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Flow Resistance Dynamics in Step-pool Channels: 2. Partitioning Between Grain, Spill, and Woody Debris Resistance

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Flow resistance dynamics in step-pool stream channels: 1. Large woody debris and controls on total resistance

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[1] Flow resistance dynamics in step-pool channels were investigated through physical modeling using a laboratory flume. Variables contributing to flow resistance in step-pool channels were manipulated in order to measure the effects of various large woody debris (LWD) configurations, steps, grains, discharge, and slope on total flow resistance. This entailed nearly 400 flume runs, organized into a series of factorial experiments. Factorial analyses of variance indicated significant two-way and three-way interaction effects between steps, grains, and LWD, illustrating the complexity of flow resistance in these channels. Interactions between steps and LWD resulted in substantially greater flow resistance for steps with LWD than for steps lacking LWD. LWD position contributed to these interactions, whereby LWD pieces located near the lip of steps, analogous to step-forming debris in natural channels, increased the effective height of steps and created substantially higher flow resistance than pieces located farther upstream on step treads. Step geometry and LWD density and orientation also had highly significant effects on flow resistance. Flow resistance dynamics and the resistance effect of bed roughness configurations were strongly discharge-dependent; discharge had both highly significant main effects on resistance and highly significant interactions with all other variables.

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1. Introduction

[2] Step-pool bed forms are ubiquitous in steep, headwater stream channels and provide an important means of energy dissipation in these high-energy systems [*Chin and Wohl*, 2005]. Flow resistance is generated in step-pool channels by the form drag of step-forming roughness features, including large clasts and/or logs, and by a tumbling flow regime in which critical or supercritical flow over step crests plunges into downstream pools, where velocity abruptly decreases and hydraulic jumps and roller eddies generate substantial turbulence [*Peterson and Mohanty*, 1960; *Wohl and Thompson*, 2000; *Wilcox and Wohl*, 2006]. Sequences of step-pool features occur in channels with gradients of 0.02 to 0.2 m/m [*Wohl and Grodek*, 1994; *Montgomery and Buffington*, 1997; *Chartrand and Whiting*, 2000], resulting in stepped profiles in which elevation loss is concentrated in steps separated by low-gradient pools [*Keller and Swanson*, 1979]. In confined, steep-gradient streams, where lateral adjustments are not available for dissipating energy [*Chin*, 1989], step-pool bed forms and the hydraulic resistance they create limit the stream energy available for sediment transport [*Heede*, 1981] and have been hypothesized to represent a channel adjustment to maximize flow resistance [*Abrahams et al.*, 1995].

[3] Many of the previous studies of step-pool channels have focused on channels in which steps are clast formed and large woody debris (LWD) is absent [e.g., *Hayward*, 1980; *Wohl and Grodek*, 1994; *Chin*, 1999; *Lenzi*, 2001; *Lee and Ferguson*, 2002]. Woody debris is prevalent in many step-pool channels, however, and historically may have been much more so prior to widespread LWD removal from stream channels and reduced recruitment of LWD as a result of timber harvest practices [*Bisson et al.*, 1987; *Montgomery et al.*, 2003]. The effects of LWD on hydraulics, sediment transport and storage, channel morphology, and habitat and substrate diversity have been well documented across a range of channel types, but especially in gravel bed pool-riffle channels [*Bilby and Likens*, 1980; *Lisle*, 1986; *Robison and Beschta*, 1990; *Shields and Smith*, 1992; *Nakamura and Swanson*, 1993; *Smith et al.*, 1993; *Gippel*, 1995; *Richmond and Fausch*, 1995; *Abbe and Montgomery*, 1996; *Piegay and Gurnell*, 1997; *Buffington and Montgomery*, 1999; *Gurnell et al.*, 2002; *Faustini and Jones*, 2003; *Piegay*, 2003].

[4] A subset of these studies has described the effects of LWD on channel morphology and flow hydraulics in steep headwater streams [*Keller and Swanson*, 1979; *Lisle*, 1986; *Bisson et al.*, 1987; *Lisle*, 1995; *Jackson and Sturm*, 2002; *Curran and Wohl*, 2003; *Faustini and Jones*, 2003; *Gomi et al.*, 2003]. Woody debris, by creating channel obstructions either alone or in conjunction with large clasts, can cause formation of step-pool features, sometimes referred to as forced steps [*Montgomery and Buffington*, 1997], which in

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turn are responsible for substantial portions of the energy dissipation and elevation loss in steep channels [*Keller and Swanson*, 1979; *Heede*, 1981; *Marston*, 1982; *Curran and Wohl*, 2003; *Faustini and Jones*, 2003]. Studies in the Pacific Northwest indicate that LWD steps are higher, create larger pools and longer low-gradient reaches upstream, and store finer sediment than steps formed only by boulders, resulting in greater variability in channel gradients and bed particle size, greater flow depths, and more widely spaced steps [*Faustini and Jones*, 2003; *MacFarlane and Wohl*, 2003]. Comparison of step-pool streams with and without LWD in the Washington Cascades found lower flow resistances in streams without LWD than recorded in LWD streams, providing indirect evidence that LWD can substantially increase total flow resistance [*Curran and Wohl*, 2003; *MacFarlane and Wohl*, 2003]. In particular, step-forming wood has a much greater influence on flow resistance than wood not incorporated in steps [*Curran and Wohl*, 2003].

[5] Because manipulation of roughness variables and direct measurement of hydraulic parameters in steep, turbulent streams is extremely difficult, physical modeling using laboratory flume experiments provides an opportunity to isolate and investigate basic processes in these channels. Previous flume studies have examined step-forming mechanisms [*Whittaker and Jaeggi*, 1982; *Grant and Mizuyama*, 1992; *Crowe*, 2002], step spacing [*Maxwell and Papanicolaou*, 2001; *Curran and Wilcock*, 2005], pool scour below steps [*Whittaker*, 1987; *Comiti*, 2003; *Marion et al.*, 2004], and flow resistance for step-pool systems without woody debris roughness [*Ashida et al.*, 1986; *Abrahams et al.*, 1995; *Maxwell and Papanicolaou*, 2001; *Lee and Ferguson*, 2002]. Flume studies have been used to document large variations in resistance with discharge, and observations that velocity consistently increases more rapidly than flow depth with discharge suggest that driving forces increase more rapidly than form drag in step-pool channels [*Lee and Ferguson*, 2002]. On the basis of flume and field results, *Abrahams et al.* [1995] proposed that step spacing and geometry evolve to conditions of maximum flow resistance, although many measurements of step-pool geometry do not conform to the conditions suggested by this hypothesis [*Curran and Wilcock*, 2005].

[6] Previous flume experiments have also investigated LWD dynamics, including debris entrainment and transport [*Braudrick et al.*, 1997; *Braudrick and Grant*, 2000], the effect of LWD on channel bed scour [*Beschta*, 1983; *Cherry and Beschta*, 1989; *Beebe*, 2000; *Wallerstein et al.*, 2001], and the effect of woody debris on stage [*Young*, 1991] and drag coefficients [*Gippel et al.*, 1992; *Wallerstein et al.*, 2002] in low-gradient rivers. *Gippel et al.* [1992] used force measurements on model LWD to determine how various LWD configuration factors affect drag coefficient. They found that LWD orientation, blockage effect (the proportion of the flow's cross-section area occupied by LWD), and shielding effect (LWD spacing, or density) had the greatest effects on drag, whereas length-to-diameter ratio and LWD height above the bed had much smaller effects. *Young* [1991] recorded similar results as *Gippel et al.* [1992], illustrating the effects of LWD piece orientation and spacing on percent stage rise upstream from LWD pieces. *Wallerstein et al.* [2002] found that logs positioned near the free surface (i.e., with low submergence values) have drag coefficients that are consistently higher than published values for cylinders because of their contribution to surface wave formation.

[7] These works have collectively provided insights into the hydraulics and morphology of step-pool channels and into the role of LWD in creating flow resistance in lower-gradient channels. Controls on hydraulic resistance in step-pool channels and the hydraulic effects of LWD in these channels are poorly understood, however, reflecting a general lag in research on physical processes in steep stream channels behind related work on lower-gradient channels. Improved understanding of these topics is needed because of the implications of flow resistance dynamics for channel form and stability, sediment transport, and aquatic habitat. Because of the position of step-pool channels in the headwaters of many drainage networks, processes in these channels strongly influence water and sediment discharge to downstream areas, thereby affecting flooding, water supply, reservoir sedimentation, and aquatic and riparian habitat. Further, because stage-discharge relationships are governed by flow resistance, increased understanding of the controls on flow resistance is needed to improve estimates of velocity and discharge in step-pool channels. Existing equations for estimating flow resistance or sediment transport in lower-gradient channels have substantial error when applied to step-pool and other high-gradient systems [*Bathurst*, 1985; *Mussetter*, 1989; *Jarrett*, 1992; *Marcus et al.*, 1992; *Yager et al.*, 2002; *Curran and Wohl*, 2003]. Management concerns in headwater streams, including the impacts of land use on woody debris loading and the potential for associated stream restoration efforts, also highlight the need for improved understanding of the role of LWD in step-pool channels.

[8] The study described here used flume modeling to investigate flow resistance dynamics in step-pool channels. By manipulating variables contributing to flow resistance via a series of flume runs, we sought to (1) measure the relative effect of step-pool structures, large woody debris (LWD), non-step-forming grains, discharge, and slope on flow resistance; (2) assess the role of interactions between these resistance components in altering flow resistance dynamics; and (3) measure how variations in LWD configurations affect hydraulic resistance in step-pool channels. A companion component of this flume experiment explored the partitioning of resistance in step-pool channels between grains, spill over step-pool bed forms, and debris resistance, as reported by *Wilcox et al.* [2006] and *Wilcox* [2005]. The results of this work are intended to increase understanding of the role of large woody debris (LWD) and other controls on flow resistance in step-pool channels in order to develop insight into the mechanics and morphology of these channels, to provide guidance for stream restoration and other management concerns in steep channels, and to elucidate how flow resistance dynamics in step-pool channels compare to lower-gradient systems.

2. Methods

[9] Darcy-Weisbach friction factor was measured for nearly 400 flume runs in order to test the effect of numerous variables contributing to flow resistance in step-pool channels, including discharge, presence/absence of grains and steps, step-pool geometry, slope, and LWD density, orien-

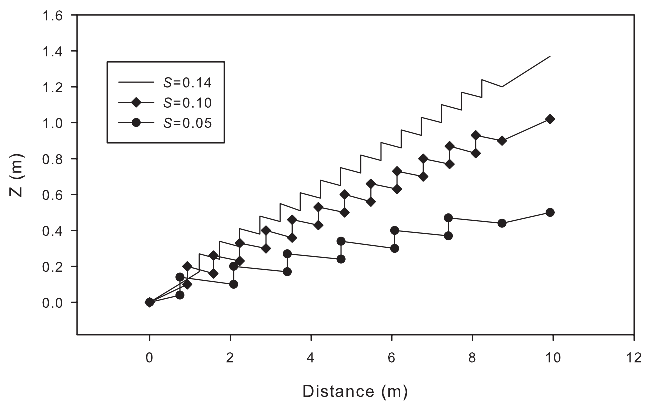

Figure 1. Longitudinal bed profiles illustrating step geometry at the three flume slopes tested here. A step height–step length–bed slope (*H*/*L*/*S*) ratio of 1.4 was maintained across the three slopes, with step length increasing as slope decreased and step height remaining constant.

tation, piece length, arrangement, and position. Roughness configurations were manipulated using a series of factorial experiments in which multiple combinations of variables contributing to resistance were tested, allowing estimates of both the main effects of different variables on flow resistance and of interactions among resistance features.

2.1. Flume Configuration

[10] The flume study was performed at Colorado State University's Engineering Research Center using a recirculating flume that is 9 m long and 0.6 m wide, with a rectangular cross section and smooth sidewalls. Flow was delivered to the flume via pipes and pumps from a reservoir of water, and a cobble-filled baffle was used to dissipate flow energy at the upstream end of the flume. Five discharges were tested: 4, 8, 16, 32, and 64 L/s. These discharges were selected to simulate a range of low-flow to high-flow conditions, resulting in varying relative submergence of roughness features and Froude numbers. Because we sought to examine the effect of a range of flow conditions on flow resistance, exact scaling of Froude number between our flume model and prototype step-pool streams was not applied. Flow for all flume runs was fully turbulent, allowing relaxation of Reynolds number scaling [*Peakall et al.*, 1996]. Flume runs were completed at three bed slopes intended to represent a range of slopes found in step-pool channels: 0.05, 0.10, and 0.14 m/m.

[11] In order to simulate step-pool bed forms and to create spill resistance, step-pool sequences were constructed using plywood for the step treads and wood blocks (two-by-fours, i.e., pieces 38 mm wide and 89 mm high) for the step risers. Step geometry was scaled to mimic the following geometric tendencies of step-pool sequences: (1) many step-pool channels are characterized by step height (*H*)–step length (*L*)–bed slope (*S*) ratios (*H*/*L*/*S*) between 1 and 2 [*Abrahams et al.*, 1995; *Curran and Wohl*, 2003; *MacFarlane and Wohl*, 2003]; (2) *H* variations with *S* often are limited [*Grant et al.*, 1990; *Curran and Wohl*, 2003]; and (3) *L* varies inversely with *S* [*Whittaker*, 1987; *Chin*, 1989; *Grant et al.*, 1990; *Wohl and Grodek*, 1994; *Wooldridge and Hickin*, 2002]. By adopting a fixed step height of 0.1 m and decreasing step length from 1.4 m at $S = 0.05$ m/m to 0.5 m at $S = 0.14$ m/m, a consistent *H*/*L*/*S* ratio of 1.4 was achieved for flume runs in which steps were present (Figure 1). The resulting step treads had a reverse gradient, whereby bed elevation increased from the base of one step to the lip of the next so that flow depths were greatest at the upstream end of each step tread, simulating a pool, and lowest at the downstream end of the step tread, simulating a step lip. In order to isolate the effect of steps on flow resistance, we also completed flume runs with a plane-bed configuration.

[12] All flume runs were completed with a nonerodible boundary and no sediment transport. The flume substrate consisted of either smooth plywood or fine gravel glued to the bed of the flume, depending on the roughness configuration being tested. For flume runs incorporating grain resistance, fine gravel with a median size (D_{50}) of 15 mm (D_{84} = 22 mm) was glued to the bed of the flume (for plane bed runs) or the step treads (for step-pool runs). This grain size mixture generally produced relative roughness ratios (D_{84}/d, where d is flow depth) within the range of 0.3–0.8 suggested by *Montgomery and Buffington* [1997] for step-pool channels under bankfull conditions. Grain size heterogeneity was lower here, however, than in natural step-pool channels as a result of the use of construction materials, rather than large clasts, to create steps.

[13] Because investigating the effects of various LWD configurations on flow resistance in step-pool channels was a central objective of this study, numerous different woody debris configurations were established by varying LWD density, length, orientation, arrangement, and position on steps. PVC cylinders (2.5 cm diameter) were fixed to the bed and/or flume walls to represent LWD and debris resistance. LWD densities were set at four levels: high, medium, low, and none. High-, medium-, and low-density LWD configurations corresponded to 10%, 5%, and 2.5% bed coverage by LWD (LWD area/bed area), or 2.3, 1.2, and 0.6 pieces/channel width, respectively. The high-density configuration scales with field results from small streams (<10 m width) within old growth forests in western Washington indicating average LWD densities of 2.2–2.4 pieces/channel width [*Bilby and Ward*, 1989].

[14] Three LWD orientations were tested: $\theta = 90°$ (perpendicular; Figure 2, left), $\theta = 30°–45°$ (ramped; Figure 2, middle), and a combination of perpendicular and ramped pieces (Figure 2, right), where θ is the angle of model LWD pieces with respect to the flume walls. We also tested the effect of three different LWD piece lengths/shapes: long cylinders (0.6 m, equal to flume width) (Figure 2), short cylinders (0.3 m, or half the flume width) (Figure 3, left), and rootwad pieces (short cylinders with three-way branched PVC junctions attached to the ends to simulate rootwads; Figure 3, right). Flume tests of three LWD arrangements were also completed: single pieces resting on the bed (Figures 2 and 3), pieces vertically stacked in pairs (Figure 4, top), and pieces arranged into LWD jams (Figure 4, bottom). To create jams, long and short pieces were interlocked with both perpendicular and ramped orientations. Flume runs for each LWD configuration were repeated at three densities, three slopes, and two discharges (8 and 32 L/s; a subset of these runs were completed at all five discharges). The variables tested in the flume are summarized in Table 1.

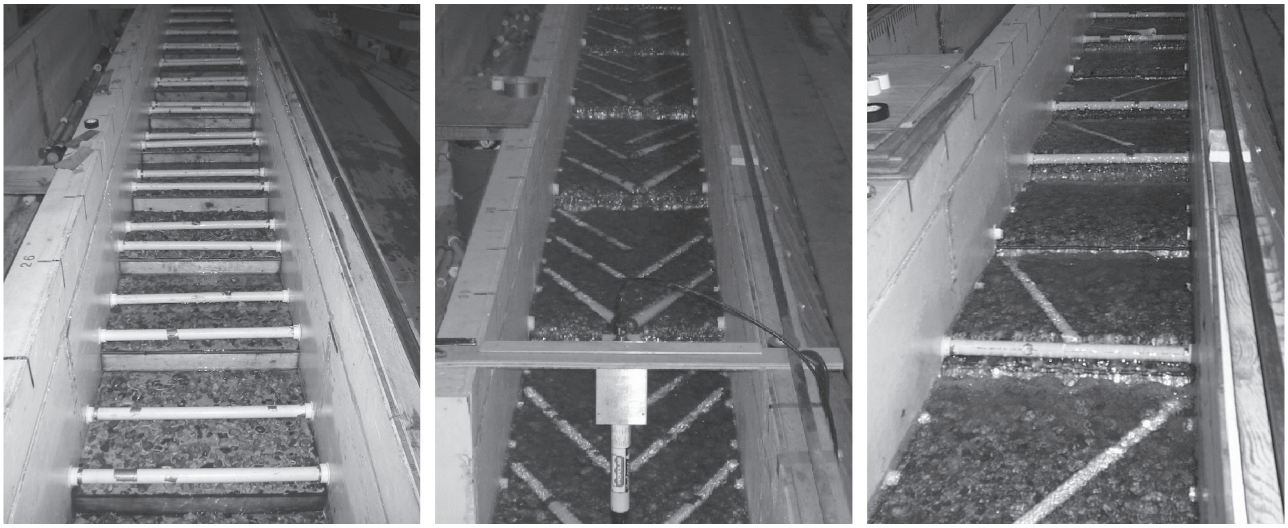

Figure 2. Upstream view of flume, showing examples of large woody debris (LWD) configurations tested to measure the effect of LWD orientation on flow resistance: (left) perpendicular (high density, S = 0.14 m/m), (middle) ramped (high density, S = 0.05 m/m), and (right) combination (medium density, S = 0.10 m/m). For all three orientations, piece length = long. Conductivity probe used for salt dilution measurements of velocity is shown in foreground of Figure 2 (middle).

[15] LWD pieces were spaced evenly on each step tread, with the number of pieces on each step tread depending on the density, piece length, and step length. Because each short piece covered half as much of the bed as a long piece, twice as many short pieces as long pieces were used to maintain a given LWD density. For example, the high-density LWD configuration comprised either 30 long pieces or 60 short pieces distributed over the length of the flume

Figure 3. Upstream view of flume, showing examples of LWD configurations employed to test effects of piece length on flow resistance: (left) short pieces (high density, combination orientation) and (right) rootwad pieces (high density, perpendicular orientation). Long pieces were also tested, as shown in Figure 2.

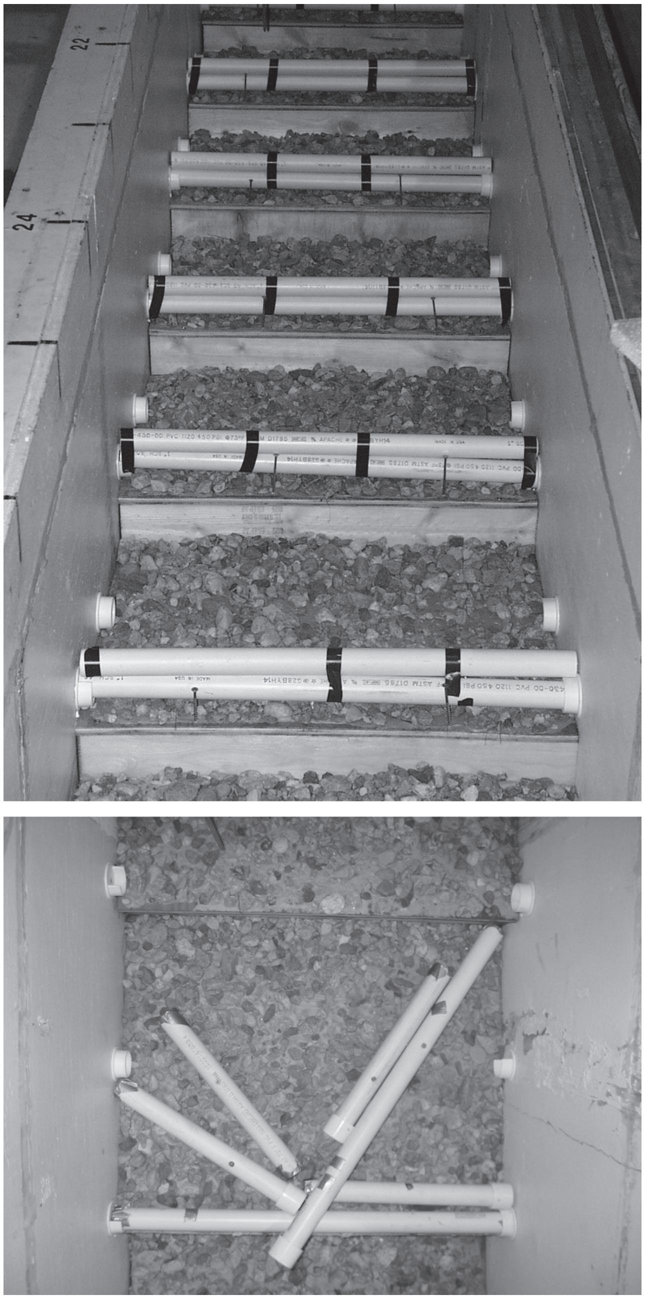

Figure 4. Two LWD arrangements assessed as part of factorial tests of the effect of LWD configuration on flow resistance: (top) stacked (high density, perpendicular) and (bottom) jams. Single pieces were also tested, as shown in Figures 2 and 3.

(Figures 2, left, and 3, left). Because step length varied with slope based on the *H*/*L*/*S* criterion discussed above, with shorter step treads at steeper slopes, the number of pieces per step was proportional to step length, in order to keep densities consistent at different slopes. For example, at the steepest slope (0.14 m/m), two long pieces were placed on each of 15 steps to create the high-density configuration (Figures 1 and 2, left), whereas at the lowest slope (0.05 m/m), five long pieces were placed on each of six steps to create an equivalent high-density configuration (Figures 1 and 2, middle). For most runs, medium and low-density LWD configurations were achieved by progressively removing the farthest upstream pieces on each step tread. LWD pieces were therefore more likely to be located near the step lip at lower-density configurations. Alternate configurations, in which LWD pieces were preferentially positioned farther upstream on the step tread rather than at the step lip, were also tested for a small number of runs, as described further below.

2.2. Calculation of Total Flow Resistance

[16] Once the particular bed configuration, slope, and discharge of interest were established, total hydraulic resistance for each flume run was measured in terms of Darcy-Weisbach friction factor (*f*):

$$f = \frac{8gRS_f}{V^2} \tag{1}$$

where g = gravitational acceleration (m/s^2), R = hydraulic radius (m), S_f = friction slope, and V = flow velocity (m/s). Reach-averaged velocity (V) was measured using a salt tracer and a Hydrolab Minisonde 4.0 conductivity probe, with salt added to a fixed point at the upstream end of the flume and the passage of the salt pulse over a fixed distance recorded by the conductivity probe at the downstream end. The travel distance (approximately 8 m, with some variation between flume configurations) was constrained by the length of the flume and was assumed to be long enough to ensure adequate mixing of the salt tracer. Traveltime was determined based on the time difference between salt addition at the upstream end and the conductivity peak at the downstream end, as measured by a synchronized watch and data logger. Many field studies have employed salt dilution methods as an alternative to point measurements for measuring reach-average velocity in turbulent, morphologically complex mountain streams [*Calkins and Dunne*, 1970; *Day*, 1976; *Beven et al.*, 1979; *Lee*, 1998; *Curran and Wohl*, 2003]. Five to six repetitions of velocity measurements were carried out for each flume configuration and discharge, and the average of these was used to calculate *f* for each run.

[17] Flow depth (d) was used in place of hydraulic radius (R) in (1), as is appropriate for flume simulations such as this one where the bed is rough but the walls are smooth [*Williams*, 1970]. Average flow depth was back calculated based on measured discharge and velocity and the fixed flume width (w) using the continuity equation for discharge ($Q = wdv$). Each subrun lasted as long as

Table 1. Variables (Factors) Tested for Their Effect on Flow Resistance and Levels at Which Each Factor Was Tested

Variables (Factors)	Levels
Discharge, L/s	4, 8, 16, 32, 64
Bed slope, m/m	0.05, 0.1, 0.14
LWD density	none, low, medium, high
LWD orientation	perpendicular, ramped, combination
LWD length	long, short, rootwad
LWD arrangement	single, stacked, jam
LWD position	near lip, midstep, upper step
Steps	yes, no
Grains	yes, no

necessary for salt concentrations to return to background levels; typically 1 to 10 minutes depending on discharge. Flow resistance results are expressed here in terms of Darcy-Weisbach friction factor because it is dimensionless, can be partitioned into distinct, additive components [*Julien*, 1998], and has been recommended for use in open channels [*ASCE*, 1963]. Friction factor can be easily converted to other terms that are also commonly used in analyses of flow resistance, such as Manning's n, boundary shear stress (τ), or $(1/f)^{0.5}$.

[18] The slope term in (1) properly refers to friction slope (S_f), which is only equivalent to bed slope (S_o) under conditions of steady uniform flow. Although the flow deviated from steady uniform conditions in our flume on a local basis, we assumed that on a reach-averaged basis, $S_f = S_o$, justifying the use of bed slope (S_o) in calculations of friction factor. To estimate the error introduced by the use of S_o rather than S_f in (1), we measured and calculated S_f for a subset of flume runs. Friction slope can be calculated as the change in total head over the length of the flume (S_f = dH/dx); total head (H) is

$$H = z + d + \frac{v^2}{2g} \tag{2}$$

where z is bed elevation, d is local flow depth, and v is local velocity. For calculating H at various positions along the flume's longitudinal profile, flow depths were measured at the centerline of the flume along a longitudinal profile, using a point gauge. Turbulence and unsteadiness in the flow caused rapid fluctuations in the water surface elevation in some locations, especially at the base of steps, reducing the accuracy of depth measurements. Local velocity at each position was back calculated from the measured depth at that position and discharge. Friction slope was then determined based on the change in H over the length of the flume. Measured S_f values differed from S_o values by less than 5%. The reasonable agreement between S_f and S_o suggests that over the length of the flume, steady uniform flow conditions are approximated and the use of S_o in (1) is justified. The accuracy of our measured discharges, which were based on pressure- transducer readings and rating curves for converting pressure to discharge, was also tested by developing independent estimates of Q for selected runs using point gauge depths, salt tracer velocities, and the continuity equation for discharge.

[19] On the basis of the guidelines of *Julien* [1998] and *Williams* [1970], no sidewall correction factor was applied to measured friction factor values. *Julien* [1998] suggests that such a correction is only needed for smooth-walled flumes when the flume width is less than five times the average flow depth, in which case the sidewall resistance is different than bed resistance. For nearly all the flume runs completed here, the width-to-depth ratio was greater than five; the median w/d for all runs was approximately nine. Application of an empirical sidewall correction equation proposed by *Williams* [1970] to our flume data suggested that sidewall resistance had small effects on measured friction factors, increasing f from <1–7% (average 3%) compared to the friction factor associated with bed roughness only. This error was considered small enough that uncorrected f values were used in subsequent analysis. These results agreed with *Williams'* [1970] finding that, in experiments of varying flow depths in a 0.6 m width flume (equal to the width of the flume used here), sidewall effects were nearly or completely absent. Roughness generated by brackets placed along the flume walls for LWD runs (Figures 2–4) was assumed to be part of LWD resistance; brackets were removed for non-LWD runs, creating smooth walls.

2.3. Analytical Methods

[20] In order to evaluate the effect of the variables in Table 1 on flow resistance, friction factor was measured for flume runs in a factorial experimental design, in which multiple factor-level combinations of the independent variables were tested. The advantage of a factorial design is that it allows analysis of interaction effects between the variables of interest, in addition to the effects of the variables acting individually (i.e., main effects). Two-way, three-way, and higher-order interaction effects may be present, depending on the number of factors tested. For example, a two-way interaction is present between two variables, or factors, if the difference in mean responses for two levels of a factor varies across levels of the second factor [*Ott and Longnecker*, 2001]. Three-way interactions can indicate that the difference in mean responses for levels of one factor change across combinations of levels of two other factors, or that the pattern of two-way interactions between the first two factors varies across the levels of the third factor [*Ott and Longnecker*, 2001].

[21] A series of factorial experiments was completed on subsets of the variables in Table 1, allowing investigation of the controls on total resistance and interactions between sources of resistance using the factor-level combinations of greatest relevance to step-pool channels. This approach resulted in a total of 388 flume runs, organized into the following factorial experiments: (1) "LWD configuration," in which multiple combinations of LWD density, orientation, piece length, and arrangement were measured; (2) "LWD position," in which the effect of placing LWD pieces preferentially near step lips or away from step lips was tested for three position configurations; (3) "Step-grain-LWD," in which flume runs were completed with and without steps and grains at four LWD configurations; and (4) "Step geometry," in which three $H/L/S$ geometries were tested (Table 2). Not all possible combinations of all levels of each variable were tested in these factorials, and certain flume runs were used in more than one factorial test. In addition, a small number of flume runs were performed that did not fit into any of these factorial experiments in order to examine the flow resistance effects of specific roughness configurations. Additional detail on each of these factorial experiments is provided in section 3 and by *Wilcox* [2005].

[22] Analyses of variance (ANOVAs) were performed on each factorial experiment in order to examine main effects and interactions between variables, with friction factor as the dependent variable. Log transformations were applied to friction factor values for statistical analyses in order to stabilize variances, although friction factor results are presented below in terms of untransformed values for ease of interpretation. Although analysis of higher-order interactions (four-way and five-way) was possible for some of

Table 2. Factorial Experiments Performed to Investigate Controls on Total Flow Resistance[a]

Factorial Experiment Name	Factor-Level Combinations Tested	Number of Flume Runs	Comments
LWD configuration	Density (low, medium, high)[b] Orientation (perpendicular, ramped, combination) Length-arrangement (long single, short single, long stacked, rootwad single) Q (8, 32 L/s) S (0.05, 0.10, 0.14 m/m)	210[c]	Length and arrangement combined for statistical analysis; steps and grains present
LWD position	LWD position (near lip, midstep, upper step) Density (low, medium) Q (8, 32 L/s)	10[d]	Steps and grains present; S = 0.05; all LWD = long-single-perpendicular
Step-grain-LWD	Grains (yes, no) Steps (yes, no) Q (4, 8, 16, 32, 64 L/s) S (0.05, 0.10, 0.14 m/m) LWD density (none, low, medium, high)[b]	168[e]	All LWD = long-single-perpendicular
Step geometry	Step geometry ($H/L/S$ = 0.7, 1.4, 2)[f] Q (4, 8, 16, 32 L/s)	12	Steps and grains present; S = 0.05; LWD absent

[a]Factor-level combinations refer to those shown in Table 1.
[b]LWD density reduced by progressively removing farthest upstream model LWD from each step tread.
[c]This analysis is six runs short of a full factorial (36 LWD configurations × 3 slopes × 2 discharges = 216) because one LWD configurations (orientation = combination, length-arrangement = rootwad single) was not tested at S = 0.14 m/m.
[d]Upper step position only tested at low density.
[e]Not all possible factor-level combinations tested.
[f]$H/L/S$: ratio of step height (H) to step length (L) to slope (S).

the factorial experiments we conducted, our ANOVA models only included main effects, two-way interactions, and, for one test, three-way interaction terms. Higher-order interactions were treated as error because of the difficulty of interpreting the meaning of such high-order interactions, creating a conservative test of variability and significance levels. The relative importance of the flow resistance variables we tested and of their interactions was evaluated based on the p values and sums of squares produced by ANOVAs for each modeled main effect and interaction term. Least squares means (LS means) and p values of differences were also calculated for significant terms to elucidate differences between the roughness effects of various factor-level combinations.

3. Results

[23] In order to facilitate and clarify reporting of the various factorial experiments and statistical tests we performed, the methods, results, and discussion of each grouping of flume runs are combined in the following section. Complete statistical results and hydraulics data for each flume run are provided by *Wilcox* [2005].

3.1. Overview of Combined Results

[24] The broad effects of the variations in discharge (Q), slope (S), and bed roughness tested here are illustrated by the wide range in measured friction factors. For runs with steps and grains, f varied by two orders of magnitude, from 0.2 (no LWD, Q = 64 L/s, S = 0.05) to 30 (high density, stacked, perpendicular LWD, Q = 8 L/s, S = 0.14). Friction factors for runs without steps, grains, or LWD (i.e., smooth plane-bed configuration) were substantially lower and less variable; all were between 0.04 and 0.11 over five different discharges and three slopes.

[25] All of the factorial analyses performed here (Table 2) showed that Q strongly influenced flow resistance and, for most flume configurations and discharge levels, was inversely correlated with friction factor (Figures 5–7). Discharge mediated the effects of all other variables, as measured in terms of interaction affects in the factorial experiments described below, through its effect on the relative submergence of bed roughness objects. High discharges tended to drown out differences in f caused by varying roughness configurations (steps, grains, LWD), resulting in less variance in measured friction factors as Q increased (Figures 5–7).

[26] Flow resistance substantially decreased as discharge increased because velocity increased more rapidly with discharge, on average, than depth (width remained constant), and because the velocity term is squared in the Darcy-Weisbach equation, whereas depth varies linearly

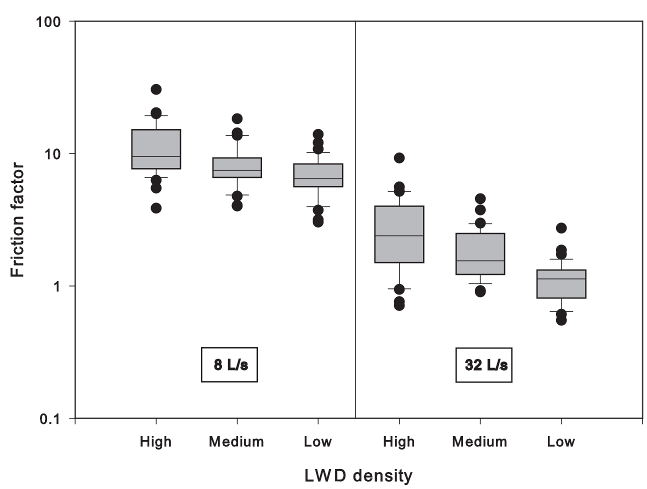

Figure 5. Friction factor versus LWD density, by Q, for 210 flume runs that tested the effect of different LWD configurations on flow resistance. For each box plot (Figures 5, 6, and 7), boxes represent 25th–75th percentile range, solid lines within boxes indicate median, bars above and below boxes show 10th and 90th percentiles, and solid circles are outliers.

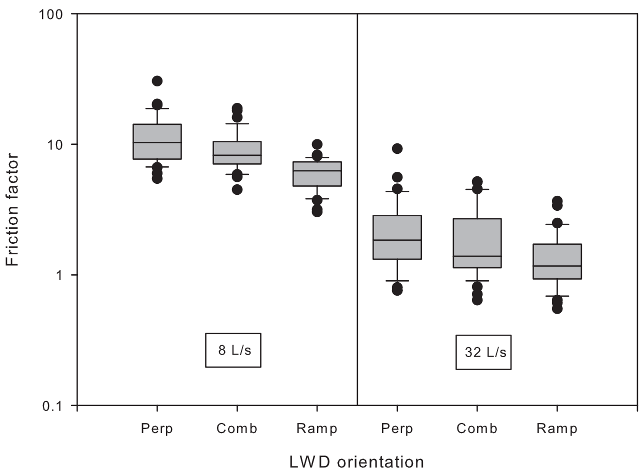

Figure 6. Friction factor versus LWD orientation, by Q, for 210 flume runs that tested the effect of different LWD configurations on flow resistance. LWD orientations include perpendicular ("Perp"), combination of perpendicular and ramped ("Comb"), and ramped at 30°–45° ("Ramp").

with f (equation (1)). The relative rates of increase in velocity and depth with discharge are quantified by the at-a-station hydraulic geometry relations [*Leopold and Maddock*, 1953] for velocity and discharge, which were as follows for all flume runs combined:

$$v = 0.073Q^{0.64} \tag{3}$$

$$d = 0.022Q^{0.36} \tag{4}$$

[27] The effect of slope on friction factor was also significant in the analyses below, although much less so than for other factors. Averaging over other variables, friction factor typically increased with slope, reflecting the collinearity between slope and friction factor expressed in (1).

3.2. Effect of LWD Configuration on Flow Resistance

[28] The largest factorial experiment performed here was designed to test the effect of LWD configuration, including LWD density, orientation, piece length, and arrangement, on flow resistance with steps and grains present. This factorial experiment comprised 210 flume runs in which we measured friction factor for 36 different LWD configurations at two discharges and three bed slopes ("LWD configuration"; Table 2), allowing analysis of the main effects of LWD variables, Q, and S, and of the two-way and three-way interactions among these variables. Because an initial analysis of subsets of these runs, with the piece length and arrangement variables treated as separate factors, suggested that both of these had small effects on friction factor compared to the other variables and did not show an interaction effect with each other, we combined length and arrangement into one factor with four levels in this ANOVA to facilitate statistical analysis (Table 2).

[29] Numerous significant two-way and three-way interactions, particularly between Q and other variables but also among different LWD variables, were documented here (Table 3). The large main effect of Q on friction factor, coupled with the interaction effects between Q and other variables (Table 3), illustrate the dominant effect of discharge on f and the mediating effect of Q on bed roughness variables.

3.2.1. LWD Density

[30] Varying the density of LWD affected flow resistance to a greater extent than did varying piece orientation, length, or arrangement in the "LWD configuration" ANOVA (Table 3). Medium and low densities of LWD resulted in f values 71% and 56% as large as those recorded for high-density configurations, respectively, averaged over other variables. The mediating effect of discharge on how density influences flow resistance is illustrated in Figure 5 and is expressed in Table 3 in terms of a highly significant two-way Q*density interaction effect.

[31] Slope also mediated the effect of debris density, resulting in a significant density*S effect. The effect of LWD density on f decreased with decreasing slope, such that at the lowest slope (S = 0.05), no significant difference in f was observed between medium and high LWD densities. This response likely reflects variation in the number of pieces per step as step length varied: at lower slopes, higher densities of LWD result in more pieces being placed on the step tread, where they are less effective in creating flow resistance, but no change in the number of "step-forming", near-lip pieces.

[32] Previous work has also illustrated that, although flow resistance initially increases with LWD density, eventually a diminishing density effect is observed because once cylinder diameter is sufficiently close (i.e., once density is high enough), wake interactions reduce the average drag compared to isolated cylinders. For example, *Gippel et al.* [1992] found that wake interactions took effect at a spacing of less than four cylinder diameters. We observed diminishing density effects at much greater spacings, however; our medium- and high-density configurations corresponded to spacings of approximately 20 and 10 cylinder diameters, respectively. This is likely because in our flume, spacing

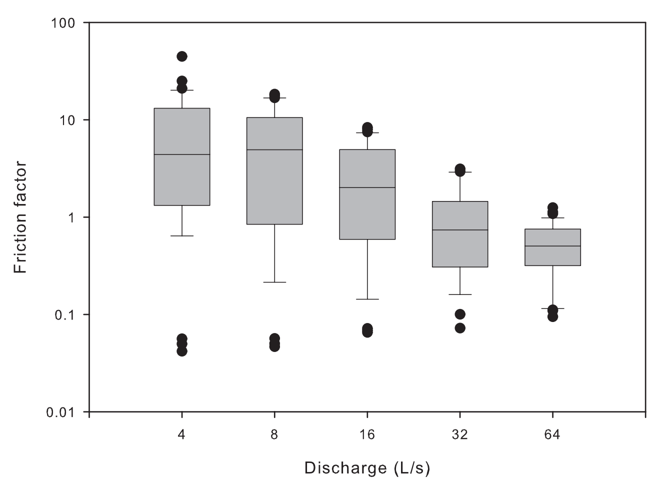

Figure 7. Distribution of friction factors at different discharge levels for "Step-grain-LWD" factorial ANOVA (n = 168), illustrating inverse relationship between Q and f. The spread in the data reflects the influence of varying bed roughness configurations (LWD, steps, grains) and slopes. For example, all outliers at the lower end of the f range ($f \leq 0.11$) represent smooth plane-bed runs.

Table 3. ANOVA Results for "LWD Configuration" Factorial Analysis of 210 Flume Runs, Showing Main Effects, Two-Way Interactions, and Three-Way Interactions[a]

Source	Degrees of Freedom	Type III Sum of Squares	Mean Square	F Value	*p* Value
		Main Effects			
Q	1	128.05	128.05	3955.9	**<0.0001**
Density	2	13.00	6.50	200.7	**<0.0001**
Orientation	2	10.59	5.29	163.6	**<0.0001**
Slope	2	7.25	3.62	112.0	**<0.0001**
Length arrangement	3	2.67	0.89	27.5	**<0.0001**
		Two-Way Interactions			
Q*slope	2	0.91	0.46	14.1	**<0.0001**
Q*length	3	1.80	0.60	18.5	**<0.0001**
Q*density	2	1.06	0.53	16.4	**<0.0001**
Q*orientation	2	0.27	0.14	4.2	*0.0186*
Density*slope	4	1.66	0.41	12.8	**<0.0001**
Density*length	6	1.19	0.20	6.1	**<0.0001**
Density*orientation	4	0.15	0.04	1.2	0.3408
Length*slope	6	1.79	0.30	9.2	**<0.0001**
Orientation*length	6	0.80	0.13	4.1	**0.0011**
Orientation*slope	4	0.06	0.01	0.5	0.7628
		Three-Way Interactions			
Q*density*slope	4	0.83	0.21	6.4	**0.0001**
Q*density*orientation	4	0.18	0.05	1.4	0.2318
Q*density*length	6	0.07	0.01	0.4	0.9063
Q*length*slope	6	0.66	0.11	3.4	**0.0047**
Q*orientation*length	6	0.47	0.08	2.4	*0.0317*
Q*orientation*slope	4	0.17	0.04	1.3	0.262
Density*orientation*slope	8	0.68	0.09	2.6	*0.0124*
Density*orientation*length	12	0.93	0.08	2.4	**0.01**
Density*length*slope	12	0.43	0.04	1.1	0.3635
Orientation*length*slope	11	1.04	0.09	2.9	**0.0025**

[a]Results that are significant at $\alpha = 0.01$ are shown in bold; those that are significant at $\alpha = 0.05$ are shown in italics.

and density effects of LWD were conflated with "position" effects. That is, at higher densities, a greater number of LWD pieces were located farther upstream on step treads, where flow depths and relative submergence of LWD pieces were greater because of the reverse gradient of steps in our flume, compared to lower-density configurations. Position effects are explored further below, but the key point here is that the diminishing effect of LWD pieces on hydraulics as LWD density increases may take effect earlier (i.e., at wider spacings) in step-pool channels than in low-gradient channels because not all potential LWD positionings along a given step-pool sequence will result in similar flow resistance.

3.2.2. LWD Orientation

[33] Debris orientation effects on flow resistance were nearly as large as density effects in the factorial ANOVA (Table 3). Rotation of pieces 30°–45° from the flume wall produced flow resistances that were, on average, slightly more than half of those recorded for perpendicular pieces for all discharges combined. Flume runs with combinations of perpendicular and ramped pieces resulted in friction factors that were intermediate, on average, between perpendicular-only and ramped-only configurations. These results are consistent with the expectation that flow resistance associated with LWD should be proportional to $\sin\theta$, which represents the fraction of the channel width obstructed by LWD. The relationship between orientation and f is influenced by discharge (i.e., a Q*orientation interaction effect is present), whereby a smaller but still significant orientation effect was observed at higher discharges than at lower discharges (Figure 6).

[34] Earlier flume studies, in which the hydraulic effect of LWD was expressed in terms of afflux or percent stage rise, produced similar results regarding the effects of piece orientation on flow resistance [*Young*, 1991; *Gippel et al.*, 1992]. These studies found that debris angled 20–40° to the flow produced one third to one half the afflux produced by perpendicular LWD [*Young*, 1991; *Gippel et al.*, 1992]. Orientation effects were dampened for more complex shapes designed to more closely approximate real debris [*Gippel et al.*, 1992], however, and field measurements of the drag on model woody debris found that orientation had no significant effect on apparent drag coefficient [*Hygelund and Manga*, 2003].

3.2.3. LWD Length and Arrangement

[35] The combined piece length-arrangement factor had smaller main effects on friction factor than other variables but strong interaction effects with other variables, especially discharge (Table 3). Although long-single pieces created significantly higher resistance than short-single and rootwad pieces at low Q ($\alpha = 0.05$), these configurations had statistically indistinguishable effects on f at high Q, illustrating the Q*length interaction. Vertically stacked pieces created significantly higher flow resistance than single pieces at high discharges, averaging over other variables, but differences in f values between these arrangements were not significant at low Q. This response reflects the ability of stacked pieces to continue to exert considerable drag on the flow at high discharges, because of their lower relative submergence than single pieces, which are drowned out at high flows. Flume runs with stacked arrangements produced the highest friction factors

recorded in this experiment at both 8 and 32 L/s (stacked arrangements were not tested at other discharges): f = 30 for Q = 8 L/s and f = 9.3 for Q = 32 L/s (density = high, length = long, orientation = perpendicular, S = 0.14 m/m). This configuration, which included stacked pieces at the lip of each step (Figure 4, top), produced considerable damming and ponding of the flow, thereby reducing velocities and increasing flow depths.

[36] In natural channels length likely has an important indirect effect on flow resistance via its influence on piece stability. Woody debris pieces that are longer than bankfull width have been found to be more stable than shorter pieces extending only partway into the channel [*Lienkaemper and Swanson*, 1987; *Hilderbrand et al.*, 1998]. This may be even more important in steep, high-energy channels, where channel-spanning pieces may be more likely to contribute to step-pool formation than shorter pieces, although we did not model this effect because fixed LWD pieces were employed.

[37] Rootwads were modeled here because of field evidence of their important physical role [*Lienkaemper and Swanson*, 1987]. Our flume results, however, indicated that appending model rootwads to LWD had minimal effects on flow resistance compared to other configurations. Pieces with rootwads produced similar f values as short single pieces and significantly lower f values than long single and long stacked pieces. Greater rootwad effects may have been observed if different rootwad shapes and/or placement configurations had been modeled, such as rootwads with larger diameters relative to the log, allowing greater protrusion above the bed, or rootwads anchoring logs pointing downstream and parallel to the flow. The rootwad configurations we modeled, in which rootwads were flush with the flume walls (e.g., Figure 3, right) were chosen to approximate rootwad arrangements that our field observations suggest would have the greatest stability, and therefore likelihood of occurrence, in steep channels.

[38] We also tested the hydraulic effects of arranging LWD pieces into jams, in which long and short pieces were interlocked with varying orientations (Figure 4, bottom). Those tests, which were not part of the "LWD configuration" factorial, indicated that jams did not produce significantly different f values than evenly spaced single pieces (including long single, short single, and rootwad configurations), averaging over density, slope, and discharge. For certain combinations of Q, slope or density, the flow resistance created by jams was significantly different than one or more of the other length-arrangement configurations. Overall, however, the flow resistance effect of organizing pieces into jams instead of other length-arrangement combinations was small.

[39] In natural step-pool channels, debris jams that form where step-forming LWD pieces trap other woody debris can produce stable debris formations and substantially influence channel morphology [*Keller and Swanson*, 1979]. Debris jams also have a large effect on physical processes in lower-gradient channels [e.g., *O'Connor and Ziemer*, 1989; *Montgomery et al.*, 2003]. In this context, our finding that organization of LWD pieces into jams did not create significantly different flow resistances than other configurations was unexpected. Although the implication may be that jams do not have a notably different effect on hydraulics and channel morphology than individual step-forming pieces in step-pool channels, it is also likely that failure to adequately capture the complexity of natural debris jams influenced our results. Moreover, changes in channel morphology resulting from LWD jams may influence flow resistance dynamics in ways that could not be captured in the fixed bed simulations employed here.

3.2.4. LWD Position

[40] We also completed a series of flume runs to test the effect of LWD position by varying whether pieces were preferentially placed near the step lip, in the middle of the step tread, or at the upstream end of the step tread ("LWD position"; Table 2). These tests documented a strong effect ($p < 0.0001$) of LWD position on friction factor. Clustering of pieces near step lips produced f values that were more than double those observed when logs were clustered farther upstream on the step tread (in either midstep or upper step positions), averaging over discharges and densities. No significant difference in friction factor was observed between two different clustering configurations (midstep and upper step) in which no pieces were at the step lip, but the distance of pieces from the lip was varied.

[41] These results, in conjunction with the field observations of *Curran and Wohl* [2003], illustrate the importance of LWD position on flow resistance in step-pool channels. Near-lip pieces can produce substantial resistance by damming the flow, thereby reducing upstream velocities. Near-lip pieces also can also interact with step-forming clasts to increase the effective height of steps, thereby increasing the vertical fall over steps and the associated spill resistance as flow plunges into downstream pools. LWD pieces placed farther upstream along step treads have less interaction with steps and, although they do create some flow resistance on their own, the overall effect is less than the resistance effect introduced by the step-LWD interaction.

3.3. Effect of Steps and Grains on Flow Resistance

[42] A factorial experiment was also completed to evaluate the effect of steps and grains on flow resistance and their interaction effects with each other and with LWD, discharge, and slope ("Step-grain-LWD"; Table 2). Steps were treated as a distinct roughness entity from grains and LWD in order to isolate their effect on flow resistance, even though nonbedrock steps are indeed composed of these elements. The "Step-grain-LWD" factorial analysis expanded the range of discharges evaluated compared to the LWD tests described above (Table 2), although certain combinations of variables were not tested, resulting in an unbalanced factorial. For example, the configuration with no steps or grains (smooth plane bed) was not tested in combination with LWD, and the plane bed with grains and LWD configuration was only tested at two of the three slopes (0.05 and 0.14 m/m). The results presented here (Table 4) are based on an ANOVA model containing only main effects and two-way interaction terms. A preliminary analysis including three-way interactions indicated that such interactions could be omitted.

[43] The presence or absence of steps strongly influenced flow resistance (Table 4), with step runs producing f values approximately five times greater than plane-bed runs, averaging over other variables. Step effects on flow resistance were mediated by other variables, as shown by

Table 4. ANOVA Results for "Step-Grain-LWD" Factorial Analysis, Showing Main Effects and Two-Way Interactions[a]

Source	Degrees of Freedom	Type III Sum of Squares	Mean Square	F Value	*P* Value
		Main Effects			
Step	1	25.76	25.76	222.3	**<0.0001**
LWD	3	42.68	14.23	122.8	**<0.0001**
Q	4	52.25	13.06	112.7	**<0.0001**
Grain	1	10.19	10.19	87.9	**<0.0001**
Slope	2	0.88	0.44	3.8	*0.0254*
		Two-Way Interactions			
Q*step	4	20.68	5.17	44.6	**<0.0001**
Q*grain	4	5.27	1.32	11.4	**<0.0001**
Q*LWD	12	5.00	0.42	3.6	**0.0002**
Q*slope	8	1.21	0.15	1.3	0.2485
Step*slope	2	1.83	0.92	7.9	**0.0006**
Step*LWD	3	1.94	0.65	5.6	**0.0013**
Step*grain	1	0.93	0.93	8.0	**0.0056**
Grain*LWD	3	8.98	2.99	25.8	**<0.0001**
Grain*slope	2	0.15	0.07	0.6	0.5352
LWD*slope	6	1.67	0.28	2.4	*0.032*

[a]Results that are significant at $\alpha = 0.01$ are shown in bold; those that are significant at $\alpha = 0.05$ are shown in italics.

significant two-way interactions between steps and other factors (Table 4). For example, steps had a much greater effect on resistance (compared to plane-bed runs) at low flows than at high flows, reflecting the *Q**step interaction. Figure 8, which illustrates the significant step*LWD interaction (Table 4), shows that the difference in flow resistance between plane-bed and step configurations increases substantially as LWD is added, especially up to medium densities of LWD. Further, adding LWD to steps produced approximately threefold to sixfold increases in friction factor compared to steps lacking LWD, depending on LWD density and averaging over other variables (Figure 8). The step*LWD interaction effect is related to the "LWD position" effect discussed above, whereby presence of LWD pieces near the lip of steps increases the effective step height and the resulting spill resistance as flow plunges over the steps.

[44] Slope also mediated the influence of steps on friction factor (Table 4). As slope increased, a greater number of steps were present over the length of the flume (Figure 1), resulting in greater energy dissipation and flow resistance associated with flow overfalls over steps. At lower slopes, step-generated flow resistance (i.e., spill resistance) was reduced.

[45] The presence or absence of grains had smaller (but still highly significant) effects on f than most other factors (Table 4). Grains interacted with steps, such that flume runs with smooth beds produced f values approximately one third as large as runs with grains when steps were absent and one half as large as runs with grains when steps were present. A significant grain*LWD interaction was also observed, whereby the presence or absence of grains influenced the effect of LWD on flow resistance. At low debris densities and discharge levels, flow depths were often insufficient to fully submerge debris pieces when grains were absent, reducing debris drag. The presence of grains, however, increased the submergence of debris pieces and their associated flow resistance at low debris densities. At high debris densities, in contrast, debris drag alone created sufficient flow depths to submerge debris pieces whether grains were present or not, decreasing the effect of grains on friction factor. The linkage of the grain*LWD interaction to stage also reflects the presence of a three-way *Q**grain*LWD interaction, as was indicated by preliminary statistical tests.

[46] This factorial also provided insight into variations in f over a broader range of discharges than the other experiments described here (Figure 7) and into interactions between Q, steps, and grains (Table 4). LS means analysis of the main effect of Q showed that the highest four discharge levels produced significantly different f values ($p < 0.01$) but that differences in f were not significant between 4 and 8 L/s (Figure 7). The LS means for the interactions between Q and other factors show that these factors had a much greater effect on resistance at low flows than at high flows, further illustrating the effectiveness of high discharge in drowning out bed roughness.

3.4. Effect of Step Geometry on Flow Resistance

[47] A final set of flume runs tested the effect of step geometry on flow resistance ("Step geometry"; Table 2). Whereas the flume runs in the factorial experiments described above maintained a consistent step geometry (*H*/*L*/*S*) (Figure 1), based on the scaling criteria described in section 2.1, in this set of runs step geometry was varied by holding both step height (H = 0.1 m) and slope (S = 0.10 m/m) constant and varying step length (L = 0.5 m, 0.7 m, 1.4 m). Step geometry effects on f were highly significant ($p < 0.0001$), with more closely spaced steps increasing flow resistance compared to more widely spaced steps, an effect that was most marked at low discharges (Figure 9). More closely spaced steps with shorter step treads result in more frequent overfalls of flow, increasing flow resistance by creating more spill resistance [*Wilcox et al.*, 2006]. The effect observed in the step geometry tests was therefore analogous to the step**S* interaction described above.

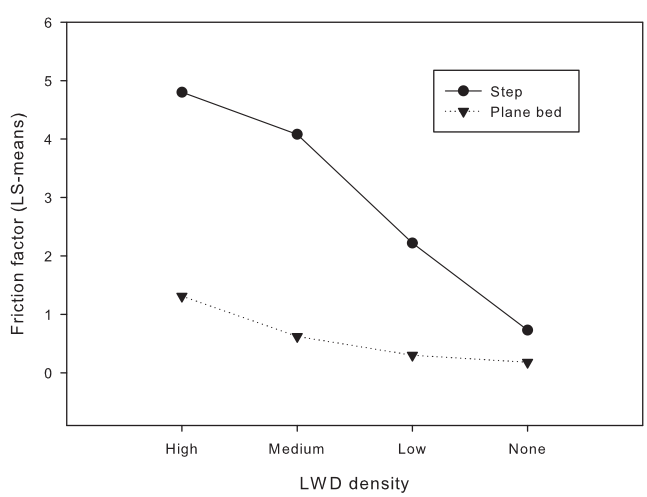

Figure 8. Interaction plot of Step*LWD interaction, based on "Step-grain-LWD" factorial ANOVA, showing LS (least squares) means of friction factor for various LWD densities and influence of presence or absence of steps.

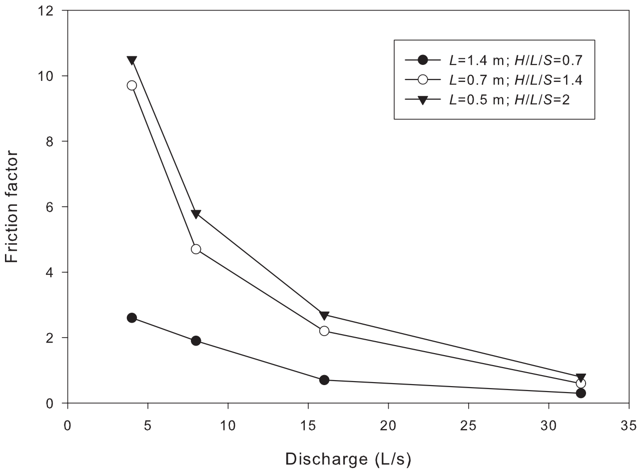

Figure 9. Results of tests of effect of step geometry on friction factor (S = 0.10 m/m, H = 0.1 m), illustrating increase in flow resistance resulting from closer step spacing, especially at lower Q.

[48] These results build on previous flume and field investigations of the effects of step geometry on flow resistance. As noted above, *Abrahams et al.* [1995] suggested that step-pool channels are adjusted such that step spacing and geometry correspond to conditions of maximum flow resistance, whereby $H/L/S$ values are typically between one and two. We did not measure a large enough range of $H/L/S$ values in the "step geometry" factorial to test the maximum flow resistance hypothesis, but our results did show that substantially higher friction factors occurred for $H/L/S$ values in the 1–2 range than for values below this range. These results are consistent with *MacFarlane and Wohl*'s [2003] observation of a significant positive correlation between H/L and flow resistance in step-pool streams lacking LWD, where the mean of $H/L/S$ values was 1.82. Such a relationship was not observed, however, in LWD-loaded reaches studied by *Curran and Wohl* [2003], where the mean of $H/L/S$ values was 1.36.

4. Discussion

4.1. Flow Resistance Interactions

[49] Manipulation of roughness variables and measurement of flow resistance interactions to the extent that was performed here is infeasible in natural channels. This flume experiment therefore provided a means of gaining new insights into flow resistance dynamics in step-pool channels through direct measurement of the effects of numerous roughness variables on flow resistance and, through the use of a factorial design, measurement of interaction effects between roughness variables. These interaction effects were shown to strongly influence flow resistance dynamics. Predictive efforts have typically neglected such interaction effects, however, and we know of no previous efforts that have measured the importance of interactions between resistance elements.

[50] Interaction effects among roughness features, although not necessarily identified as such, have been observed in step-pool channels in field settings. For example, *Keller and Swanson* [1979] observed that the relative effect of large woody debris on energy dissipation decreases with channel slope. This agrees with our finding that the effect of increasing LWD density on f was smaller at lower slopes than at higher slopes, as expressed by the two-way LWD density*slope interaction shown in Table 3 and described in section 3.2.1. Step*LWD interactions have been observed where large, step-forming boulders create accumulation loci for LWD, thereby creating larger steps that in turn trap finer sediment upstream and alter associated grain roughness [*Faustini and Jones*, 2003]. In wood-rich pool-riffle channels, hydraulic roughness created by LWD and other sources of form drag have been found to cause textural fining, likely by reducing the shear stresses applied to the bed and available for sediment transport [*Buffington and Montgomery*, 1999].

4.2. Discharge Effects on Flow Resistance

[51] The discharge dependence of roughness conditions, which was illustrated here in terms of both an inverse relationship between Q and f and highly significant two-way interactions between Q and bed roughness variables, has also been well documented in field conditions across a range of channel types [*Beven et al.*, 1979; *Hayward*, 1980; *Jarrett*, 1992; *Bathurst*, 2002; *Lee and Ferguson*, 2002; *Heritage et al.*, 2004] and with respect to resistance associated with LWD [*Lisle*, 1986; *Shields and Smith*, 1992; *Gippel*, 1995]. Our flume data support *Chin*'s [2003] conceptual model describing the effect of discharge variations in step-pool channels. This model suggests that the role of step-pool sequences varies temporally such that at low flows, when the vertical fall of flow over steps is most pronounced, the effectiveness of steps in reducing stream energy is maximized, whereas flow resistance and energy dissipation decrease as discharge increases and the water surface profile becomes less stepped [*Chin*, 2003].

[52] The hydraulics of spill over steps and associated changes in flow resistance with discharge are influenced by the morphologic characteristics of individual step-pool sequences. As discharge increases, flow over steps often transitions first from concentrated flow over the lowest part of the step crest to flow spilling over the entire width of the step, and subsequently to flow in which all step-forming features are submerged sufficiently to dampen their effect on resistance. The presence of channel-spanning LWD perched above the low-flow step crest can add further complexity to flow resistance-discharge relationships in step-pool channels. Because the step-pool sequences employed in our flume had planar step treads and straight step lips with uniform elevation, our modeling did not capture these details of spill hydraulics.

[53] The effect of changing discharge on relative submergence and flow resistance patterns in step-pool channels can also be conceptualized in terms of the difference between nappe flow and skimming flow, which are engineering terms used to describe flow over stepped structures such as spillways [*Chanson*, 1994]. At lower discharges, flow over step-pool sequences is analogous to nappe flow, in which the flow cascades over each step as a series of free-fall jets, resulting in wake interference flow and turbulence generation at the base of steps [*Wohl and Thompson*, 2000]. Under these conditions, relative submergence of steps is low, allowing the steps and any roughness objects on the

step treads to exert considerable drag on the flow and to create high flow resistances. At higher discharges, flows may become more analogous to skimming flow, in which water flows become more parallel to a plane between successive step lips [*Chanson*, 1994], drowning out steps and dramatically decreasing flow resistance.

[54] The hydraulic geometry results presented here (equations (3) and (4)) and the similar results of *Lee and Ferguson* [2002] show that the strong discharge dependence of flow resistance in step-pool channels is driven by more rapid increases in velocity than in depth with discharge. This effect was exaggerated in the flume results presented here and those of *Lee and Ferguson* [2002] because a rectangular cross-section channel was employed, forcing changes in discharge to be entirely accommodated by changes in velocity and depth, but not in width. This geometry is a reasonable first-order approximation of natural step-pool channels up to their bankfull level, however, because many such channels tend to have low width-to-depth ratios and quasi-rectangular cross sections. Our hydraulic geometry results showed larger increases in velocity with discharge than have been reported for lower-gradient rivers [*Leopold and Maddock*, 1953; *Knighton*, 1975; *Ferguson*, 1986].

[55] Our flume results and the preceding discussion suggest that the effect of discharge on flow resistance is likely substantially greater in step-pool channels than in lower-gradient streams. In lower-gradient streams, bed roughness materials are typically entirely submerged even at low flows, and discharge increases produce more subtle increases in relative submergence. Relative submergence of bed roughness features such as LWD and large clasts changes rapidly with discharge in step-pool channels, however, as discussed above, resulting in a strong stage and discharge dependence of flow resistance in such channels [*Lee and Ferguson*, 2002]. Further, the marked decreases in flow resistance associated with the transition from a flow regime resembling nappe flow to one resembling skimming flow, as described here and in *Lee and Ferguson* [2002], are absent from lower-gradient systems.

4.3. Relating Flume Results to Natural Channels

[56] Extrapolation of the results described above to field settings should take into account the simplifications employed in our flume model. The treatment of steps as a distinct roughness feature, separate from grains and woody debris and constructed using two-by-fours, was one key simplification. Although steps in natural channels are composed of large clasts and/or woody debris (with the exception of bedrock steps), we treated steps as distinct to facilitate identification of the unique resistance contributions of steps (spill resistance), grain resistance on step treads, and form resistance from woody debris as well as their interactions. Because our experiment did not treat grains as step-forming agents and sources of form and spill resistance [*Wilcox et al.*, in press], grain roughness was also oversimplified. Whereas step-pool channels typically exhibit a wide grain size distribution, with boulder-sized step-forming clasts and smaller (gravel/cobble) sediments in pools [e.g., *Hayward*, 1980; *Wohl et al.*, 1997; e.g., *Lee and Ferguson*, 2002; *MacFarlane and Wohl*, 2003], a relatively narrow range of grain sizes was employed here. Further, our representation of pools through the use of planar step treads with a reverse slope did not fully capture the energy dissipation associated with morphologically complex natural pools.

[57] Debris roughness was also oversimplified, given the use of smooth PVC cylinders of a fixed diameter to represent LWD, three-way PVC junction attachments to represent rootwads (Figure 3, right), and arrangements of short and long pieces to represent debris jams (Figure 4, bottom). Previous flume studies modeling the effects of LWD have also employed smooth cylinders [*Young*, 1991; *Gippel et al.*, 1992; *Braudrick et al.*, 1997; *Wallerstein et al.*, 2001].

[58] Our use of fixed bed configurations, with immobile grains, LWD, and steps, also may affect the application of our flume results to natural channels with deformable beds. For example, our modeling did not allow for analysis of how feedbacks between increasing discharge and transport of sediment and LWD, including destruction of step-pool sequences and/or pool scour at high flow, would affect flow resistance dynamics. Further, the LWD resistance effects modeled here, including interaction effects with other roughness features, do not account for the influence of LWD on channel form and step spacing [e.g., *Faustini and Jones*, 2003] and associated indirect effects on flow resistance. Moreover, because the flume walls were smooth and straight, bank roughness, bank erosion, and channel curvature effects were not modeled here.

[59] The range of friction factors measured here (0.04–44) is at the low end of the range reported for step-pool channels in field studies (0.1–9000) [*Beven et al.*, 1979; *Mussetter*, 1989; *Lee*, 1998; *Curran and Wohl*, 2003; *MacFarlane and Wohl*, 2003]. This difference is likely at least partly due to the simplifications discussed above; the more complex roughness features in natural step-pool channels would likely generate greater flow resistance. In addition, the field data cited here for the most part represent low-flow conditions; our flume results suggest that analogous friction factor values for high-flow conditions would be substantially lower.

[60] Although predictive equations for dependent variables of interest are a common product of flume studies, no such model for flow resistance in step-pool channels is developed here. Condensing the results of our flume runs into a predictive equation for flow resistance, although possible, was not a goal of this study and would have limited applicability to natural channels in light of the design simplifications discussed above and the absence of variables such as step-forming grain size from our flume model.

4.4. Implications for Stream Restoration

[61] Stream restoration efforts have typically focused on pool-riffle channels and have commonly employed LWD placement as a means of promoting pool scour and other habitat objectives [*Bisson et al.*, 1987; *Hilderbrand et al.*, 1997; *Larson et al.*, 2001; *Roni and Quinn*, 2001]. The evidence of the important hydraulic role of LWD in step-pool channels presented here and in field studies suggests that stream restoration efforts incorporating LWD placement may also be merited in steep streams where LWD abundances have been reduced by land use practices. Restoring LWD in mountain stream channels could, by increasing flow depths and reducing flow velocities, create more

complex aquatic habitats, promote sediment storage, promote step formation, and contribute to scour of deeper plunge pools.

[62] Although stream restoration efforts are not typically framed in the context of maximizing flow resistance, many stream restoration objectives, such as creating low-velocity refugia or habitat complexity [*Bisson et al.*, 1987; *Brookes and Shields*, 1996], are fundamentally related to flow resistance. Attempting to maximize flow resistance in high-energy steep channels (e.g., through LWD placement) may therefore promote achievement of habitat objectives. Such an approach would be a departure from typical river management practices in low-gradient rivers, which have often sought to minimize flow resistance in order to minimize flood risk and to maximize channel conveyance [*Gippel et al.*, 1992, 1996]. Maximizing resistance in headwater areas, in addition to advancing habitat objectives, could also reduce downstream flood risks by slowing the delivery of high flows to higher-order channels.

[63] The flume results presented here, in conjunction with related field observations cited above, provide guidance for how LWD placement can be employed to maximize flow resistance in step-pool channels. LWD pieces placed near the lip of steps, rather than farther upstream along step treads, are especially likely to increase flow resistance. In near-lip positions, LWD pieces interact with step-forming clasts to increase the effective height of steps, creating a damming effect upstream and increasing the vertical overfall into downstream pools and associated pool scour. LWD pieces placed farther upstream along steps have less interaction with steps and, although they do create some flow resistance on their own, the overall effect is less than the resistance effect introduced by the step*LWD interaction. Increases in LWD density beyond a certain amount are therefore likely to have diminishing effects in terms of flow resistance, although LWD pieces located along step treads likely provide important microhabitats and habitat complexity for aquatic organisms. Our results also suggest that vertical stacking of LWD pieces increases flow resistance compared to equivalent distributions of single pieces resting on the bed, although such configurations are unlikely to be stable unless they consist of channel-spanning pieces. Further, the LWD orientation effects documented here suggest that restoration efforts using pieces oriented perpendicular to flow will maximize flow resistance compared to other piece orientations, although, as with non-step-forming pieces, nonperpendicular orientations may be important for habitat diversity. Perpendicular pieces may also trap both coarse and fine sediment, promoting formation of new steps.

[64] Woody debris restoration efforts in step-pool channels are likely to be most effective if the size of debris employed is appropriately scaled to channel size. *Marston* [1982] found that, in the Oregon Coast Range, log steps are most common in third-order streams. Lower-order streams are typically highly confined, causing large fallen trees to often remain perched above the channel, whereas higher-order streams have stream power sufficient to remove in-stream LWD before log steps can fully develop [*Marston*, 1982]. In first- and second-order streams with widths less than 4 m, relatively small wood (10–40 cm diameter) may be more important in step formation than larger wood [*Jackson and Sturm*, 2002]. Even smaller debris (<10 cm diameter) can be a significant step-forming agent in the smallest headwater streams.

5. Conclusions

[65] The flume results reported here provide new insights into controls on hydraulic resistance in step-pool channels. The factorial experimental design we employed allowed measurement of interactions between LWD configurations, steps, grains, discharge, and slope and of the relative importance of roughness variables. Interactions between roughness variables, including significant two-way and three-way interaction effects between steps, grains, and LWD, strongly influenced flow resistance dynamics, highlighting the difficulties of flow resistance prediction in step-pool channels. For example, as a result of interactions between steps and woody debris, the flow resistance created by steps with woody debris was far greater than by steps lacking LWD, suggesting important differences between natural step-pool streams with and without LWD. LWD position on steps, density and orientation also had highly significant effects on flow resistance. LWD position had particularly important effects on flow resistance, because pieces located near step lips increased the effective height of steps and dammed the flow. Additional pieces located farther upstream along step treads had smaller effects on flow resistance, suggesting that, under certain conditions, LWD position can influence flow resistance to a greater extent than LWD density in step-pool channels.

[66] Flow resistance dynamics and the effect of bed roughness configurations were also mediated by discharge, which had strong direct effects on total resistance and had highly significant interactions with all other variables. A discharge dependence of roughness conditions occurs in many channel types, but the effect appears to be more marked in step-pool channels because velocity increases more rapidly than depth as discharge increases. These flume results provide guidance for how management or restoration approaches in headwater stream channels can seek to maximize flow resistance through LWD placement or retention, which in turn may achieve benefits in terms of sediment storage and aquatic habitat diversity.

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