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Large woody debris and flow resistance in step-pool channels, Cascade Range, Washington

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Abstract

Total flow resistance, measured as Darcy–Weisbach *f*, in 20 step-pool channels with large woody debris (LWD) in Washington, ranged from 5 to 380 during summer low flows. Step risers in the study streams consist of either (1) large and relatively immobile woody debris, bedrock, or roots that form fixed, or "forced," steps, or (2) smaller and relatively mobile wood or clasts, or a mixture of both, arranged across the channel by the stream. Flow resistance in step-pool channels may be partitioned into grain, form, and spill resistance. Grain resistance is calculated as a function of particle size, and form resistance is calculated as large woody debris drag. Combined, grain and form resistance account for less than 10% of the total flow resistance. We initially assumed that the substantial remaining portion is spill resistance attributable to steps. However, measured step characteristics could not explain between-reach variations in flow resistance. This suggests that other factors may be significant; the coefficient of variation of the hydraulic radius explained 43% of the variation in friction factors between streams, for example. Large woody debris generates form resistance on step treads and spill resistance at step risers. Because the form resistance of step-pool channels is relatively minor compared to spill resistance and because wood in steps accentuates spill resistance by increasing step height, we suggest that wood in step risers influences channel hydraulics more than wood elsewhere in the channel. Hence, the distribution and function, not just abundance, of large woody debris is critical in steep, step-pool channels.
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Keywords: Step-pool; Large woody debris; Flow resistance

1. Introduction

Past timber harvest practices in the headwaters of forested drainage basins in the Pacific Northwest included complete harvest of streamside trees and removal of in-stream large woody debris. By the mid-1970s, studies concluded that removing wood from these steep forested streams affects sediment transport, slope stability, and stream productivity (e.g., Swanson et al., 1976). Woody debris in steep forested channels is critical to the retention of sediment and nutrients in headwater areas (Swanson et al., 1976; Bilby, 1981; Mosley, 1981), attenuation of the transport of sediment from point inputs (Pearce and Watson, 1983; Keller et al., 1995), and creation of aquatic and riparian habitat (Bisson et al., 1987; Abbe and Montgomery, 1996). The concern that riparian corridors and, specifically, wood in stream channels are important

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components of forest ecosystems in turn led to efforts to rehabilitate forest channels through the artificial addition of woody debris. However, the expense, technical challenge, and high failure rates of channel rehabilitation underscore the need for a quantitative understanding of the hydraulics of steep channels and the hydraulic effects of large woody debris.

Step-pool channels are a subset of steep channels with longitudinally alternating sequences of discrete, coarse, channel-spanning falls and finer, lower-gradient sections that resemble, respectively, the risers and treads of a staircase (Fig. 1), as described by various researchers and summarized by Montgomery and Buffington (1997). Risers are simply referred to as "steps" and treads are usually referred to as "pools" although they may consist of pools, riffles, or runs. Step-pool channels contain organized, discrete, channel-spanning steps as opposed to the disorganized and continuous distribution of individual large clasts that occur in cascade channels (Montgomery and Buffington, 1997). Steps are typically less than a channel width in length, regularly spaced, and formed by large rock clasts, bedrock, woody debris, or a combination of these materials that generate turbulent conditions described as tumbling flow (Peterson and Mohanty, 1960). The strength of this hydraulic effect varies with water level such that the number of steps clearly identifiable during high flow is less than during low flow. Step-pool channels are important to the study of forested headwaters in that their morphology can be partly the result of stream hydraulics and partly the result of materials that are large relative to channel dimensions such as large woody debris. Although many steps are arranged by the stream, woody debris can "force" step locations in small channels where large pieces become trapped or accumulate across the channel (Montgomery and Buffington, 1997).

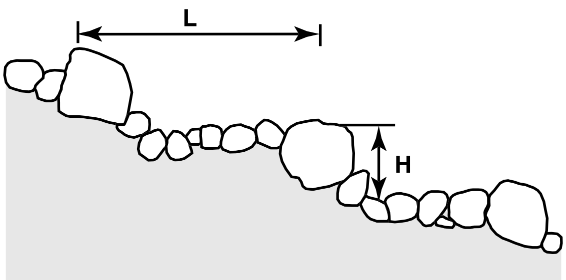

Fig. 1. Schematic showing longitudinal profile of a typical reach in a step-pool channel. L is step spacing and H is step height.

Although the effects of wood on channel morphology (Mosley, 1981; Robison and Beschta, 1990; Abbe and Montgomery, 1996), channel conveyance (Shields and Gippel, 1995), and flow resistance (Buffington and Montgomery, 1999; Manga and Kirchner, 2000) have been documented in larger, lower-gradient channels, similar investigations are rare for steeper streams (greater than 0.03 m/m) and do not address the complex hydraulics of step-pool channels. Detailed analysis of flow resistance in step-pool channels with wood may provide a better understanding of both step-pool hydraulics and the effects of removing or adding woody debris.

The division of total flow resistance into components is an established tool for investigating relationships between flow resistance and physical channel characteristics (Einstein and Barbarossa, 1952; Leopold et al., 1960; Rouse, 1965). Using the principle of linear superposition, flow resistance can be partitioned into components representing various physical processes so long as the components are independent of one another. The dominant component in the absence of bedforms or obstructions to flow is grain resistance, or the shear generated by grains distributed along the flow boundary. A second component, form resistance, is the result of drag forces or pressure differences between the upstream and downstream sides of an obstacle to flow and is related to the geometry of the flow blockage and flow velocity. In forested step-pool channels, a principal component of form resistance is large woody debris. Other potential sources of form resistance, such as local channel expansions and contractions and bed topography other than steps, may also be significant. Spill resistance is the resistance associated with flow accelerations and decelerations (Leopold et al., 1960) and is generated at steps in the step-pool streams where flow plunges from step to pool. A local phenomenon that occurs when supercritical flow is transformed to subcritical flow, spill resistance results in energy dissipation through turbulence. Using the Darcy–Weisbach friction factor, f, to represent the total flow resistance, f can be partitioned as $f = f_g + f_{form} + f_{spill}$, where f_g, f_{form}, and f_{spill} are grain, form, and spill friction factors, respectively.

Most investigations of flow resistance in steep channels have focused on gravel-bed rivers with gradients less than 0.05 m/m and bedforms that include pools, riffles, and bars, where authors conclude that grain and form resistance dominate and spill resistance is a negligible component of total energy dissipation (e.g., Bathurst, 1982; Prestegaard, 1983). However, in step-pool channels, where gradients typically exceed 0.03 m/m and may be as great as 0.13 m/m or more (Montgomery and Buffington, 1997; Chartrand and Whiting, 2000), the substantial energy dissipated in roll waves, free drops at steps, and other free surface distortions suggest that spill resistance is a major component (Wohl and Thompson, 2000). Although other researchers have noted that spill resistance is important in step-pool streams (e.g., Abrahams et al., 1995), there have been no reports that quantify the relative magnitude of flow resistance components. O'Connor (1994a) computed grain resistance in steep, low-order streams in the Olympic Mountains of Washington and found that grain resistance accounted for only about 25% of the total flow resistance, but did not separate the remaining resistance into components.

Large woody debris in step-pool channels produces both form resistance (at nonstep-forming positions) and spill resistance (at step-forming locations). The form resistance of large woody debris is a substantial portion of total flow resistance in low-gradient channels (Shields and Gippel, 1995; Buffington and Montgomery, 1999; Manga and Kirchner, 2000) and some steep channels (O'Connor, 1994a), but the magnitude of form resistance in step-pool streams has not been quantified.

In this study, we measured hydraulic and geomorphic characteristics of 20 step-pool channels in the central and southern Cascade Range in Washington State (Fig. 2) during low flows and assessed the relative contributions of grain, form, and spill resistance to total flow resistance. From measurements of channel characteristics, including channel and step geometry and large woody debris size and function, we examined correlations of steps and large woody debris to flow resistance and the role of wood in forming steps. The primary goal of this study is to improve understanding of the hydraulic effects of large woody debris in step-pool channels, particularly with regard to the potential effects of adding or removing debris.

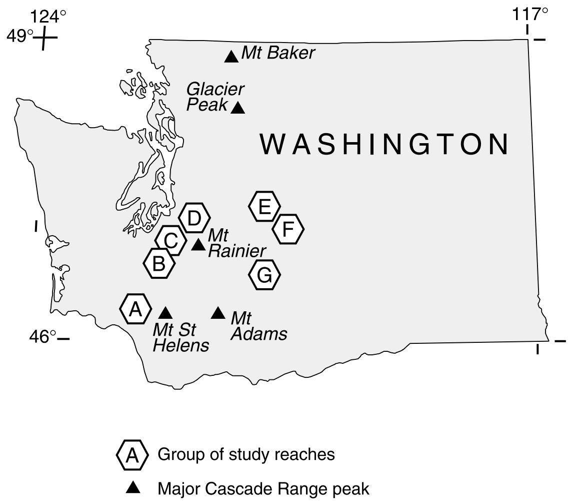

Fig. 2. Location of study reaches. Study streams are (A) Nineteen and O'Neil Creeks, (B) Hard Creek, (C) Diorama, Kellogg, Lost, Ohop, Spine, and Thicket Creeks, (D) Scatter Creek, (E) Davis, Newport, Bear, and Spring Creeks, (F) First and Second Creeks, and (G) McLaine, South Fork Foundation, and North Fork Foundation Creeks.

2. Field setting and methods

This study focused on providing information on physical and hydraulic conditions in previously harvested areas, with the goal of improving understanding of the hydraulic conditions that are affected when wood is added or removed from streams. We investigated channels in previously harvested areas rather than undisturbed areas because wood in these channels is likely to be similar in diameter to wood available for stream rehabilitation. Sites were selected along step-pool reaches containing wood that were adjacent to second-growth forests to ensure that harvest activities had not disturbed channel morphology for at least several decades. Straight, undivided channels with little in-channel or overhanging vegetation and few undercut or protruding banks were sought so that flow resistance from sources other than grains, bedforms, and woody debris could be considered negligible. However, channels could not be found that consistently met all these requirements, so additional sources of resistance must be considered.

Twenty reaches on nineteen first- and second-order step-pool streams in the central and southern Cascade

Range, Washington (Fig. 2) that met the project criteria were selected. The study reaches have gradients of 0.06–0.18 m/m and bankfull widths of 2.0–4.8 m and are within drainage basins having areas of less than 10 km^2. The average elevation of the study reaches is 632 m on the western side of the Cascade Range crest and 1007 m on the eastern side (Table 1), reflecting regional variations in the elevation of headwater areas. The study reaches are underlain by geologic materials that include volcanic, metamorphic, and sedimentary rocks and glacial till (Table 1) (Schuster, 1992; field observations). Streambeds consist primarily of alluvium, but colluvial deposits are present along several reaches and bedrock is exposed in parts of a few reaches. The vegetation in the study area includes a mix of coniferous and deciduous species common to the Cascade Range.

The study reaches began at an arbitrary point and extended downstream to a distance of at least 10 channel widths, typically 50–60 m, to encompass local variability of step-pool units (Fig. 3). Ten to eleven cross-sections, spaced roughly 5 m apart, were surveyed with a total station (theodolite and electronic distance measurement instrument) during similar hydrologic conditions—low flows in June and July 1997—to determine reach-average hydraulic radius, wetted channel width, and estimated bankfull channel width. A longitudinal profile was surveyed along the channel thalweg to obtain reach-average gradient and reach length, and the bed elevation at the crest and base of each step riser was surveyed to determine step spacing (L) and height (H) (Fig. 1). Step riser composition was noted as large woody debris (logs greater than 10 cm in diameter and 1 m in length), fine woody debris (smaller logs and twigs), rock clasts, bedrock, or a combination of these materials. The orientation, diameter, and flow blockage area of each piece of large woody debris were also recorded (Curran, 1999).

Reach-average velocity was calculated by injecting a salt tracer at a distance of 10–20 channel widths upstream of the study reach and recording the resulting change in specific conductance at the top and bottom of the study reach. Such tracer techniques have been used in many other studies and may be more appropriate than point measurements for determining reach-average flow velocity in shallow, turbulent streams (Calkins and Dunne, 1970; Kellerhals, 1970; Day, 1977; Beven et al., 1979; Beven and Carling, 1992; Spence and McPhie, 1997). The travel time between the top and bottom of the study reach obtained from the specific conductance curves is divided by the reach length. Travel time must be determined by comparing similar points on the upstream and downstream curves, either time of first arrival, time of peak, or time of centroid. Calkins and Dunne (1970) suggest that the centroid method is more appropriate because they observed that first arrival and peak times varied with reach length. In practice, however, specific conductance returned to near-background levels quickly but lingered at levels slightly above background for an extended period, making it difficult to extend measurements long enough to obtain the full tail of the curve for centroid calculations. Peak travel times are expected to be faster than centroid travel times, because the downstream curve is more attenuated than the upstream curve, but are easier to obtain and may be more appropriate if the long tail reflects delaying processes such as subsurface flow through gravels (Abrahams et al., 1995). The difference between peak and centroid travel times was 3% and 8%, respectively, for two curves with tails returning to near-background levels within a period roughly equal to two times the period between time of first arrival and time of peak arrival, and more than 20% for a curve with a long tail. Measurement of reach length includes inherent uncertainty because the distance measured increases with the number of survey points. Reach length was defined for this study as the surveyed distance along the thalweg (see Fig. 3 for typical distribution of survey points), which we estimated could increase as much as 10% with additional survey detail. A 5% change in the ratio of travel time to reach length would amount to about a 10% change in f.

Bed material size was determined by a method modified from Wolman (1954). A formal sampling grid was difficult to maintain because of the small channel size and the limited number of clasts in steps, so the reach was subdivided into step and pool classes (step risers and step treads, respectively). The intermediate (b axis) diameter of 100 clasts in each class was measured and used to compile grain size curves for each class (Curran, 1999). A composite estimate of channel grain size (D_{50}) required for the hydraulic computations in this study was determined by combining the step and pool classes assuming that we sampled equal areas of each class. We expect that this overestimates D_{50} because, although not quantified in our

Table 1
Study site characteristics and measured channel parameters

Group identifier (see Fig. 2) and major drainage	Stream name	Drainage area (km^2)	Study reach elevation (m)	Slope, S (m/m)	Reach-average velocity, v (m/s)	Hydraulic radius, R (m)	Coefficient of variation of R	Bankfull width (m)	D_{50} (m)	General surficial geology[a]	Number of LWD per 100 m[b]	Average LWD diameter (m)	LWD flow blockage area per 100 m (m^2)
A—Coweeman River	Nineteen	0.72	497	0.11	0.051	0.11	0.58	2.0	0.033	T volc	44	0.33	0.79
	O'Neil	0.55	485	0.12	0.055	0.077	0.42	2.1	0.036	T volc	37	0.35	2.1
B—Deschutes River	Hard	2.2	510	0.093	0.13	0.18	0.42	4.8	0.087	T volc	58	0.33	10
C—Puyallup River	Diorama[c]	0.83	671	0.071	0.18	0.16	0.64	3.7	0.075	T volc	94	0.26	19
	Kellogg	2.6	628	0.11	0.25	0.17	0.45	4.8	0.075	T volc	48	0.21	12
	Lost[c]	0.92	609	0.12	0.25	0.13	0.28	3.3	0.065	T volc	26	0.25	2.9
	Ohop	0.75	684	0.091	0.11	0.063	0.46	2.1	0.028	T volc	43	0.20	1.5
	Spine[c]	0.13	671	0.12	0.16	0.077	0.51	2.2	0.033	T volc	31	0.19	3.0
	Thicket[c]	0.43	858	0.17	0.21	0.10	0.28	2.9	0.083	T volc	34	0.28	5.6
D—White River	Scatter	1.2	709	0.15	0.19	0.10	0.44	2.8	0.073	T volc	66	0.21	3.2
E—Cle Elum Lake	Bear	1.5	808	0.11	0.079	0.11	0.55	3.1	0.100	T sed	47	0.30	8.6
	Davis	1.8	808	0.097	0.070	0.085	0.70	3.5	0.068	T volc	8	0.24	2.4
	Newport	2.8	808	0.079	0.056	0.13	0.62	3.6	0.130	T volc/Q gl	3	0.28	0.27
	Spring	0.86	932	0.06	0.043	0.041	0.77	2.7	0.037	T volc	25	0.27	3.8
F—Taneum Creek	First	4.0	920	0.12	0.13	0.066	0.53	2.8	0.043	Pre-C meta	28	0.23	2.3
	Second[c]	1.9	932	0.17	0.13	0.055	0.39	2.2	0.033	Pre-C meta	30	0.36	6.4
G—North Fork Ahtanum Creek	McClaine	3.7	1130	0.18	0.21	0.14	0.54	3.3	0.080	T volc	14	0.22	1.2
	North Fork Foundation	9.6	1190	0.093	0.52	0.18	0.15	3.9	0.092	T volc	40	0.23	3.6
	South Fork Foundation, Reach I	4.0	1330	0.089	0.20	0.067	0.34	3.4	0.047	T volc	21	0.18	1.5
	South Fork Foundation, Reach II	5.2	1210	0.093	0.21	0.11	0.24	2.9	0.061	T volc	38	0.21	7.8

LWD = large woody debris; diam = diameter.

[a] T volc = Tertiary volcanic rock; T sed = Tertiary sedimentary rocks; Q gl = Quaternary glacial till; Pre-C meta = pre-Cretaceous metamorphic rocks.

[b] Values shown are counts of LWD wetted at the time of the survey; counts of LWD within the bankfull channel width are an average of about twice these values.

[c] Informal name.

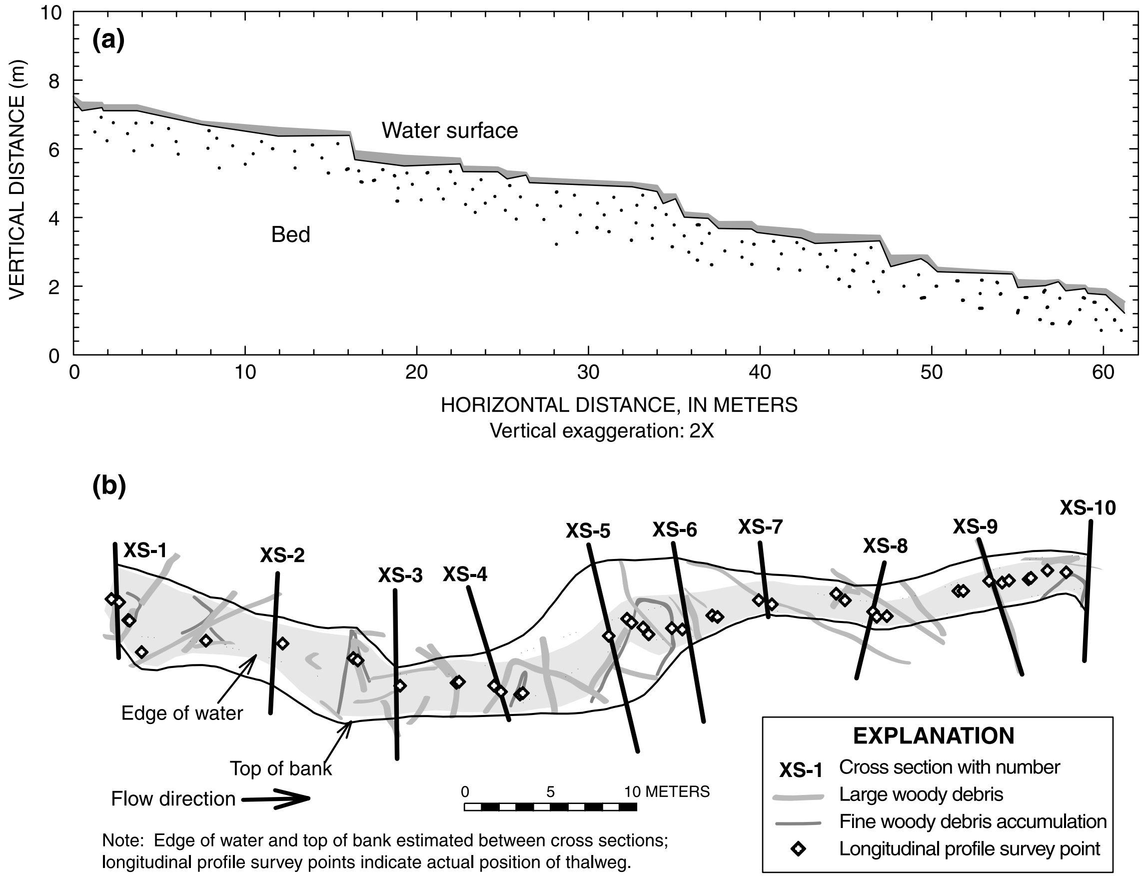

Fig. 3. (a) South Fork Foundation Creek, Reach II, longitudinal profile, showing typical arrangement of step-pool units. (b) South Fork Foundation Creek, Reach II, map showing typical distribution of woody debris, cross-sections, and variation in channel width.

surveys, the area of step treads exceeds the area of step risers. Although misleading for purposes such as sediment transport calculations, this overestimate is not critical for our flow resistance calculations. A fourfold variation in D_{50} could translate into a twofold variation in grain resistance, for example, but grain resistance is still small relative to other forms of flow resistance in step-pool streams.

3. Results

3.1. Step characteristics

Characteristics of 347 steps (i.e., step risers) in 20 Cascade Range streams are presented in terms of step geometry, step composition, the spatial distribution of steps, and the contribution of steps to elevation loss (Table 2). Steps in the study streams are an average of 0.38 m high ($\sigma = 0.12$ m) and are spaced an average of 1.2 bankfull channel widths apart ($\sigma = 0.04$). The steps have an average ratio of step height to step spacing (H/L) of 0.15 ($\sigma = 0.04$) and collectively account for an average of 79% of the reach water surface drop at low flow. The averages given here are calculated from reach-averaged values, such that each stream is weighted equally regardless of length or number of steps. Other characteristics such as pool volume and sediment storage that were measured but are not pertinent to the present discussion are presented in Curran (1999).

Step risers are composed of clasts, woody debris, clasts and woody debris combined, and more rarely, bedrock (Fig. 4). The average D_{50} of step-forming

Table 2
Step characteristics

Stream	Average step spacing, in bankfull channel widths	Average step height, H (m)	Average step spacing, L (m)	$\overline{H/L}$	Percentage of water surface drop occurring at steps (%)	D_{50} of step-forming clasts (m)
Nineteen	2.4	0.34	4.0	0.12	72	0.176
O'Neil	1.6	0.28	3.2	0.11	69	0.062
Hard	1.0	0.39	3.8	0.12	91	0.101
Diorama	1.1	0.43	3.9	0.16	90	0.116
Kellogg	0.6	0.37	2.9	0.17	86	0.173
Lost	0.8	0.33	2.2	0.20	86	0.130
Ohop	1.7	0.16	3.4	0.06	47	0.062
Spine	1.0	0.28	1.9	0.16	91	0.066
Thicket	0.8	0.41	2.0	0.22	91	0.137
Scatter	1.0	0.43	2.4	0.21	88	0.133
Bear	1.2	0.39	3.2	0.15	79	0.166
Davis	1.6	0.46	5.9	0.11	71	0.181
Newport	1.4	0.43	5.3	0.11	80	0.232
Spring	1.7	0.31	4.3	0.12	73	0.058
First	0.7	0.26	2.0	0.16	80	0.045
Second	0.8	0.31	1.7	0.23	81	0.055
McLaine	2.2	0.80	5.3	0.14	76	0.118
North Fork Foundation	1.1	0.52	4.1	0.14	76	0.060
South Fork Foundation I	1.1	0.28	3.6	0.17	70	0.049
South Fork Foundation II	1.2	0.33	3.5	0.14	80	0.098

clasts is 0.15 m ($\sigma = 0.05$ m). By comparison, the average diameter of large woody debris in the study reaches, including both step-formers and pieces on step treads, is considerably larger, 0.26 m ($\sigma = 0.05$ m). The diameter of step-forming wood cannot be given because our survey did not include a distinction between step-forming and nonstep-forming pieces.

The distribution of step heights (Fig. 5) indicates that it is common to have both particularly low and particularly high steps. High steps have an important influence on energy losses. On average, the highest step in each reach accounted for 14% of the total drop in water surface, more than twice the drop that would be expected if all step heights were equal. Analysis of step composition (Fig. 6) indicates that large woody debris is more common in these high steps than clasts. This is consistent with field observations of exceptionally high steps formed by wood or wood/clast jams.

A common but often untested assumption of step-pool morphology is that the steps are regularly spaced. The large number of steps surveyed at a range of sites for this study constituted a large dataset from which we could statistically test this assumption. A χ^2 test of the goodness of fit of the Poisson distribution to the spacing of 309 steps in the study streams normalized by bankfull width shows that the steps are nonrandomly distributed (significant at $p < 0.025$) (Zar, 1996). Steps were plotted by bankfull width (Fig. 7) and divided into "plots" with a length equal to two bankfull widths for this analysis; 38 steps were omitted from this analysis because they fell into partial plots. Further examination of the distribution of step spacing shows that $\sigma^2 < \mu$ and $\sigma^2/\mu < 1.0$, where σ^2 is the variance and μ is the mean, indicating that the distribution is more uniform than clustered (Zar, 1996) (Figs. 3 and 7).

3.2. Total flow resistance in study streams

Reach total flow resistance was calculated as the total Darcy–Weisbach friction factor, $f = 8gRS/v^2$ (Knighton, 1998), using reach-average values for hydraulic radius (R), channel slope (S), and flow velocity (v) (Table 1). At the flow conditions surveyed, f in the study streams ranged from 5 to 380 (Table 3). None of the streams is gaged so bankfull indicators were used to assess relative flow conditions. Hydraulic radii ranged from 6% to 35% of bankfull depth, indicating that streamflow was low during our surveys. This is important to consider when comparing flow

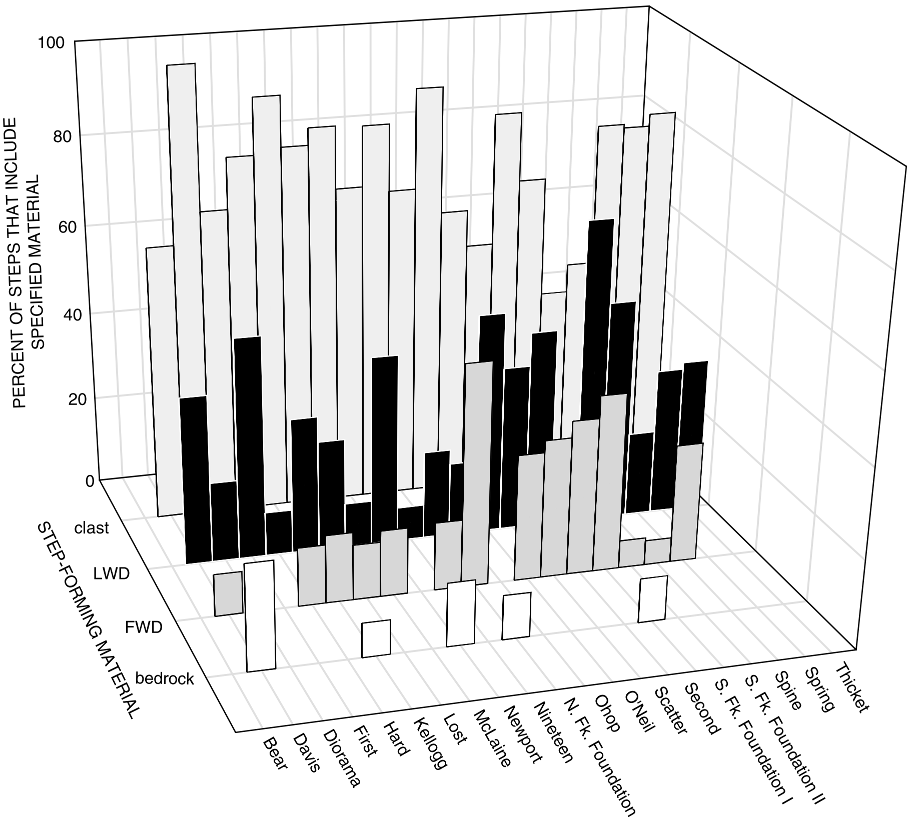

Fig. 4. Composition of steps in Cascade Range study streams includes rock clasts, large woody debris (LWD), fine woody debris (FWD), and bedrock. Percentages do not sum to 100 because steps may be composed of more than one material.

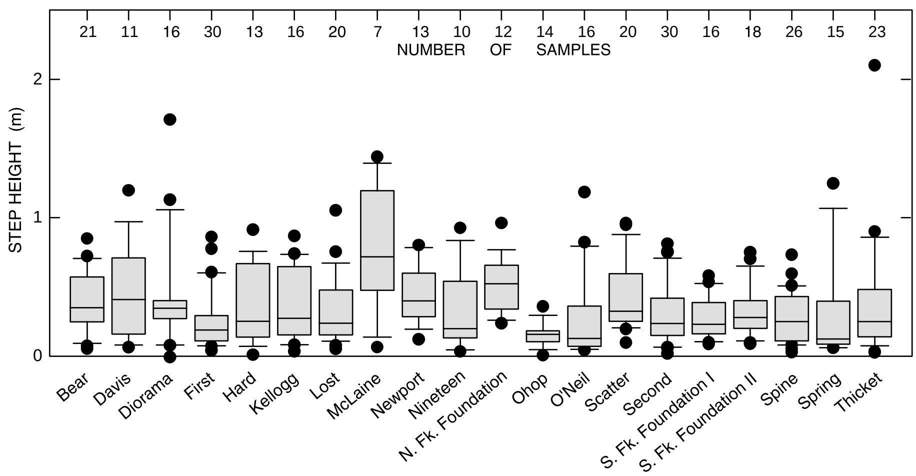

Fig. 5. Distribution of step heights in Cascade Range study streams. Box boundaries indicate the 75th, 50th, and 25th percentiles, bars indicate 95th and 5th percentiles. Dots indicate steps outside the 95th and 5th percentiles.

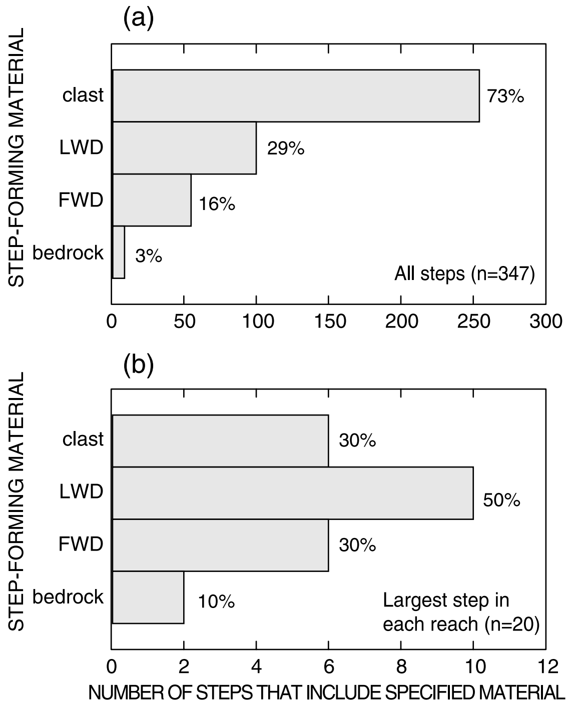

Fig. 6. Differences in step composition between (a) all steps and (b) a subset consisting of the highest step in each reach. Although clasts generally dominate step composition, large woody debris is the most common step-forming material in the highest steps in the study reaches.

resistance between streams because flow resistance generally decreases with increasing discharge as roughness elements (including steps) become small relative to flow depth. Curran (1999) showed that f in a step-pool stream decreased from 14 at summer low flow to 5 at bankfull flow.

Regardless of flow conditions, however, the friction factors in the study streams are high in comparison to gravel-bed streams with gradients ≤ 0.05 m/m, where reported values of f range from 0.06 to 5.5 (Bathurst, 1985; Jarrett, 1984; Thorne and Zevenbergen, 1985). The high values of f that we calculated arise from energy losses from hydraulic conditions common to step-pool streams, including hydraulic jumps, flow separations, vertical falls, extreme turbulence, and channel expansions and contractions. In streams with comparable gradients, using similar reach-average techniques, Beven et al. (1979) computed values of f from about 1 to 48, with an extreme value of 1328. Using cross-section values rather than reach averages, Marcus et al. (1992) obtained values of 2.6 and 5.3 for f in a plunge pool sequence with gradients of 0.16 and 0.10 m/m, respectively, but indicated difficulty in measuring slope and hydraulic radius at a cross-section in such a geometrically variable setting.

3.3. Flow resistance components

To assess the relative influence of various channel elements on flow resistance in step-pool streams, we partitioned flow resistance into grain resistance; form resistance, assumed to be the result of nonstep-forming large woody debris; and spill resistance, assumed to be generated solely at steps. Resistance associated with channel bends, banks, vegetation, and flow expansions and contractions was initially neglected because our choice of field sites was intended to minimize these elements. As the following analysis shows, this was a flawed assumption. It is apparent from the poor correlation between flow resistance and step characteristics that other factors, probably flow expansions and contractions in particular, are significant. Lacking a technique for estimating the magnitude of the flow resistance of these additional factors from the available data, we caution that the values for spill resistance that we calculated may have large error terms.

We calculated grain resistance using Millar and Quick's (1994) adaptation of the Keulegan equation, where the median grain size, D_{50}, is substituted for the roughness parameter k_s:

$$f_g = \left[2.03\log\left(\frac{12.2R}{D_{50}}\right)\right]^{-2}, \quad (1)$$

where f_g is the grain friction factor, and R is the reach-average hydraulic radius, approximately equal to flow depth. Millar and Quick recommend the median grain size rather than a larger measure, such as D_{84}, to avoid incorporating form resistance.

Form resistance in steep streams is generated by individual large roughness elements, including boulders and large woody debris, and by irregularities in channel geometry. In step-pool streams, large clasts are generally associated with steps. In step-pool streams with wood, we assume that nonstep-forming wood is typically the primary source of form roughness. Our field observations suggest that irregularities in channel

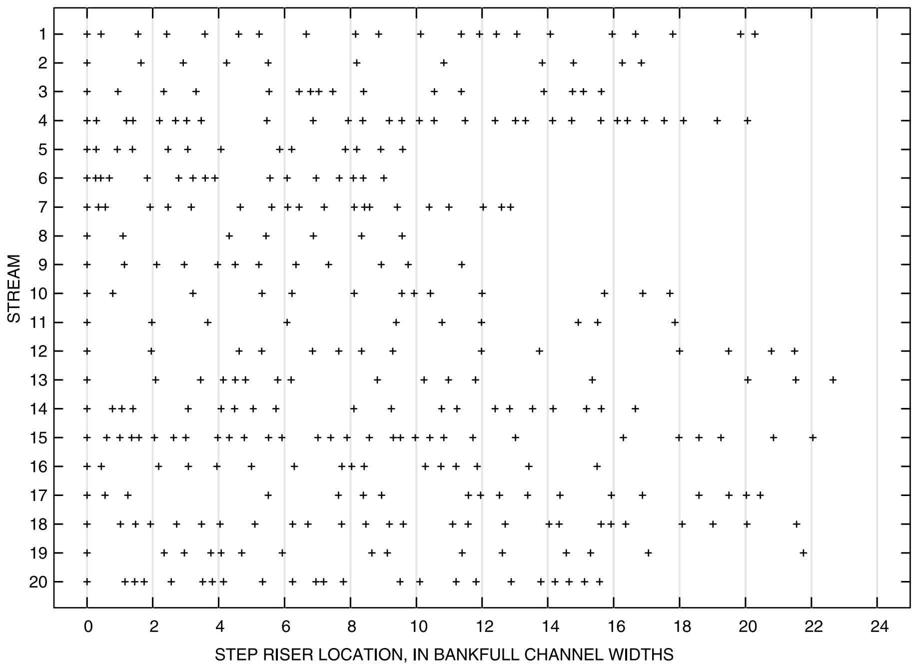

Fig. 7. Spacing of steps in Cascade Range study streams. Step spacing is nonrandom, as determined by a statistical comparison of a tally of the number of steps in two bankfull-width lengths of stream to a Poisson distribution.

geometry, such as contractions and expansions, are largely associated with steps. Field data to address the magnitude of energy losses in contractions and expansions or channel bends are not directly available because we chose relatively straight channels and initially assumed that channel geometry flow resistance effects were minimal. This may not be the case, however, so for the purposes of this study we assign form resistance due to other than large woody debris drag to an error term.

Objects in flow have an inherent drag coefficient, but their hydraulic effect is compounded when they block sufficient flow to interact with flow boundaries. The flow blockage ratio for an object is defined as the ratio of the area of the object projected perpendicularly to flow (A_i) to the product of the local flow width (B_i) and hydraulic radius (R). The effective drag coefficient for objects with a large flow blockage ratio can be many times greater than the drag coefficient for objects in flow of infinite extent (Gippel et al., 1992). Shields and Gippel (1995) quantified the form resistance of large woody debris jams in low-gradient channels from the flow blockage ratio of the jam and an appropriate drag coefficient for that ratio. Their expression for the form friction factor for large woody debris (LWD) can be simplified to:

$$f_{\mathrm{lwd}} = \frac{4\sum_{i=1}^{n} C_{\mathrm{d}i}A_i}{BL_{\mathrm{r}}}, \tag{2}$$

where $C_{\mathrm{d}i}$ is the drag coefficient for the ith element of LWD, A_i is the flow blockage area (projected area of LWD perpendicular to flow) for that element, B is the reach-average flow width, and L_{r} is the reach length. The kinetic energy correction factor in Shields and Gippel's (1995) original equation has been set equal to 1 here because our velocity measurements reflect the effects of a nonuniform velocity distribution across the section.

The drag coefficient, $C_{\mathrm{d}i}$, was determined experimentally by Shields and Gippel as a function of the blockage ratio A_i/BR:

$$C_{\mathrm{d}i} = \frac{C'_{\mathrm{d}}}{a\left[1-\frac{A_i}{BR}\right]^b}, \tag{3}$$

Table 3
Total friction factor and grain, form, and spill friction factors in study streams

Group identifier (see Fig. 2) and major drainage	Stream name	f[a]	f_g[b]	f_{form}[c]	f_{spill}[d] ($f - f_{form} - f_g$)	$(f_g + f_{form})/f$ (%)	f_{spill}/f (%)
A—Coweeman River	Nineteen	380	0.094	0.31	380	0.1	99.9
	O'Neil	231	0.12	0.57	230	0.3	99.7
B—Deschutes River	Hard	76	0.12	0.89	75	1.3	98.7
C—Puyallup River	Diorama	26	0.12	2.0	24	8.2	91.8
	Kellogg	24	0.12	1.2	23	5.4	94.6
	Lost	19	0.13	0.61	18	3.9	96.1
	Ohop	41	0.12	0.32	41	1.1	98.9
	Spine	27	0.12	0.61	26	2.7	97.3
	Thicket	32	0.18	1.1	31	4.0	96.0
D—White River	Scatter	35	0.16	0.37	34	1.5	98.5
E—Cle Elum Lake	Bear	152	0.19	1.2	151	0.9	99.1
	Davis	133	0.17	0.42	132	0.4	99.6
	Newport	256	0.21	0.28	256	0.2	99.8
	Spring	103	0.19	0.98	102	1.1	98.9
F—Taneum Creek	First	35	0.15	1.0	34	3.4	96.6
	Second	46	0.14	2.7	43	6.1	93.9
G—North Fork Ahtanum Creek	McClaine	45	0.14	0.22	45	0.8	99.2
	North Fork Foundation	5	0.13	0.71	4.2	17	83.0
	South Fork Foundation I	11	0.16	0.45	10	5.3	94.7
	South Fork Foundation II	19	0.14	2.1	17	12	88.0

The grain and form friction factor are calculated then subtracted from the total friction factor to determine the spill friction factor.
[a] f represents total flow resistance calculated from measured hydraulic and channel parameters.
[b] f_g represents grain resistance, or distributed roughness of the channel boundary.
[c] f_{form} represents form resistance from large woody debris.
[d] f_{spill} represents spill resistance from steps, regardless of composition.

where C'_d is a drag coefficient in flow of infinite extent, and a and b are experimentally determined coefficients. Values for C'_d vary with orientation, decreasing at oblique angles to flow. For cylinders at about 50°–60° to flow, the average orientation of wood in the study streams (Fig. 3), $C'_d = 0.9$ (Gippel et al., 1992). Shields and Gippel determined that $a = 0.997$ and $b = 2.06$ from flume experiments with a Froude number of 0.35 and a range of blockage ratios from 0.03 to 0.30. Although Froude numbers and blockage ratios in the study streams can locally be quite high, we adopted these values because these flume studies are the closest available simulation of study hydraulics. Determination of the blockage ratio became problematic because, in some cases, flow blockage areas (A_i) proved to be greater than the product of reach-averaged values for B and R. Because the abundance of wood in the study streams made determination of hydraulic radius at each log impractical, we used a visually estimated value of 0.6 for the blockage ratio in the study streams, which equates to $C_d = 6$. This requires extrapolation of Shields and Gippel's formulation beyond the range of flow blockage ratios used in its development, but our resulting value for C_d lies within the range of values determined from flume experiments by Gippel et al. (1992). C_d is sensitive to changes in the blockage ratio, ranging from 1.9 to 25 over a range of blockage ratios from 0.3 to 0.8, for example (and again extrapolating the equation). Applying this range of C_d to a typical study reach, Spring Creek, generates a range of f_{lwd} from 0.31 to 4.1, both of which are quite small relative to the total friction factor of 103.

Formulations for calculating spill resistance from field parameters do not exist, so we determined spill resistance as the total flow resistance for the reach minus the grain resistance and form resistance, or $f_{spill} = f - f_g - f_{form}$, where $f_{form} = f_{lwd}$. Like other measurements of resistance determined by subtraction (e.g., bar resistance in work by Parker and Peterson, 1980;

grain shear in O'Connor, 1994a,b), it includes any omissions or errors involved in the choice of flow resistance components, equations, and measurements. Potential omissions that may be significant for the Cascade Range sites include flow resistance generated at bends, contractions and expansions, and individual large boulders; examining these would require a more detailed survey.

Comparison of the relative magnitude of the three resistance components (Table 3) shows the limited effect of the distributed roughness of the channel boundary (f_g) and the form resistance of nonstep-forming wood (f_{form}). For all reaches, the sum of f_g and f_{form} is less than 20% of the total flow resistance and for 18 of the 20 reaches, is less than 10% of the total resistance.

4. Discussion

4.1. Steps and spill resistance

It is evident from our examination of flow resistance components that spill resistance plays a large role in the hydraulics of step-pool channels (Table 3). The magnitude of spill resistance is much larger than grain resistance or form resistance, assuming that the magnitude of any uncalculated elements of form resistance is on the order of form resistance from large woody debris. According to Leopold et al. (1960), spill resistance is the result of a sudden forced change in velocity and is generated at discrete features such as an extremely sharp bend or where water spills over an obstruction. Leopold notes that spills often generate locally supercritical flow and intense energy dissipation. This description clearly identifies the resistance associated with the water surface drops over steps as spill resistance.

The cumulative water surface drop associated with steps serves as a first-order approximation of energy loss related to steps. Using study averages, this approximation seems to closely match spill resistance. In the study streams, an average of 79% of the total water surface drop is accounted for by steps (Table 2). This is comparable to the 80–90% of total flow resistance attributed to spill resistance, which is generated primarily at steps, plus errors. On a stream-by-stream basis, however, the percentage of water surface drop at steps does not correlate to spill resistance (Fig. 8), suggesting that error terms (other factors that affect resistance) may vary.

4.2. Estimating total flow resistance

Estimates of total flow resistance are useful for scientific and engineering purposes but cannot be made without an understanding of the channel elements that create resistance. Using the result of this study, that steps are the most hydraulically critical element in step-pool channels, we sought relations between total flow resistance and channel characteristics, particularly step characteristics. We first tested the ability of existing equations for estimation of the total friction factor in steep streams, most notably Jarrett's (1984) and Mussetter's (1989), to estimate friction factors in the Cascade Range step-pool channels. Although Jarrett's equation, $n=0.39\,S_f^{0.38}\,R^{-0.16}$, where n is Manning's n friction factor, was developed from channels with gradients less than 0.04 m/m, it came close to estimating the flow resistance for channels as steep as 0.16 m/m studied by Marcus et al.

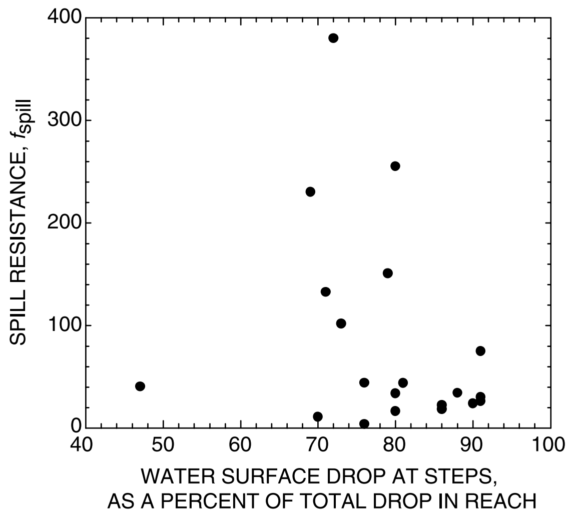

Fig. 8. Variations in spill resistance are not explained by the percentage of the total water surface drop that occurs at steps in the Cascade Range study streams. However, the amount of water surface drop generated at steps (on average over all the study streams) relative to the total water surface drop is about the same proportion as the amount of spill resistance relative to total resistance.

(1992), except where those channels contained plunge pools and hydraulic jumps. Jarrett's equation did not work well for the Cascade Range step-pool channels (Fig. 9). The Mussetter (1989) equation:

$$\sqrt{\frac{8}{f}} = 1.11\left[\frac{h}{D_{84}}\right]^{0.46}\left[\frac{D_{84}}{D_{50}}\right]^{-0.85} S_f^{-0.39},$$

where h is flow depth, D_{84} is the particle size for which 84% of the particles are finer, and S_f is the friction slope, was derived from a suite of streams that partly overlapped the range of gradients and morphologies of the streams in this study. However, Mussetter's equation also could not predict the magnitude or pattern of the friction factors for the Cascade Range step-pool channels in the study streams (Fig. 9).

We suggest that existing empirical equations for steep streams fail to characterize flow resistance in Cascade Range step-pool channels because they were developed from measurements in channels with different physical characteristics, in particular, more uniform longitudinal geometry. Existing equations include grain size distribution, hydraulic radius, and slope, or some combination of these, such as relative submergence (R/D_{84})—factors that primarily relate to grain and form resistance. Because spill resistance at steps constitute most of the total resistance in step-pool channels, more successful empirical relations are likely to include factors related to step characteristics. Such was the case for flume experiments (Abrahams et al., 1995), where it was shown that at-a-site variations in flow resistance could be related to the ratio $H/L/S$, for example.

We used linear regression analyses to test the relations between step characteristics and the total flow resistance of the reach. No significant relations (at $p<0.05$) could be established between f and step characteristics such as H, L, or H/L, suggesting that step geometry may not be a good metric for estimating flow resistance. Other step-related factors, such as local expansions and contractions or the effectiveness of hydraulic jumps, may be significant. For example, the coefficient of variation of the hydraulic radius, a measure of reach heterogeneity that provides a rough indication of channel expansions and contractions, explained 43% of the variation in friction factors between streams ($r^2=0.43$, $p<0.05$). It is this result that leads us to suggest that sources of form resistance other than large woody debris (the error term in our calculation of spill resistance) need to be more closely examined.

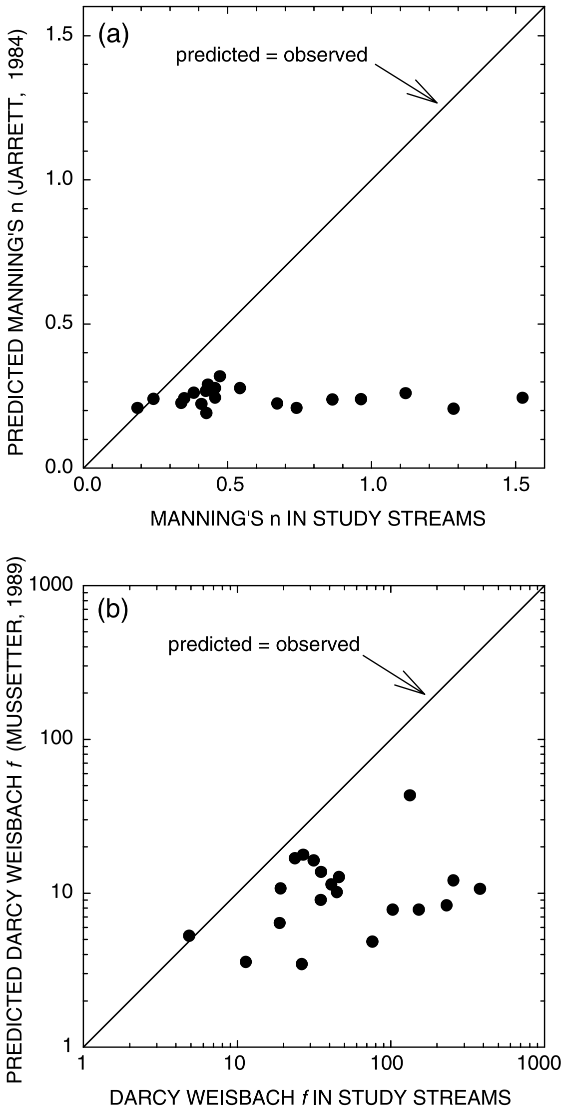

Fig. 9. Existing equations for estimation of friction factors in steep channels do not work well in the Cascade Range study streams. (a) Jarrett's (1984) equation for Manning's n underestimated the study reach values for all but the two streams with the least flow resistance. (b) Mussetter's (1989) equation for Darcy–Weisbach f more closely matched the range of study reach values, but underestimated the friction factor in all but one stream. A log scale was applied to (b) because the values span two orders of magnitude.

4.3. The role of wood in steps

Channels with steps formed of wood, rock clasts, and both materials together may have more complicated relations between channel materials and step characteristics than channels with rock clasts alone. We analyzed relations between step spacing and height and properties of step-forming materials in the Cascade Range step-pool channels to determine ways that steps reflect the influence of more than one material and to attempt to discern the role of wood in steps.

We examined the spatial distribution of steps along the study reaches to gain greater understanding of their origin, specifically, whether they could be considered hydraulically arranged. Because steps are arranged in a statistically more uniform than random nature despite stream gradients as great as 0.18 m/m (Table 1), we examined the possibility that some of the steps have locations determined by processes other than hydraulic forces. Streams steeper than about 0.065 m/m without wood generally have a cascade-type morphology and few pools, whereas similarly steep streams with wood have a step-pool morphology (Montgomery and Buffington, 1997). Montgomery and Buffington referred to forced step-pool channels as those in which large woody debris forms most steps. By this measure, the reaches in the present study are not forced step-pool streams because clasts are more commonly included in steps than large woody debris. However, from field observations, it appears that large immobile pieces or clusters of wood or bedrock do control the location of some steps in the study streams, creating discrete forced steps. If all steps were forced, the spatial distribution of steps could be expected to be random. The overall nonrandom arrangement of the steps in the study streams suggests that steps have been hydraulically arranged between forced steps. We make a distinction here between forced steps and hydraulically arranged steps and suggest that streams with large woody debris can contain a mixture of both. This mixture has also been observed by Wohl et al. (1997) and Heede (1972, 1981).

Step height may depend on the diameter of the step-forming material. Our surveys enable us to examine the height and composition of individual steps, but only a reach average of step-forming clast diameter and a reach average of all large wood debris diameters, regardless of whether they form steps or not. These data show that average step height does correlate with the log of the median size of the step-forming clasts but not with the log of the reach-average large woody debris diameter (Fig. 10). However, it is apparent that large woody debris is more common than clasts in the highest steps (Fig. 6). A survey of other studies that examined relations between step height and step-forming material shows mixed results. In step-pool channels of the Santa Monica Mountains of southern California, Chin (1999) showed that step height correlated with the particle size of the step-forming clasts. Wohl et al. (1997), in a study of Montana step-pool channels, found a strong correlation between step height and clast diameter as well as a weak but statistically significant correlation to wood diameter. Similarly, Grant et al. (1990) observed consistent step

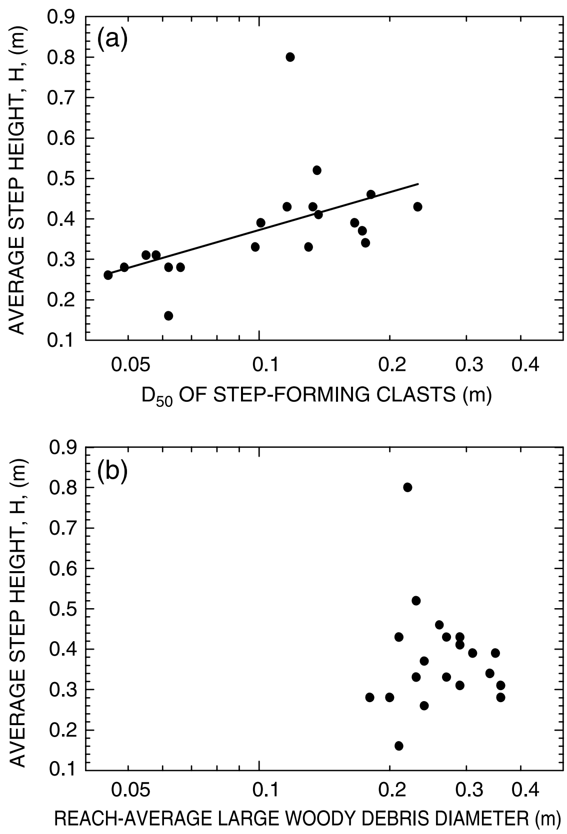

Fig. 10. Average step height correlates to (a) the log of the median diameter of step-forming clasts ($r^2=0.64$, $p<0.05$ when a stream with a large bedrock step, McClaine Creek, is excluded) but not to (b) the log of the reach-average large woody debris diameter.

heights across study reaches and suggested this to be a function of step-forming clast size and shape. Chartrand and Whiting (2000) found that step height was best correlated to median size of the step-forming clasts. However, Wohl and Grodek (1994) found no relation between step height and clast size. Wohl et al. (1997) found no significant relation between step height and composition using reach averages, but did not examine the highest steps separately.

Results of this and other studies suggest that clasts may have more influence than wood on average step height, whereas wood may create exceptionally large steps. The presence of wood may increase the maximum possible step size if clast size has a limiting effect on step height. Wood may force the location of individual steps, but may also be a component of hydraulically arranged steps within the same reach.

4.4. The overall role of wood in step-pool streams and implications of changing wood abundance in step-pool streams

Large woody debris can control channel morphology, as in the case of forced steps. Large woody debris also directly affects channel hydraulics by generating spill resistance (and possibly form resistance) at steps and form resistance elsewhere in the channel. From the hydraulic analysis of flow resistance components (Table 3) and analysis of step-forming material (Fig. 6), it is clear that step-forming wood contributes more to the total flow resistance than nonstep-forming wood.

Our analysis indicates that clast size is correlated to average step height but large woody debris is important for formation of especially high steps. Using step height as a rough indicator of energy loss, step composition is not a significant variable for determining energy loss if step heights are comparable between materials. Wood was more common than clasts in exceptionally high steps in the Cascade Range streams we studied. The implication of this relation is that large woody debris may disproportionately lead to the formation of high steps that will dissipate large amounts of energy in step-pool channels.

These results imply that an increase in the abundance of wood in a steep channel will have a stronger effect on flow resistance if that wood forms step risers than if it rests solely on step treads. Thus, it is the distribution and function, rather than the abundance, of wood that determines the influence of wood in step-pool channels. This is further supported by the lack of correlation between wood abundance, measured as pieces per 100 m or as total flow blockage area (Table 1), and total flow resistance (Table 3) ($r^2 < 0.1, p > 0.05$).

5. Conclusions

Analyses of channel geometry and low-flow hydraulics along 20 step-pool reaches in the Washington Cascade Range yielded estimates of friction factors (f) ranging from 5 to 380 during low flows. These values are high relative to lower-gradient gravel-bed mountain rivers, and reflect the energy loss due to secondary circulation, hydraulic jumps, vertical falls, extreme turbulence, and channel expansions and contractions. Partitioning the flow resistance into grain resistance, form resistance from large woody debris, and spill resistance from steps shows that a large proportion of the total flow resistance is generated at steps. Grain and form resistance accounted for less than 10% of the total flow resistance in all but two of the study reaches. Although these values may be conservative estimates because some components of form resistance, such as channel expansion and contraction, are unaccounted for, these figures indicate the dominance of spill resistance, which is on the order of 90% of total flow resistance, in step-pool streams.

Large woody debris exerts a strong indirect control on spill resistance in the step-pool channels described here by accentuating step height. The cumulative water surface drop associated with steps serves as a first-order approximation of energy loss related to steps. Using an average of all study reaches, this approximation closely matches spill resistance. Water surface drop over the steps is in turn related to the presence of large woody debris. Large woody debris is more common than clasts in the tallest steps, and the presence of this debris seems to be required to form exceptionally tall steps.

Other forms of resistance contributed by large woody debris in step-pool channels may not be as important as spill resistance. In lower-gradient channels, where form resistance accounts for a much greater proportion of the total resistance, large woody debris abundance can strongly influence total flow resistance. The dominance of spill resistance combined with the much larger values of total flow resistance in step-pool channels, however, makes it clear that step-forming wood contributes more to the total flow resistance than nonstep-forming wood. This is supported by the lack of correlation between wood abundance, measured as pieces per 100 m or as total flow blockage area, and total flow resistance. Thus, it is the distribution and function, rather than the abundance, of wood that determines the influence of wood on flow resistance in step-pool channels.

It is important to understand the hydraulics of step-pool channels in forested basins because these channels have been and will continue to be impacted by forest management practices, and the morphology that makes these channels unique is difficult to restore. The research summarized here implies that a decrease in the abundance of large woody debris in the step risers of step-pool channels can result in a decrease in average step height, and thus a decrease in spill resistance and total flow resistance. The research also implies that an increase in the abundance of wood in a steep channel will have a stronger effect on flow resistance if that wood forms step risers than if it rests solely on step treads. These implications may be used to guide stream rehabilitation efforts on headwater channels that would naturally have large woody debris incorporated into channel bedforms.

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References

Abbe, T.B., Montgomery, D.R., 1996. Large woody debris jams, channel hydraulics and habitat formation in large rivers. Regulated Rivers 12, 201–221.

Abrahams, A.D., Li, G., Atkinson, J.F., 1995. Step-pool streams: adjustment to maximum flow resistance. Water Resources Research 31 (10), 2593–2602.

Bathurst, J.C., 1982. Flow resistance in boulder-bed streams. In: Hey, R.D., Bathurst, J.C., Thorne, C.R. (Eds.), Gravel-bed Rivers. Wiley, Chichester, pp. 443–465.

Bathurst, J.C., 1985. Flow resistance estimation in mountain rivers. Journal of Hydraulic Engineering 111 (4), 625–643.

Beven, K., Carling, P., 1992. Velocities, roughness and dispersion in the lowland River Severn. In: Carling, P.A., Petts, G.E. (Eds.), Lowland Floodplain Rivers: Geomorphological Perspectives. Wiley, Chichester, pp. 71–93.

Beven, K., Gilman, K., Newson, M., 1979. Flow and flow routing in upland channel networks. Hydrological Sciences Bulletin 24 (3), 303–325.

Bilby, R.E., 1981. Role of organic debris dams in regulating the export of dissolved and particulate matter from a forested watershed. Ecology 62 (5), 1234–1243.

Bisson, P.A., Bilby, R.E., Bryant, M.D., Dolloff, C.A., Grette, G.B., House, R.A., Murphy, M.L., Koski, K.V., Sedell, J.R., 1987. Large woody debris in forested streams in the Pacific Northwest: past, present, and future. In: Salo, E.O., Cundy, T.W. (Eds.), Streamside Management Forestry and Fishery Implications. University of Washington Institute of Forest Resources, Seattle, pp. 143–190. Contribution no. 57.

Buffington, J.M., Montgomery, D.R., 1999. Effects of hydraulic roughness on surface textures of gravel-bed rivers. Water Resources Research 35 (11), 3507–3521.

Calkins, D., Dunne, T., 1970. A salt tracing method for measuring channel velocities in small mountain streams. Journal of Hydrology 11, 379–392.

Chartrand, S.M., Whiting, P.J., 2000. Alluvial architecture in headwater streams with special emphasis on step-pool topography. Earth Surface Processes and Landforms 25, 583–600.

Chin, A.H., 1999. The morphologic structure of step-pools in mountain streams. Geomorphology 27, 191–204.

Curran, J.H., 1999. Hydraulics of large woody debris in step-pool channels, Cascade Range, Washington. MS thesis, Colorado State University, Fort Collins, CO.

Day, T.J., 1977. Field procedures and evaluation of a slug dilution gauging method in mountain streams. Journal of Hydrology, New Zealand 16 (2), 113–133.

Einstein, H.A., Barbarossa, N.L., 1952. River channel roughness. Transactions of the American Society of Civil Engineers 117, 1121–1146.

Gippel, C.J., O'Neill, I.C., Finlayson, B.L., 1992. The Hydraulic Basis of Snag Management. Center for Environmental Applied Hydrology, Department of Civil and Agricultural Engineering, University of Melbourne, Parkville, Australia.

Grant, G.E., Swanson, F.J., Wolman, M.G., 1990. Pattern and origin of stepped-bed morphology in high-gradient streams, Western Cascades, Oregon. Geological Society of America Bulletin 102, 340–352.

Heede, B.H., 1972. Influences of a forest on the hydraulic geometry of two mountain streams. Water Resources Bulletin 8 (3), 523–530.

Heede, B.H., 1981. Dynamics of selected mountain streams in the Western United States of America. Zeitschrift fur Geomorphologie 25 (1), 17–32.

Jarrett, R.D., 1984. Hydraulics of high-gradient streams. Journal of Hydraulic Engineering 110 (11), 1519–1539.

Keller, E.A., MacDonald, A., Tally, T., Merrit, N.J., 1995. Effects of large organic debris on channel morphology and sediment storage in selected tributaries of Redwood Creek, Northwestern California. In: Nolan, K.M., Kelsey, H.M., Marron, D.C. (Eds.), Geomorphic processes and aquatic habitat in the Redwood Creek Basin, Northwestern California. United States Geological Survey Professional Paper, 1454-P, pp. 1–29.

Kellerhals, R., 1970. Runoff routing through steep natural channels. Journal of the Hydraulics Division 96 (HY11), 2201–2217.

Knighton, D., 1998. Fluvial Forms and Processes: A New Perspective. Arnold, London. 383 pp.

Leopold, L.B., Bagnold, R.A., Wolman, M.G., Brush Jr., L.M., 1960. Flow resistance in sinuous or irregular channels. United States Geological Survey Professional Paper 282-D. 134 pp.

Manga, M., Kirchner, J.W., 2000. Stress partitioning in streams by large woody debris. Water Resources Research 36, 2373–2379.

Marcus, W.A., Roberts, K., Harvey, L., Tackman, G., 1992. An evaluation of methods for estimating Manning's *n* in small mountain streams. Mountain Research and Development 12 (13), 227–239.

Millar, R.G., Quick, M.C., 1994. Flow resistance of high-gradient gravel channels. In: Cotroneo, G.V., Rumer, R.R. (Eds.), Hydraulic Engineering '94, Proceedings of the 1994 Conference, vol. 1. American Society of Civil Engineers, Buffalo, NY, pp. 717–721.

Montgomery, D.R., Buffington, J.M., 1997. Channel-reach morphology in mountain drainage basins. Geological Society of America Bulletin 109 (5), 596–611.

Mosley, M.P., 1981. The influence of organic debris on channel morphology and bedload transport in a New Zealand forest stream. Earth Surface Processes and Landforms 6, 571–579.

Mussetter, R.A., 1989. Dynamics of mountain streams. PhD dissertation, Colorado State University, Fort Collins, CO.

O'Connor, M.D., 1994a. Sediment transport in steep tributary streams and the influence of large organic debris. PhD dissertation, University of Washington, Seattle, WA.

O'Connor, M.D., 1994b. Energy losses in steep tributary streams at flows near the threshold of bedload entrainment. In: Cotroneo, G.V., Rumer, R.R. (Eds.), Hydraulic Engineering '94, Proceedings of the 1994 Conference, vol. 1. American Society of Civil Engineers, Buffalo, NY, p. 778.

Parker, G., Peterson, A.W., 1980. Bar resistance of gravel-bed streams. Journal of the Hydraulics Division 106 (HY10), 1559–1575.

Pearce, A.J., Watson, A., 1983. Medium-term effects of two landsliding episodes on channel storage of sediment. Earth Surface Processes and Landforms 8, 29–39.

Peterson, D.F., Mohanty, P.K., 1960. Flume studies of flow in steep, rough channels. Journal of the Hydraulics Division 86 (HY9), 55–76.

Prestegaard, K.L., 1983. Bar resistance in gravel bed streams at bankfull stage. Water Resources Research 19, 472–476.

Robison, E.G., Beschta, R.L., 1990. Coarse woody debris and channel morphology interactions for undisturbed streams in Southeast Alaska, USA. Earth Surface Processes and Landforms 15, 149–156.

Rouse, H., 1965. Critical analysis of open-channel resistance. Journal of the Hydraulics Division 91 (HY4), 1–25.

Schuster, J.E., 1992. Geologic Map of Washington. Washington State Department of Natural Resources, Olympia, WA.

Shields Jr., F.D., Gippel, C.J., 1995. Prediction of effects of woody debris removal on flow resistance. Journal of Hydraulic Engineering 121 (4), 341–354.

Spence, C., McPhie, M., 1997. Streamflow measurement using salt dilution in tundra streams, Northwest Territories, Canada. Journal of the American Water Resources Association 33 (2), 285–291.

Swanson, F.J., Lienkaemper, G.W., Sedell, J.R., 1976. History, physical effects, and management implications of large organic debris in Western Oregon streams. USDA Forest Service General Technical Report PNW-56. 15 pp.

Thorne, C.R., Zevenbergen, L.W., 1985. Estimating mean velocity in mountain rivers. Journal of Hydraulic Engineering 111 (4), 612–624.

Wohl, E.E., Grodek, T., 1994. Channel bed-steps along Nahal Yael, Negev Desert, Israel. Geomorphology 9, 117–126.

Wohl, E.E., Thompson, D.M., 2000. Velocity characteristics along a small step-pool channel. Earth Surface Processes and Landforms 25, 353–367.

Wohl, E., Madsen, S., MacDonald, L., 1997. Characteristics of log and clast bed-steps in step-pool streams of northwestern Montana, USA. Geomorphology 20, 1–10.

Wolman, M.G., 1954. A method of sampling coarse river-bed material. Transactions-American Geophysical Union 35 (6), 951–956.

Zar, J.H., 1996. Biostatistical Analysis. Prentice-Hall, New Jersey. 662 pp.