	0.06	0.22	16.2	0.98	38.8	0.0	0.014	1.35	12.5
21W	50–65 yr hemlock	16.0	29	0.47	0.0	0.000	0.26	0.05	0.10	0.21	0.15	0.36	15.6	1.41	26.0	6.2	0.019	1.84	9.92
13S	50–65 yr hemlock	21.0	22	13.5	10.3	0.223	0.45	0.22	0.00	0.84	0.39	1.23	64.2	1.57	43.4	26.8	0.025	1.61	21.2
13E	50–65 yr hemlock	13.0	17	0.0	8.5	0.170	0.34	0.11	0.23	0.68	0.28	0.97	64.7	1.42	42.9	16.3	0.011	0.71	14.7
13M	50–65 yr hemlock	35.0	15	4.68	1.2	0.038	0.11	0.08	0.00	0.57	0.38	0.95	67.2	1.18	22.2	14.2	0.036	2.32	10.6
13R	50–65 yr hemlock	24.0	28	8.87	5.4	0.101	0.30	0.25	0.00	1.27	0.20	1.47	61.5	1.41	57.7	42.5	0.045	2.90	14.9
29N	old–growth	3.9	40	0.0	19.8	0.475	0.87	0.00	0.16	0.55	0.24	0.79	67.0	2.26	95.5	0.0	0.458	18.44	9
29M	old–growth	0.4	32	0.0	1.6	0.033	0.23	0.07	0.00	0.23	0.07	0.30	23.0	0.89	31.8	11.8	0.082	3.30	28
29S	old–growth	4.9	27	0.0	12.2	0.219	0.31	0.22	0.09	0.70	0.44	1.14	24.9	1.34	47.9	39.6	0.081	3.26	16
SD W	old–growth	1.0	109	11.2	23.9	0.338	0.42	0.08	0.00	1.01	0.34	1.35	77.5	2.33	51.9	12.0	0.261	14.72	30
SD E	old–growth	0.9	56	0.0	2.7	0.116	0.35	0.06	0.06	0.40	0.12	0.52	16.7	1.67	25.9	12.1	0.078	4.40	31
SD M	old–growth	0.0	109	5.0	28.1	0.494	0.59	0.10	0.00	0.49	0.39	0.89	33.9	2.44	52.6	3.2	0.338	19.06	25
EL E	old–growth	0.9	40	0.0	11.9	0.157	0.47	0.20	0.08	0.39	0.12	0.51	48.7	1.06	61.2	31.4	0.056	3.61	29
EL W	old–growth	17.9	11	2.24	3.0	0.129	0.78	0.26	0.19	0.78	0.06	0.84	31.5	1.75	64.4	33.6	0.073	4.70	32
								RMR Streams (N = 19)											
SS1	40 yr hemlock	4.0	23.5	NM	0.0	0.000	0.84	0.28	0.05	0.42	0.28	0.7	NM	1.4	134	47.50	0.12	6.85	20
SS2	40–50 yr conifer	7.6	25	NM	0.0	0.000	0.43	0.24	0.00	0.24	0.38	0.61	NM	1.42	79	69.02	0.08	4.34	17
SS3	50–60 yr conifer	12.0	19	NM	0.0	0.000	0.26	0.09	0.18	0.18	0.09	0.26	NM	1.98	65	24.00	0.14	7.99	5
SS4	30 yr hemlock	30.4	12	NM	0.0	0.000	0.34	0.25	0.08	0.08	0.13	0.21	NM	1.27	121	38.10	0.16	7.82	7
SS5	50–yr conifer	23.6	16	NM	0.0	0.000	0.40	0.13	0.04	0.27	0.27	0.53	NM	1.33	63	8.63	0.49	25.42	17
R1	virgin; 21 Blow	miss		NM	0.0	0.000	0.52	0.28	0.00	0.36	0.80	1.16	NM	1.19	97	43.36	0.10	6.52	22
R4	PCT'd reprod	11.0	24	NM	0.0	0.000	0.36	0.30	0.00	0.50	0.41	0.91	NM	1.5	188	84.08	0.32	20.86	5
R6	conifer reprod	1.0	30	NM	0.0	0.000	0.39	0.16	0.00	0.52	0.33	0.85	NM	1.53	91	41.14	0.19	12.52	15
R7	~ 20 yo reprod	26.0	12	NM	0.0	0.000	0.31	0.31	0.00	0.91	0.46	1.37	NM	1.4	93	90.99	0.25	16.90	12
R8	20 – 30 yo reprod	24.0	15	NM	0.0	0.000	0.45	0.42	0.00	0.97	0.36	1.33	NM	1.36	97	70.98	0.11	7.76	31
R9	virgin, mature	1.0	20	NM	0.0	0.000	0.30	0.15	0.04	0.75	0.19	0.93	NM	1.64	111	36.98	0.10	8.15	9
R10	reprod	3.0	23	NM	0.0	0.000	0.27	0.04	0.04	0.11	0.00	0.11	NM	1.18	77	19.52	0.10	8.15	14
R11	reprod	14.0	11	NM	0.0	0.000	0.66	0.33	0.29	1.14	0.40	1.54	NM	1.65	90	51.13	0.12	8.31	20
R12	mature reprod	3.0	26	NM	0.0	0.000	0.48	0.22	0.00	1.17	0.30	1.47	NM	1.73	97	59.30	0.14	10.27	21
R13	young reprod	3.0	12	NM	0.0	0.000	0.25	0.00	0.25	0.04	0.00	0.04	NM	0.36	104	0.00	0.05	3.32	30
R14	reprod	9.0	14	NM	0.0	0.000	0.48	0.31	0.11	1.08	0.74	1.82	NM	1.28	157	69.55	0.04	3.05	9
R15	old–growth	1.0	25	NM	0.1	0.022	0.33	0.09	0.00	0.20	0.20	0.40	NM	1.26	86	21.56	0.06	4.40	16
R16	reprod (PCT'd)	17.0	11	NM	0.0	0.000	0.73	0.33	0.15	0.44	0.29	0.73	NM	1.53	95	34.06	0.08	5.87	17
R17	mature reprod	5.0	25	NM	0.0	0.000	0.51	0.20	0.00	0.94	0.27	1.21	NM	2.02	96	41.85	0.17	11.64	16

(and network topology), (4) upland and riparian vegetation, (5) sediment loading, (6) flows, (7) LWD loading, and (8) time since last disturbance. Since LWD loading can be partly controlled by riparian silvicultural practices and since previous studies have repeatedly demonstrated the beneficial role of wood in channels, there has been a push toward a philosophy that all streams need big wood to provide good habitat. There are several dangers associated with this trend. It fuels a perception that all streams should support good habitat and that wood will cure any stream with poor habitat. This discounts the importance of the other dominant landscape variables that control habitat characteristics in a stream. It now seems clear that large stream wood relationships should not be extrapolated downward to small streams.

[50] The heteroskedasticity of the relationship between percent fines and stream power may be useful for prioritizing efforts to reduce fine sediment production from forest road systems. At low stream power, there is a lot of variability in the percentage of fine sediment, from very high to very low. Differences in management, creep rates, soils, etc., are likely to have a strong effect on the percentage of fine sediments. At high stream gradients, fine sediment concentrations are uniformly low, indicating that management is not likely to affect fine sediments in steep streams.

[51] The measured scarcity of pools is highly dependent on the definition of a pool. Using the standard requirement of a minimum residual pool depth of 10 cm, pools are almost nonexistent in the small channels we surveyed. With a more flexible minimum residual depth of 5% of the active channel width, pools comprise about 6% of the channel length. This begs the question, what is the appropriate definition of a pool in a small stream? Since fish are not present, their habitat requirements cannot be used as a guide, and amphibian preferences for tiny pools are unknown. Many times during associated amphibian surveys, the amphibian catcher would report that an amphibian was caught in a pool, but the residual pool depth would be well below even our flexible requirement. In our judgment, a pool in the eyes of a torrent salamander is far smaller than most geomorphologists would be willing to count. The appropriate definition of a pool in these streams remains an open question.

[52] Many stream researchers describe their study streams as small, medium, or large, but there is no standard definition of what these terms mean. In this data set, a two-component definition of small streams as first- or second-order and as having channel widths <4 m was not incompatible, but there is no reason that there would be similar correspondence between stream width and stream order in other physiographic regions. Using channel width as a descriptor of stream size can be problematic because two streams with identical flows might have different average widths due to differences in gradient or LWD loading. Using an estimate of mean annual flow might be a better way to classify stream size, but it is sometimes difficult to get good climatic data with which to estimate flow. Furthermore, in landscapes with significant groundwater fracture flow, there is little relationship between basin area and flow. In the regression analysis conducted here, channel width often entered the channel morphology regressions instead of other metrics of channel size, so channel width may have advantages over inaccurate estimates of mean annual flow and power in basins of this size.

[53] Forward stepwise multiple linear regression is a problematic methodology for evaluating geomorphic processes in streams. Important relationships are likely to be nonlinear, but the number of possible independent variables and the large amount of covariance make it difficult to prescreen and linearize the independent variables. Stream power and unit power are useful variable combinations with theoretical justifications, but it is likely that other useful variable combinations exist which could simplify stream assessments. Several important ‘‘variables,’’ including geology, disturbance history, and management history are difficult or impossible to quantify in a regression analysis. The results of these regressions are not meant to serve as predictive equations but instead were used to elucidate the relative importance of the many geomorphically important variables.

Appendix A

[54] Table A1 presents all the measured channel metrics used in the descriptive analysis and in the forward stepwise regression. Selection of the managed forest streams in the IHSR data sets is described by *Jackson et al.* [2001]. The old growth streams in the IHSR data set were pseudorandomly selected from streams in National Forest and National Park land on the northern end of the Olympic Peninsula. The RMR streams were pseudo-randomly selected to represent a range of headwater stream types found on commmercial forest land in the Olympic foothills and lowlands. There was no attempt to control for geology or elevation in stream selection. Because the USGS 1:24,000 quad maps are usually drawn from aerial photographs of full-canopy forest, topographic resolution at the scale of these headwater basins is often poor. Therefore, drainage area is the variable with the greatest potential percentage error. The annual precipitation used to estimate mean annual flow was interpolated from isohyetal maps for Washington State, and there may be significant error associated with this estimate. The errors in drainage area measurement and annual precipitation estimation are directly translated into the estimates for mean annual flow, stream power, and unit stream power. All other variables are based on direct channel measurements and are accurate at the reach scale.

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