Flow resistance dynamics in step-pool channels:
2. Partitioning between grain, spill, and woody debris resistance

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[1] In step-pool stream channels, flow resistance is created primarily by bed sediments, spill over step-pool bed forms, and large woody debris (LWD). In order to measure resistance partitioning between grains, steps, and LWD in step-pool channels we completed laboratory flume runs in which total resistance was measured with and without grains and steps, with various LWD configurations, and at multiple slopes and discharges. Tests of additive approaches to resistance partitioning found that partitioning estimates are highly sensitive to the order in which components are calculated and that such approaches inflate the values of difficult-to-measure components that are calculated by subtraction from measured components. This effect is especially significant where interactions between roughness features create synergistic increases in resistance such that total resistance measured for combinations of resistance components greatly exceeds the sum of those components measured separately. LWD contributes large proportions of total resistance by creating form drag on individual pieces and by increasing the spill resistance effect of steps. The combined effect of LWD and spill over steps was found to dominate total resistance, whereas grain roughness on step treads was a small component of total resistance. The relative contributions of grain, spill, and woody debris resistance were strongly influenced by discharge and to a lesser extent by LWD density. Grain resistance values based on published formulas and debris resistance values calculated using a cylinder drag approach typically underestimated analogous flume-derived values, further illustrating sources of error in partitioning methods and the importance of accounting for interaction effects between resistance components.

1. Introduction

[2] Total flow resistance in stream channels can be partitioned into components that are related to specific channel features, and such partitioning has implications for hydraulics, sediment transport, and channel morphology. A number of variables that are related to flow resistance, including bed shear stress, friction slope, Darcy-Weisbach friction factor, shear velocity, and flow depth, can be partitioned into distinct components [*Einstein and Barbarossa*, 1952; *Julien*, 1998]. For example, Darcy-Weisbach friction factor can be partitioned as follows:

$$f_{total} = f_{grain} + f_{form} \qquad (1)$$

where f_{grain} is friction factor caused by grains in the absence of bed forms, f_{form} is the additional flow resistance created by bed forms or other sources of form drag, and f_{total} is total flow resistance:

$$f_{total} = \frac{8gRS_f}{V^2} \qquad (2)$$

where g is gravitational acceleration, R is hydraulic radius, S_f is friction slope, and V is flow velocity.

[3] Grain resistance represents the channel bed roughness that causes energy losses as a result of skin friction and form drag on individual grains in the bed [*Einstein and Barbarossa*, 1952; *Parker and Peterson*, 1980]. In plane bed channels, which lack bed forms, total resistance is typically assumed to equal grain resistance (i.e., $f_{total} = f_{grain}$) [*Julien*, 1998]. Where bed forms or other sources of resistance may be present, grain resistance is usually approximated by some version of the relation originally proposed by *Keulegan* [1938] for calculating the resistance created by a rough bed alone and based on the logarithmic law of the wall. The Keulegan relation can be expressed in terms of friction factor as follows:

$$f_{grain} = \left[2.03 \log \left(\frac{12.2d}{k_s} \right) \right]^{-2} \qquad (3)$$

where f_{grain} is the grain resistance component of Darcy-Weisbach friction factor, d is flow depth, and k_s is roughness height (modified from *Einstein and Barbarossa* [1952]).

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Estimates of grain resistance using Keulegan-type equations are convenient and widely used because this method requires only measurements of flow depth (or hydraulic radius in channels with small width-to-depth ratios) and grain size, as well as selection of an appropriate scale for roughness height (k_s). Roughness height can be expressed as mD_x, where m is a coefficient that typically ranges from 1 to 7 and D_x is some characteristic grain size (usually D_{50}, D_{84}, or D_{90}) [*Kamphuis*, 1974; *Bray*, 1982; *Millar and Quick*, 1994; *Julien*, 1998]. Grain resistance in the Keulegan relation is therefore a function of relative submergence of bed particles (d/D_x).

[4] Form resistance arises from pressure drag on irregularities of the bed surface [*Leopold et al.*, 1964; *Griffiths*, 1989; *Parker*, 2004]. The relative importance of grain versus form resistance and the dominant sources of form resistance typically vary depending on channel type and position in the channel network. Bed forms, including dunes and other transient bed forms in sand bed channels and bars and pool-riffle sequences in gravel bed streams, can dominate resistance in lower reaches and midreaches of stream networks, and resistance from channel bends increases in importance at lower gradients [*Leopold et al.*, 1960, 1964; *Parker and Peterson*, 1980; *Bathurst*, 1993]. Riparian vegetation also contributes to form resistance along many river channels at moderate to high flows [*Darby*, 1999; *Tabacchi et al.*, 2000].

[5] Two types of form resistance that may be particularly important in step-pool channels and that are a focus of this study are spill resistance and resistance associated with large woody debris (debris resistance). Spill resistance is generated by waves and turbulence at locations of sharp velocity reductions [*Leopold et al.*, 1964]. In step-pool channels, spill resistance occurs as a result of the tumbling flow that characterizes these channels, whereby jets of critical or supercritical flow over step crests plunge into downstream pools, producing abrupt decreases in velocity, hydraulic jumps, roller eddies, and substantial turbulence [*Peterson and Mohanty*, 1960; *Wohl and Thompson*, 2000]. Field studies in the Washington Cascades have suggested that spill resistance accounts for 90% or more of total resistance in step-pool channels containing large woody debris (LWD) [*Curran and Wohl*, 2003].

[6] LWD can be an important source of form resistance in both step-pool [*Curran and Wohl*, 2003] and lower-gradient systems [*Gippel*, 1995; *Shields and Gippel*, 1995; *Buffington and Montgomery*, 1999; *Manga and Kirchner*, 2000]. For example, *Manga and Kirchner* [2000] used field measurements and simple theoretical models to show that in a spring-dominated stream in which LWD occupies less than 2% of streambed area, LWD contributes approximately half of total flow resistance. *Shields and Gippel* [1995] calculated that in two low-gradient, sand bed reaches, LWD had accounted for 15–40% and 1–10% of total resistance prior to its removal, with the lower contribution in the latter reach resulting from the greater amount of resistance attributed to bends in that reach. Woody debris also has been found to have a substantial effect on physical processes in step-pool streams where it is present [*Keller and Swanson*, 1979; *Lisle*, 1995; *Curran and Wohl*, 2003; *Faustini and Jones*, 2003]. Most previous studies of step-pool channels, however, have focused on systems where LWD is absent [e.g., *Hayward*, 1980;

Wohl and Grodek, 1994; *Chin*, 1999; *Lenzi*, 2001; *Lee and Ferguson*, 2002].

[7] In this paper we investigate the partitioning of flow resistance in step-pool channels. For the purposes of this study, we delineate flow resistance in step-pool channels into grain, spill, and LWD components:

$$f_{total} = f_{grain} + f_{spill} + f_{debris}, \qquad (4)$$

where f_{spill} and f_{debris} are the components of Darcy-Weisbach friction factor associated with spill over steps and with LWD, respectively. These resistance components in reality often are not fully distinct (e.g., LWD can contribute to spill resistance), a complication that is explored further in this experiment and is discussed in section 4.

[8] This work seeks to increase understanding of interactions between hydraulic driving forces and the resisting forces created by roughness elements such as step-pool sequences and LWD in steep channels. These topics are poorly understood, hindering advances in analyses of flow, channel form, and sediment transport processes in step-pool channels and of how steep channels are different from the low-gradient channels upon which much fluvial geomorphic knowledge is based. This study also explores the contribution of LWD to hydraulics and flow resistance in step-pool channels, which may in turn shed light on forestry management issues and on how the widespread reductions in LWD abundance in headwater streams may have altered the hydraulics of these channels.

[9] In the experiment described in this paper, flow resistance was measured both for isolated roughness components and for multiple bed roughness combinations using flume modeling. Estimates of the percent contributions of grain, spill, and debris resistance to total resistance were developed, and the effects of discharge, slope, and LWD density on partitioning were tested. The flume modeling also was employed to test errors associated with standard methods for quantifying resistance partitioning, whereby resistance is assumed to be additive and resistance components that are difficult to measure are indirectly estimated by subtraction from measurable terms. Finally, independent estimates of resistance partitioning were developed, using published equations for grain resistance and cylinder-drag-based estimates of debris resistance, for comparison to flume results. A companion component of this flume study examined controls on total flow resistance in step-pool channels, measured the effect of a range of different LWD configurations on flow resistance, and measured interaction effects among resistance components [*Wilcox and Wohl*, 2006].

2. Methods

2.1. Flume Methods and Configuration

[10] We investigated the partitioning of flow resistance in step-pool channels using flume measurements of Darcy-Weisbach friction factor (f_{total}) and a factorial design that allowed us to isolate and measure the relative contributions of flow resistance from grains (f_{grain}), spill (f_{spill}), and LWD (f_{debris}). This was achieved by completing a series of flume runs in which f_{total} was measured for bed configurations with and without grains and steps, with various woody debris configurations, and at multiple slopes and discharges, alter-

ing one of the independent variables contributing to flow resistance at a time and holding others constant. A total of 206 flume runs were used in the partitioning analysis; additional flume runs that tested a broader range of LWD configurations are analyzed in our companion study [*Wilcox and Wohl*, 2006]. The paper describing that study [*Wilcox and Wohl*, 2006] and *Wilcox* [2005] provide additional details on the flume methods and configurations used here, beyond the basic information provided below.

[11] The flume study was performed at Colorado State University's Engineering Research Center using a flume that is 9 m long and 0.6 m wide, with a rectangular cross section and smooth sidewalls. Flume runs were completed at three slopes intended to represent a range of slopes found in step-pool channels: 0.05, 0.10, and 0.14 m/m, and at five discharges selected to produce varying relative submergence of roughness features and Froude numbers: 4, 8, 16, 32, and 64 L/s. For each flume run, we established one of these target discharges and slopes, measured reach-averaged velocity (based on salt dilution), and back-calculated average flow depth using the continuity equation for discharge. Friction factor (f_{total}) was then calculated using equation (2), substituting d for R and bed slope (S) for S_f (see *Wilcox and Wohl* [2006] for further details).

[12] Each flume run tested the flow resistance effect of some combination of bed roughness objects representing grain, spill, and/or debris resistance. A relatively uniform mixture of grain sizes ($D_{16} = 10$ mm, $D_{50} = 15$ mm, $D_{84} = 22$ mm) was glued to the bed in order to create grain roughness without any sediment transport. In order to simulate step-pool sequences and to create spill resistance, step risers and treads were constructed using wood blocks (two-by-fours, i.e., pieces 38 mm wide and 89 mm high) and plywood. Step-pool sequences were constructed with a step height (H)-step length (L)-bed slope (S) ratio ($H/L/S$) of 1.4 [after *Abrahams et al.*, 1995], creating a reverse gradient on each step tread. LWD was modeled by PVC cylinders (2.5 cm diameter), which were fixed to the bed and/or flume walls to represent debris resistance.

2.2. Test of Additive Partitioning Approach

[13] Many studies of resistance partitioning employ the same basic method, whereby total resistance is divided into (1) one or more components that can be measured or calculated, and (2) a component that is difficult to measure directly using existing methods. The difficult-to-measure component, which is often the focus of the particular study, is estimated by measuring total resistance (using equation (2) or an analogous resistance equation) and subtracting the measurable components. This approach is based on the premise that flow resistance is additive [*Einstein and Barbarossa*, 1952], such that

$$f_{total} = f_{measurable} + f_{unmeasurable} \qquad (5a)$$

$$f_{unmeasurable} = f_{total} - f_{measurable}. \qquad (5b)$$

Because direct measurement of form resistance is difficult, previous analyses of resistance partitioning have often employed this additive approach to quantify the relative contributions of form resistance and grain resistance [*Einstein and Barbarossa*, 1952; *Parker and Peterson*,

1980; *Prestegaard*, 1983; *Curran and Wohl*, 2003; *MacFarlane and Wohl*, 2003]. Grain resistance is treated as the measurable component, calculated using (3) or an analogous expression based on relative submergence, and form resistance is the unmeasurable component, calculated as the leftover value in (5b) (form resistance = total resistance − grain resistance). This additive approach has been used to quantify bar resistance in gravel bed rivers [*Parker and Peterson*, 1980; *Prestegaard*, 1983], spill resistance in step-pool channels [*Curran and Wohl*, 2003; *MacFarlane and Wohl*, 2003], resistance to overland flow [*Hu and Abrahams*, 2004] and resistance associated with bed load transport [*Gao and Abrahams*, 2004].

[14] Estimates of resistance partitioning between grains, spill, and form drag from LWD were developed by *Curran and Wohl* [2003] using this additive approach. After measuring f_{total} for a series of stream reaches using equation (2), they calculated f_{grain} using a form of the Keulegan equation and f_{debris} using a cylinder-drag-based method developed by *Shields and Gippel* [1995]. Spill resistance, which was treated as the unmeasurable component, was then derived by subtracting grain and debris components from total resistance:

$$f_{spill} = f_{total} - f_{grain} - f_{debris}. \qquad (6)$$

[15] Many of the studies employing this approach have achieved a similar result: the unmeasurable, or leftover component is estimated to be the largest contributor to total flow resistance [e.g., *Einstein and Barbarossa*, 1952; *Prestegaard*, 1983; *Curran and Wohl*, 2003; *MacFarlane and Wohl*, 2003]. The consistency of these findings, regardless of whether the leftover value represents bar resistance, spill resistance, or some other component of flow resistance that is difficult to measure, suggests that the additive method may at least partly predetermine the outcome and inflate the values of any leftover term(s). Whereas these applications of the additive approach treat individual resistance components as if they are isolated and can be evaluated in the absence of other components, combinations of resistance components can produce interaction effects that substantially increase total resistance [*Wilcox and Wohl*, 2006]. Further errors can arise because leftover or unmeasurable terms are sensitive to any error in calculations of the terms on the right side of (5b).

[16] We tested the sensitivity of partitioning estimates to the additive method by calculating grain, spill, and debris resistance using various sets of flume runs in which the order of calculating each resistance component differed. We took advantage of the factorial design we employed, in which friction factor was measured for numerous combinations of grains (presence/absence), steps (presence/absence), and model LWD (multiple configurations), to calculate resistance components using the following four "ordering" methods: (1) grains, then steps, then LWD ($f_{grain} + f_{spill} + f_{debris}$); (2) grains, then LWD, then steps ($f_{grain} + f_{debris} + f_{spill}$); (3) steps, then grains, then LWD ($f_{spill} + f_{grain} + f_{debris}$); (4) steps, then LWD, then grains ($f_{spill} + f_{debris} + f_{grain}$). For each of these methods, the component listed first was directly measured, and subsequently components were calculated as leftover values, as explained further below. Values of f_{grain}, f_{spill}, and f_{debris} calculated by these four

Figure 1. Flume configurations used in partitioning analysis: (left) plane bed with grains, (middle) steps with grains (Q = 8 L/s, S = 0.14 m/m), and (right) steps with grains and LWD (high density, long-single-perpendicular configuration).

methods and of their fractional contribution to f_{total} could then be compared. Additional potential ordering combinations, in which debris was measured first in the absence of steps or grains, followed by addition of steps and grains, were not tested.

[17] For method 1, in order to measure grain resistance, we first measured Darcy-Weisbach friction factor (f_{total}) for flume runs with a plane-bed configuration (only grains on the bed and no steps or debris) (Figure 1, left) at three slopes and five discharges. We assumed that for each of these plane bed runs,

$$f_{total} = f_{grain}. \tag{7}$$

This produced 15 unique f_{grain} values, one for each discharge-slope combination, although one of these (f_{grain} at S = 0.05 m/m, Q = 32 L/s) was eliminated because of flow calibration problems. Because we could not directly measure f_{grain} for subsequent flume runs in which steps and debris were present, equation (3) was used, in combination with data from plane-bed runs, to calculate f_{grain} for such runs. Values of roughness height (k_s) in (3) were determined for each Q-S combination by setting the right-hand sides of equations (2) and (3) equal to each other for each of the 14 plane-bed runs and then using a simple optimization procedure to solve for k_s. The resulting values of k_s, which ranged from 0.06 to 0.12 m, or $2.6-5.4*D_{84}$ depending on the specific Q-S combination, were then used in (3) to calculate f_{grain} for flume runs with steps and debris. This approach produced f_{grain} values that vary with the ratio of flow depth to characteristic grain size. Our treatment of grain resistance was designed to measure the f_{grain} contribution from grains on step treads, rather than the form resistance created by large, step-forming clasts in step-pool channels. Simplifications and potential errors in this analysis are discussed in section 4.

[18] Next, spill resistance values were calculated by measuring f_{total} for runs with steps and grains (but no LWD)

(Figure 1, middle) at the same Q-S combinations as were used for calculating f_{grain} and then subtracting out the grain resistance values derived using (3) for each of those runs:

$$f_{spill} = f_{total} - f_{grain}. \tag{8}$$

This method produced f_{spill} values for each of 14 Q-S combinations. These f_{spill} values were then carried over and applied to subsequent runs with analogous discharges and slopes in which model LWD was added.

[19] Finally, debris resistance was calculated by measuring total resistance for 102 runs with steps, grains, and debris (Figure 1, right). These runs comprised various combinations of discharges, slopes, and LWD densities, orientations, lengths, and arrangements (Table 1). To derive values for f_{debris} for each of these runs, we rearranged (4) as follows:

$$f_{debris} = f_{total} - f_{grain} - f_{spill}. \tag{9}$$

Values for f_{grain} were calculated using (3) and the k_s values we determined based on plane-bed runs, and values for f_{spill} from (8) were carried over for specific Q-S combinations. Using this additive approach, we determined the fractional contribution of f_{grain}, f_{spill}, and f_{debris} to f_{total} for 99 runs (3 of the 102 runs were eliminated because of flow calibration errors) (Table 1).

[20] Method 2 employed a slightly different ordering than method 1, whereby we partitioned total resistance by calculating f_{grain} first, f_{debris} second, and f_{spill} third. For method 2, grain resistance was determined as in method 1, based on plane bed with grain runs and (3). Next, we measured f_{total} for plane bed with LWD runs (Figure 2, left), in which long-single-perpendicular pieces were added at three densities. These tests were completed at four discharges (4, 8, 16, and 64 L/s) and two slopes (0.05 and

Table 1. Flume Runs Used for Testing Additive Approach to Partitioning Between Grain, Spill, and Debris Resistance[a]

		LWD Configuration						
		Long-Single-Perpendicular						
Q (L/s)	S (m/m)	Methods 1 and 3	Method 2	Method 4	Long-Single-Ramp, Methods 1 and 3	Long-Stacked-Perpendicular, Methods 1 and 3	Short-Single-Perpendicular, Methods 1 and 3	Short-Single-Ramp, Methods 1 and 3
4	0.05	x	x	x				
	0.10	x		x				
	0.14	x	x	x				
8	0.05	x	x	x	x	x	x	x
	0.10	x		x	x	x	x	x
	0.14	x	x	x	x	x	x	x
16	0.05	x	x	x				
	0.10	x		x				
	0.14	x	x	x				
32	0.05							
	0.10	x			x	x	x	x
	0.14	x			x	x	x	x
64	0.05	x	x	x				
	0.10	x		x				
	0.14	x	x	x				

[a]Four methods, in which ordering of calculation of resistance components was varied, were tested for runs with steps, grains, and LWD. Each of the LWD configurations shown here was tested at three LWD densities (high, medium, and low).

0.14 m/m). On the basis of these runs, we calculated f_{debris} for eight discharge-slope combinations as:

$$f_{debris} = f_{total} - f_{grain}. \qquad (10)$$

Finally, for runs with steps, grains, and LWD (Figure 1, right), spill resistance was calculated as the leftover value using (6). Because f_{debris} values from plane-bed runs could only be carried over to subsequent step runs with the same LWD configurations (long-single-perpendicular) and Q-S combinations, method 2 comprised a total of only 24 runs (Table 1).

[21] For method 3, we calculated f_{spill}, then f_{grain}, then f_{debris}. Flume runs with smooth plywood steps (no grains, no

debris) (Figure 2, middle) were completed for the same Q-S combinations as in method 1, where:

$$f_{total} = f_{spill}. \qquad (11)$$

These "step without grain" runs, which can be viewed as analogous in some respects to bedrock step-pool sequences, were used to determine baseline values of spill resistance at each slope and discharge. Grain resistance was then calculated by measuring total resistance for runs with steps and grains (the same set of runs used to calculate f_{spill} in method 1) and then subtracting out the baseline spill resistance value determined using (11) for a given slope and discharge:

$$f_{grain} = f_{total} - f_{spill}. \qquad (12)$$

Figure 2. Flume configurations used in partitioning analysis: (left) plane bed with grains and LWD (density is high, orientation is perpendicular, and length is long), (middle) steps without grains (S = 0.14 m/m), and (right) steps without grains, with LWD (high density, long-single-perpendicular configuration).

Finally, friction factor was measured for runs with steps, grains, and model LWD, and f_{debris} was calculated as in method 1 (equation 9), for the same 99 runs (Table 1). Methods 1 and 3 produce similar estimates of f_{debris}, because f_{debris} is in both cases calculated as the remainder or leftover value, although small differences arise because of differences in methods for calculating f_{grain}.

[22] Method 4 employed a similar procedure, starting with smooth steps and calculating f_{spill} as in method 3; then adding long-single-perpendicular debris to smooth steps (Figure 2, right), at three densities, four discharges, and three slopes; and finally calculating f_{grain} as the leftover value in runs with steps, grains, and LWD. Method 4 comprised 36 runs (Table 1).

[23] As a further test of the additive partitioning approach, we compared the sum of spill, grain, and debris resistance components measured separately to the total resistance measured for flume runs with steps, grains, and LWD. This analysis was applied to the 24 flume runs tested in method 2. For those runs, the combination of ($f_{grain} + f_{debris}$) measured using plane-bed runs with grains and LWD, in the context of method 2, was added to f_{spill} values measured with smooth steps only, as part of methods 3 and 4, for runs with analogous Q and S values. The resulting values of $[(f_{grain} + f_{debris}) + f_{spill}]$ were then compared to f_{total} values for runs with steps, grains, and LWD present and with analogous Q and S values. This analysis employed $f_{grain} + f_{debris}$ values because we did not measure f_{debris} in isolation (i.e., LWD with a smooth plane bed) in our experiment.

[24] Among the four ordering methods described above, we further explored the results of method 1 in terms of how the observed partitioning dynamics (i.e., percent contributions of f_{grain}, f_{spill}, and f_{debris} to f_{total}) varied with discharge, slope, and LWD density. Analyses of variance were performed to assess the main effects and two-way interactions between the independent variables (Q, S, and LWD density) on %f_{grain}, %f_{spill}, and %f_{debris}. Analysis of the controls on total resistance is presented by *Wilcox and Wohl* [2006].

2.3. Grain Resistance Calculations

[25] As noted above, studies of flow resistance partitioning have typically calculated grain resistance using empirical and/or theoretically based equations and used the resulting values to indirectly estimate form resistance. For comparison with the f_{grain} values we derived using the fitted Keulegan method (described above in the context of method 1), we also calculated f_{grain} using two published equations for grain resistance, both of which are based on some measure of relative submergence (d/D_x) [*Parker and Peterson*, 1980; *Bathurst*, 2002]. The equation of *Parker and Peterson* [1980], which employs a variation on (3), was developed for gravel bed rivers and can be expressed as:

$$f_{grain} = 8 * \left[2.5 \ln \left(\frac{11d}{2D_{90}} \right) \right]^{-2} \qquad (13)$$

where $k_s = 2D_{90}$ [after *Kamphuis*, 1974] and represents grain resistance only.

[26] We also tested a power law relation developed for calculating bed grain roughness, including both skin friction and form roughness created by large clasts, in steep ($S > 0.008$ m/m) channels [*Bathurst*, 2002]. The *Bathurst* [2002]

equation does not assume a logarithmic velocity profile and can be expressed as follows:

$$f_{grain} = 8 * \left[3.1 \left(\frac{d}{D_{84}} \right)^{0.93} \right]^{-2}. \qquad (14)$$

Equations (13) and (14) were applied to 94 flume runs with grains glued to the bed, including 38 plane-bed runs and 56 step runs. These included runs with no LWD and with low, medium, and high densities of long-single-perpendicular LWD, each repeated at multiple Q-S combinations. To solve (13) and (14), we used flow depths for each flume run and D_x values determined from the sediments used in the flume to represent grain roughness, where $D_{84} = 22$ mm and $D_{90} = 23$ mm.

2.4. Cylinder Drag Calculations of Debris Resistance

[27] In addition to the flume-measured values of debris resistance developed using the additive approaches described above, we calculated f_{debris} based on calculations of form drag associated with woody debris. This approach is referred to here as the "cylinder drag" method because it assumed that drag created by woody debris is governed by the same factors as drag on a cylinder. The procedure draws on methods developed in several previous studies [*Ranga Raju et al.*, 1983; *Gippel et al.*, 1992; *Shields and Gippel*, 1995; *Manga and Kirchner*, 2000; *Hygelund and Manga*, 2003]. The downstream force on a submerged log can be calculated as follows:

$$F_d = \frac{\rho C_d^{app} \bar{u}^2 A \sin \theta}{2} \qquad (15)$$

where F_d is drag force acting on a piece of LWD, ρ is density of water, C_d^{app} is apparent drag coefficient, $\bar{u}$ is depth-averaged approach velocity, A is submerged cross-sectional area of the LWD piece, and θ is the angle of the LWD piece relative to downstream [*Hygelund and Manga*, 2003]. Whereas C_d is the drag coefficient in flow without boundary effects (i.e., in an infinitely large volume of fluid under steady conditions), C_d^{app} is the drag coefficient measured for a specific set of geometric and hydraulic conditions and corrected for the blockage effect of LWD [*Ranga Raju et al.*, 1983; *Shields and Gippel*, 1995; *Hygelund and Manga*, 2003; *Manga and Kirchner*, 2000].

[28] Data on C_d values for various model LWD configurations analogous to those employed in our study have been developed from measurements with a dynamometer in a towing carriage and a flume [*Gippel et al.*, 1992]. The following relation for translating C_d values into values of C_d^{app} appropriate for use in cylinder drag calculations has been proposed:

$$C_d^{app} = \frac{C_d}{a[1 - B]^b} \qquad (16)$$

where a and b are experimentally determined coefficients and B is blockage ratio [*Ranga Raju et al.*, 1983; *Shields and Gippel*, 1995]. The blockage ratio is the ratio of the frontal area of an object to the cross-sectional flow area and, for a submerged, cylindrical LWD piece, is defined as:

$$B = \frac{L' d_{LWD} \sin \theta + \pi \left(\frac{d_{LWD}}{2} \right)^2 \cos \theta}{A_{flow}} \qquad (17)$$

Table 2. Results of Test of Additive Approach to Resistance Partitioning, Showing Average Percent Contributions to f_{total} for Runs With Steps, Grains, and LWD for Four Methods in Which Ordering of Calculation of Resistance Components Was Varied[a]

Method	Ordering	$\%f_{grain}$	$\%f_{spill}$	$\%f_{debris}$	Number of Flume Runs
1	(1) grain, (2) step, (3) LWD	8 ± 8	33 ± 20	59 ± 20	99
2	(1) grain, (2) LWD, (3) step	9 ± 11	74 ± 25	17 ± 17	24
3	(1) step, (2) grain, (3) LWD	32 ± 19	10 ± 10	59 ± 20	99
4	(1) step, (2) LWD, (3) grain	28 ± 24	12 ± 10	59 ± 26	36

[a]These data represent varying LWD configurations, discharges, and slopes, all of which combine with measurement errors to produce the large standard deviations around mean values shown here.

where L' is piece length, d_{LWD} is cylinder diameter, and A_{flow} is cross-sectional area of the flow [*Gippel et al.*, 1992]. For pieces oriented perpendicular to the flow ($\theta = 90°$), (17) reduces to $B = (L'd_{LWD})/A$, and, where piece length is the same as flow width and $\theta = 90°$, $B = d_{LWD}/d$.

[29] Data from flume studies suggest that, for blockage ratios between 0.03 and 0.4, a and b in (16) are approximately one and two, respectively [*Gippel et al.*, 1992; *Shields and Gippel*, 1995]. Field measurements of drag coefficients for model LWD, however, found no relationship between B and C_d^{app} and that at larger B values, C_d^{app} was approximately 2.1 [*Hygelund and Manga*, 2003].

[30] Once the drag force associated with debris has been determined, the associated shear stress (τ_{debris}) can be calculated by dividing drag force acting on a single piece of LWD (15) by the total area of the bed covered by debris divided by the number of pieces of debris, producing:

$$\tau_{debris} = \frac{\rho C_d^{app} \bar{u}^2 d_{LWD}}{2X} \quad (18)$$

where X is distance between logs [*Nelson et al.*, 1993; *Hygelund and Manga*, 2003]. For evenly spaced perpendicular pieces resting on the bed, X is equal to reach length divided by the number of pieces. τ_{debris} can then be converted into the debris component of Darcy-Weisbach friction factor:

$$f_{debris} = \frac{8\tau_{debris}}{\rho \bar{u}^2} = \frac{4C_D^{app} d_{LWD}}{X}. \quad (19)$$

Equation (19), which is similar to the equation proposed by *Shields and Gippel* [1995] for calculating form resistance resulting from LWD formations, assumes that wake interaction effects between LWD pieces are minimal. Calculation of f_{debris} by this method does not require data on approach velocities ($\bar{u}$ cancels out), and (18) can be omitted.

[31] We used (19) to calculate f_{debris} for 82 flume runs containing model LWD. These included all of the runs tested in method 1 (Table 1) that had blockage ratios (B) less than 0.4, as well as 11 plane-bed runs for which $B < 0.4$. At higher B values, which occurred at low discharges where LWD pieces were either barely submerged or only partially submerged, (16) is invalid. The LWD runs tested here and included in method 1 represent the subset of the larger number of LWD runs we completed [*Wilcox*, 2005; *Wilcox and Wohl*, 2006] that had configurations for which C_d values were available from *Gippel et al.* [1992]. *Gippel et al.* [1992] measured drag force for a number of model LWD configurations, and many of their measurements employed

model debris with similar dimensions and orientations as were used in our study, in a flume with the same width as our flume (0.6 m). We derived C_d values for single pieces oriented perpendicular to flow based on the following empirical relation developed by *Gippel et al.* [1992] for pieces with $L'/d_{LWD} < 21$:

$$C_d = 0.81\left(\frac{L'}{d_{lwd}}\right)^{0.062}. \quad (20)$$

Equation (20) produced C_d values of 0.99 and 0.94 for long ($L' = 0.6$ m) and short ($L' = 0.3$ m) perpendicular pieces, respectively.

[32] *Gippel et al.* [1992] reported C_d values of approximately $C_d = 0.6$ and $C_d = 0.75$ for cylinders oriented 30° and 45° to the flow direction, respectively. On the basis of these values, we adopted a C_d value of 0.7 for our ramped pieces, which were oriented between 30° and 45° to the flow. *Gippel et al.* [1992] also reported C_d values for stacked pieces, but all of our flume runs with stacked configurations produced blockage ratios greater than 0.4 and therefore were excluded from cylinder drag calculations.

[33] Drag coefficient values were combined with blockage ratios calculated for each flume run, using (17), to calculate C_d^{app} using (16), with $a = 1$ and $b = 2$. Finally, f_{debris} was calculated using (19) and compared to values derived using additive methods.

3. Results

3.1. Test of Additive Partitioning Approach

[34] The averages of the percent contributions of grain, spill, and debris resistance to total resistance, calculated using the four ordering methods we tested for evaluating additive approaches to resistance partitioning, are shown in Table 2 and Figure 3. The order in which resistance components were added to the flume substantially influenced partitioning results (Table 2 and Figure 3). Partitioning estimates using the additive approach consistently inflated the contribution of a given resistance component when that component was calculated as a leftover value (i.e., added second or third) compared to when that component was isolated and measured directly.

[35] For all of the methods in which model LWD was added to existing step configurations (methods 1, 3, and 4), f_{debris} was found to be responsible for slightly less than 60% of total flow resistance. In contrast, method 2, in which debris was added to plane-bed configurations, resulted in a much smaller f_{debris} contribution. Calculations of the spill resistance contribution were strongly sensitive to ordering,
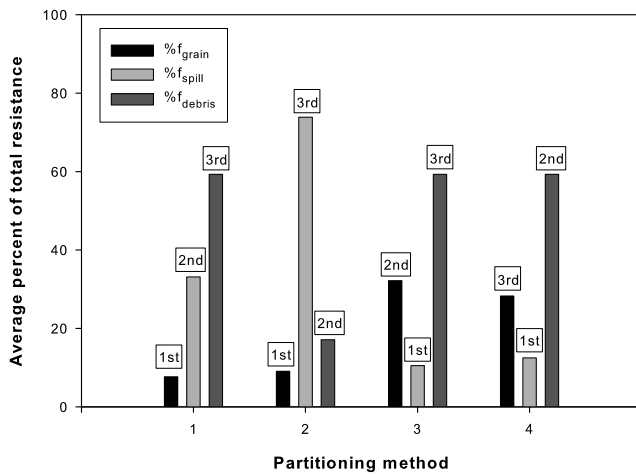
Figure 3. Results of test of additive approach to resistance partitioning based on four methods of measuring grain, spill, and LWD resistance (f_{grain}, f_{spill}, and f_{debris}, respectively) in which ordering of calculation of each component was varied, as indicated by boxes above each bar. Bars represent average of percent contributions of f_{grain}, f_{spill}, and f_{debris} to total flow resistance for runs included in each partitioning method, where $\%f_{grain} + \%f_{spill} + \%f_{debris} = 100$ for each run.

ranging from 10% when smooth steps were added first and $f_{total} = f_{spill}$ (methods 3 and 4) to 74% for method 2, where spill resistance is the leftover value for runs with steps, grains, and debris (equation 6). Grain resistance contributions also were sensitive to ordering but were never more than approximately one third of the total. For methods in which f_{grain} was calculated using equation (3) (methods 1 and 2), grain resistance was on the order of 10% of the total, whereas higher f_{grain} contributions (about 30%) were estimated for methods in which f_{grain} was calculated as a leftover value (methods 3 and 4).

[36] Several conclusions can be drawn that are insensitive to ordering (i.e., that applied to all four methods). First, form resistance consisting of spill resistance (from steps) and debris resistance combined was responsible for the largest proportion of total flow resistance (68–92%). Second, grain resistance was a relatively small component of total resistance (8–32%) when steps and/or debris were present. Third, the conclusion of *Curran and Wohl* [2003] that spill resistance is dominant in step-pool channels was supported only if some portion of the resistance assigned to f_{debris} for runs with steps is assumed to actually represent part of f_{spill}. This analysis also suggested that whichever resistance component was added first and measured in isolation (either steps or grains) accounted for only approximately 10% of the resistance that would occur if steps, grains, and LWD were all present (Table 2). Although debris resistance was never measured independently (i.e., with a smooth plane bed), this latter conclusion may apply to f_{debris} as well, in light of the low f_{debris} contributions observed for plane bed with grain runs.

[37] Comparison of the sum of resistance components $[(f_{grain} + f_{debris}) + f_{spill}]$ measured separately to f_{total} measured for runs with steps, grains, and LWD present and analogous Q and S values showed that the whole (f_{total}) is substantially greater than the sum of the parts under most conditions (Figure 4). This comparison is consistent with the analysis of ordering methods above and highlights the importance of nonlinear and synergistic effects of combining resistance components in step-pool channels, particularly steps and LWD. An exception to this pattern occurred at the highest discharge we tested (64 L/s), when the sum of resistance components was similar to f_{total} (Figure 4).

3.2. Controls on Resistance Partitioning

[38] Results based on method 1 were further explored to assess controls on resistance partitioning. The distribution of partitioning estimates for all the flume runs included in method 1 are shown in Figure 5, illustrating the variability resulting from differences in Q, S, and LWD configuration. The relative contributions of grain, spill, and debris resistance in these runs were strongly mediated by discharge, which had highly significant effects ($p < 0.0001$) on $\%f_{grain}$, $\%f_{spill}$, and $\%f_{debris}$ in analyses of variance. On the basis of the magnitude of the sums of squares and p values, discharge effects on partitioning were substantially larger than those of slope or LWD density. Both the magnitude of f_{spill} and its contribution to total resistance were inversely proportional to discharge, suggesting that reductions in f_{total} with increasing discharges were disproportionately caused by decreases in spill resistance as steps were drowned out (Figures 6 and 7). From low to moderate discharges (4–16 L/s), $\%f_{debris}$ increased as debris pieces became fully submerged, beyond which $\%f_{debris}$ leveled off. At low discharges (4 and 8 L/s), $\%f_{spill}$ and $\%f_{debris}$ were typically similar in magnitude, whereas $\%f_{debris}$ dominated at higher discharges when steps were drowned out (Figure 6). Percent grain resistance increased with increasing discharge (Figure 6), reflecting the more rapid decreases in f_{total} than in f_{grain} with Q.

[39] Slope significantly affected spill resistance, with higher f_{spill} magnitudes and contributions to f_{total} occurring
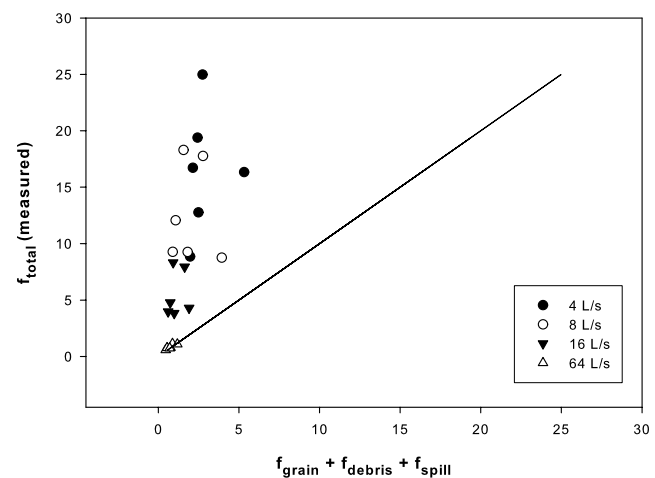

Figure 4. Comparison of resistance calculated as sum of components measured separately (x axis) versus measured total resistance for 24 runs with steps, grains, and LWD (y axis). Values on the x axis were calculated by adding ($f_{grain} + f_{debris}$) values derived from plane bed with LWD runs to f_{spill} values measured for runs with smooth steps and analogous discharges and slopes. Solid line illustrates 1:1 relationship.
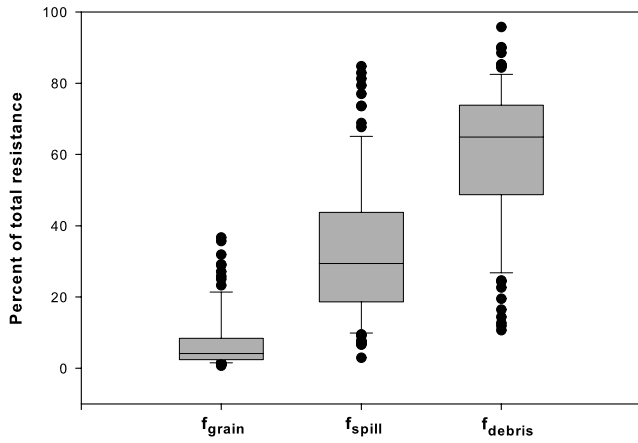
Figure 5. Percent contributions of grain, spill, and debris resistance to total flow resistance for 99 runs with grains, steps, and LWD completed at varying debris densities, discharges, and slopes, where $\%f_{grain} + \%f_{spill} + \%f_{debris} = 100$ for each run. Results are based on method 1, in which f_{grain} is calculated using a Keulegan relation, $f_{spill} = f_{total} - f_{grain}$ from runs with steps and grains, and $f_{debris} = f_{total} - f_{spill} - f_{grain}$. Boxes represent 25th–75th percentile range, solid lines within boxes indicate median, bars above and below boxes show 10th and 90th percentiles, and circles are outliers.

at steeper slopes (Figure 7). This effect was only present at low discharges, however, as indicated by least squares means for the $Q*S$ interaction and as shown in Figure 7. At higher discharges, slope effects on $\%f_{spill}$ were subsumed by the Q effects discussed above. The slope effect observed at low discharges is likely attributable to the step geometry employed here, whereby a greater number of steps were present over the length of the flume at higher slopes [see *Wilcox and Wohl*, 2006], creating more opportunity for spill resistance generation as flow plunges over steps. Slope had marginally significant effects on $\%f_{debris}$ and was not significant for $\%f_{grain}$.

[40] Debris density also significantly influenced resistance partitioning, with higher f_{debris} contributions at higher model
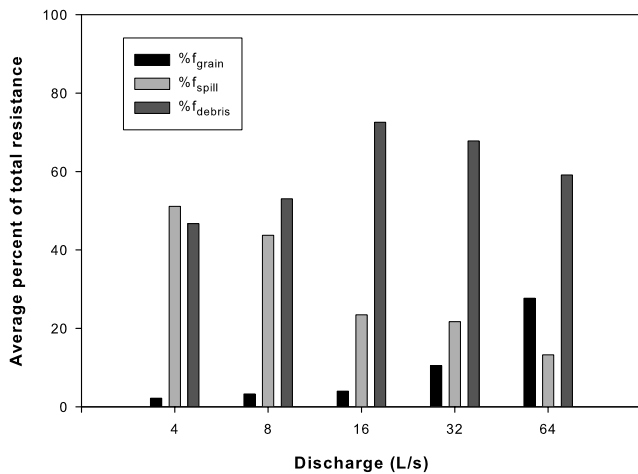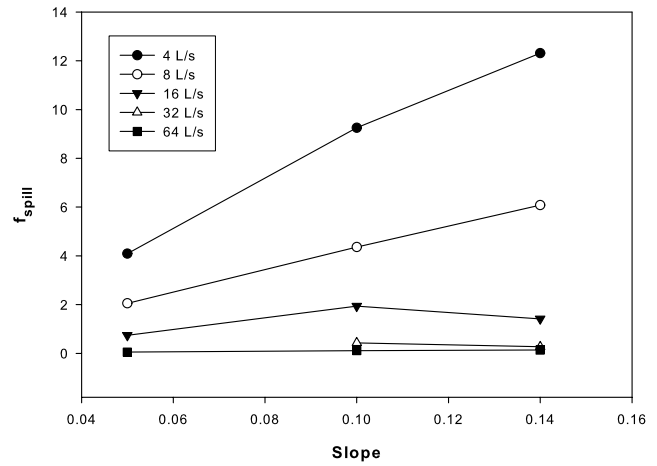

Figure 7. Variations in spill resistance with discharge and slope, where f_{spill} is calculated for 14 flume runs with steps and grains and no LWD ($f_{spill} = f_{total} - f_{grain}$).

LWD densities (Figure 8). At high debris densities, an average of approximately two thirds of total resistance was attributable to debris when grains, steps, and debris were present, whereas the f_{debris} contribution to f_{total} averaged slightly less than half at low debris densities. Conversely, the contributions of spill and grain resistance to f_{total} both decreased with increasing debris density (Figure 8).

3.3. Independent Calculations of Resistance Components

3.3.1. Grain Resistance

[41] Comparisons of grain resistance values generated by (13) and (14) with measured f_{grain} showed that for nearly all runs, these equations produced lower estimates of f_{grain} than our "fitted Keulegan" method (see section 2.2) (Figure 9). The f_{grain} values calculated using the Parker and Peterson equation (13) show a linear but consistently deviating relationship with our flume-derived f_{grain} results (Figure 9), reflecting the similar, semilogarithmic form of equations (3) and (13) but the different coefficients, especially for
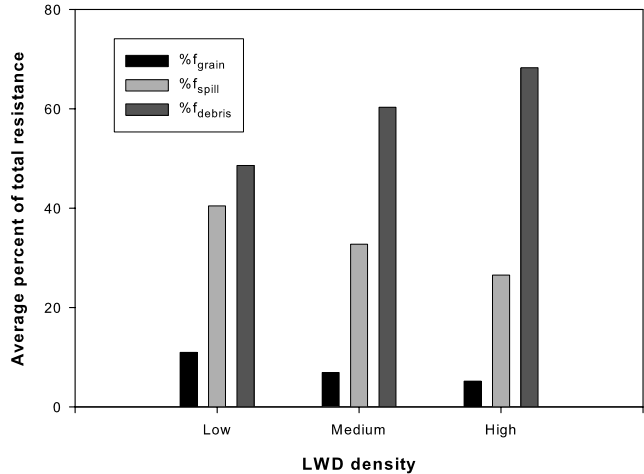

Figure 6. Effect of discharge on resistance partitioning between grains, spill, and LWD, based on method 1 results for 99 flume runs.

Figure 8. Effect of LWD density on resistance partitioning between grains, spill, and LWD, based on method 1 results for 99 flume runs.
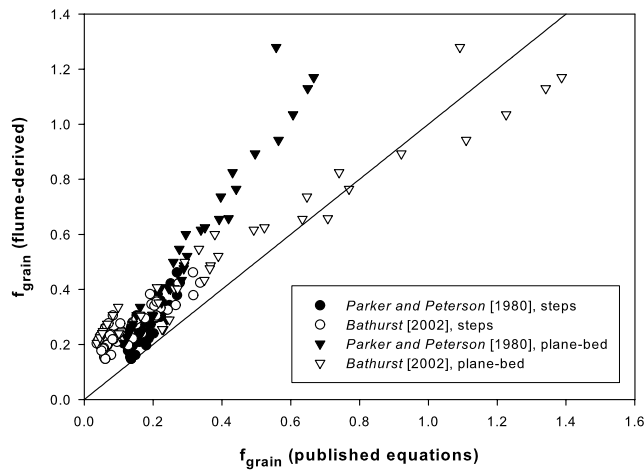
Figure 9. Comparison of grain resistance (f_{grain}) values for 94 flume runs with plane-bed or step configurations, calculated using either published equations for grain resistance [*Bathurst*, 2002; *Parker and Peterson*, 1980] (x axis values) or a flume-derived Keulegan relation with roughness height (k_s) values developed from plane-bed runs (y axis values). Solid line illustrates 1:1 relationship.

roughness height (k_s), used in these equations. The Bathurst equation (14) produces values that are similar to or slightly greater than flume-derived results at $f_{grain} > \sim 0.6$ (Figure 9). These correspond to runs with relative submergence (d/D_{84}) values on the order of one and specifically to plane-bed runs at low discharges. The Bathurst equation (14) consistently underestimates f_{grain} compared to flume results at higher d/D_{84} values, corresponding to $f_{grain} < 0.6$ in Figure 9, including runs with steps and plane-bed runs at intermediate to high discharges. Employing f_{grain} values from (13) and (14) to estimate the contribution of grain resistance to f_{total} indicates even smaller grain resistance contributions (3–6% of f_{total}, on average) than estimated in method 1 above.

3.3.2. Debris Resistance

[42] For runs with steps, debris resistance values calculated using the cylinder-drag-based approach were substantially smaller than f_{debris} estimates generated by additive method 1 for most of the discharges tested (Figure 10, top). The exception occurred at the highest measured discharge, 64 L/s, for which f_{debris} values were similar (and consistently small) for both methods (Figure 10). This comparison included flume runs completed with various slopes and LWD configurations, but compared to discharge, these factors had minimal effect on the differences in f_{debris} values between additive and cylinder drag methods. Differences in f_{debris} values between these methods may be caused by several factors. As discussed below, the additive approach inflates f_{debris} values (for method 1) by incorporating step-debris interaction effects into f_{debris}, whereas the drag approach does not account for such interaction effects. The drag-based method also may introduce error in a number of steps, such as in the conversion of C_d to C_d^{app}.

[43] We also compared f_{debris} results for plane-bed runs only, using both the cylinder drag approach and additive method 2, in which f_{total} was measured for plane-bed with LWD runs and f_{debris} was derived using (10). For the 11

plane-bed runs compared here (i.e., those with $B < 0.4$), the agreement between these methods was substantially better than in the preceding comparison for step runs (Figure 10, bottom). This suggests that the cylinder drag approach is more appropriate for calculating the resistance created by fully submerged debris pieces resting on a plane-bed than for LWD on steps because of the additional resistance produced by LWD-step interactions.

4. Discussion

[44] Standard approaches to resistance partitioning typically (1) assume that resistance components are isolated and additive and (2) indirectly quantify difficult to measure components by subtraction of measurable components from total resistance. This flume experiment showed that such methods tend to inflate the values assigned to the unmeasurable or leftover components and that the total resistance
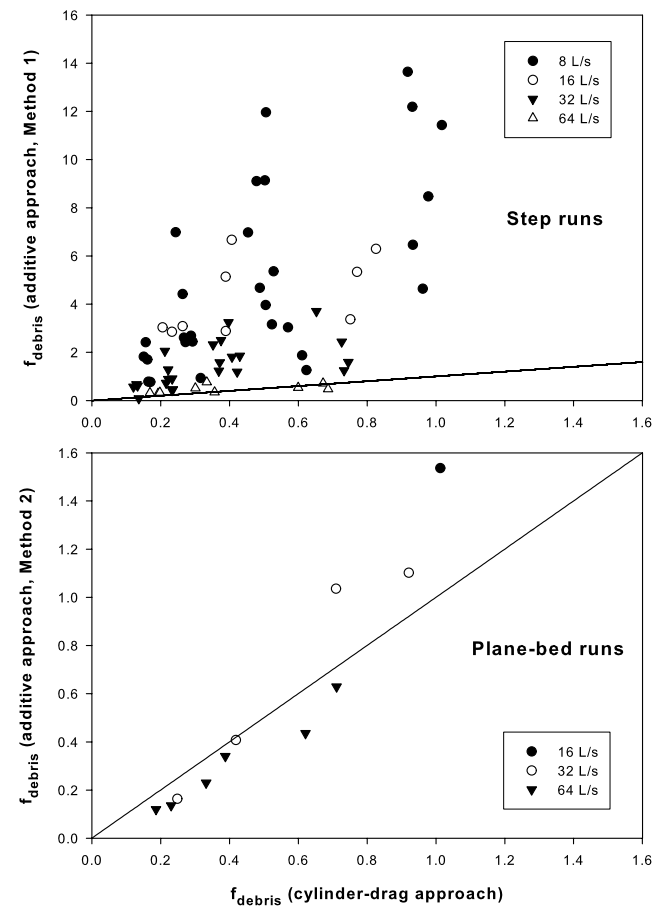

Figure 10. Comparison of two methods of calculating f_{debris} for (top) runs with steps and (bottom) plane-bed runs. Values on the x axis are calculated using a cylinder drag approach, based on cylinder drag coefficients and LWD spacing. Values on the y axis are calculated using an additive approach, where, for step runs, $f_{debris} = f_{total} - f_{spill} - f_{grain}$ (method 1) and, for plane-bed runs, $f_{debris} = f_{total} - f_{grain}$ (method 2). Solid lines illustrate 1:1 relationships. Results are differentiated by discharge to illustrate influence of Q on f_{debris} estimates; flume runs at low discharges (4 L/s for step runs and 4 and 8 L/s for plane-bed runs) were excluded because of insufficient submergence of debris pieces.

measured for combinations of bed roughness variables can be substantially greater than the sum of those components measured separately. Partitioning estimates produced by additive approaches are therefore highly sensitive to the choice of measurable versus unmeasurable terms and to how each term is calculated, and leftover values are sensitive to any errors in calculation of measurable terms.

[45] These results illustrate the importance of interaction effects between resistance components, whereby the presence of one type of roughness (e.g., LWD) can substantially affect the momentum extraction by other types of roughness (e.g., steps). Interaction effects can produce synergistic increases in total flow resistance with certain combinations of resistance components. Because any such increases in f_{total} are typically assigned to leftover values in additive approaches to resistance partitioning, values of leftover terms are inflated. For example, addition of LWD to steps causes large increases in f_{total}, likely because LWD both creates form drag on debris pieces and, where LWD is positioned near step lips, increases the spill resistance effect of steps. Where f_{debris} is calculated after f_{spill} (e.g., methods 1, 3, and 4 above), however, any such synergistic effects are assigned entirely to f_{debris}. Interactions between grains and LWD also skew partitioning results. For flume runs with smooth steps (no grains) and LWD, conducted in the context of method 4, f_{debris} contributions are small at low flows because of incomplete submergence of debris pieces. Addition of grains to step treads results in flow depths sufficient to fully submerge debris, increasing the drag created by debris pieces, but all such increases in debris resistance are assigned to the f_{grain} term, as the leftover value in method 4.

[46] Synergistic increases in flow resistance resulting from interaction effects also create errors in additive partitioning methods by invalidating the basic premise that resistance components can be evaluated independently and then treated as if they are additive. Partitioning errors therefore may be greater in systems with stronger interactions between resistance components. Although we do not know of any studies that have quantified interaction effects in lower-gradient channels, we hypothesize that such effects may be greater in step-pool channels. Our companion study [*Wilcox and Wohl*, 2006] quantifies interaction effects using factorial analyses of variance that illustrate highly significant interactions between steps, grains, and debris in affecting total flow resistance. That study also concludes that such interactions are an important factor controlling flow resistance dynamics in step-pool channels.

[47] In the context of step-pool channels, the delineation of flow resistance into grain, spill, and debris components provides a useful conceptual framework for considering resistance partitioning. As discussed above, however, these components are not independent, as additive approaches assume, and identification of their contributions to total resistance can be problematic. Delineations between resistance components in step-pool channels are less clear-cut than in the low-gradient channels to which the concept of resistance partitioning originally was applied and where a sharper distinction can be drawn between grain and form roughness. For example, in sand bed channels, individual sand grains on the bed are responsible for grain roughness, whereas organization of these grains into ripples, dunes, or other bed forms creates form roughness. In step-pool

channels, individual grains contribute to skin friction resistance, form resistance, and spill resistance, and LWD also contributes to multiple types of flow resistance.

[48] Despite the difficulties of delineating resistance components in step-pool channels and the errors introduced both by additive partitioning approaches and by simplifications employed in the flume modeling (as discussed in detail by *Wilcox and Wohl* [2006]), this flume study does allow a number of conclusions to be drawn. Our results suggest that LWD, by creating form drag, damming the flow, and altering spill dynamics over steps, can be an important source of flow resistance in step-pool channels. Although f_{debris} was delineated here as a separate component from f_{spill}, the results showed that LWD pieces positioned near the lip of steps, by contributing to the structure of steps and increasing their effective height, substantially increase the spill resistance effect of steps compared to steps without LWD. These results strongly support the finding that in field settings, step-pool reaches containing LWD, sometimes referred to as forced step-pools [*Montgomery and Buffington*, 1997], can have substantially greater flow resistance than those lacking LWD [*Curran and Wohl*, 2003; *MacFarlane and Wohl*, 2003]. Because of its potentially large role in creating flow resistance in step-pool channels, LWD is likely important in reducing the shear stress available for bed/bank erosion and sediment transport in these channels. LWD removal from mountain streams and reduced recruitment as a result of forestry practices may therefore alter flow resistance and sediment transport dynamics, as well as aquatic habitat characteristics associated with these hydraulic factors.

[49] Quantifying the contribution of LWD to flow resistance in field settings remains an important challenge, however. The tests of the cylinder-drag-based approach performed here suggest that this approach underestimates debris resistance in step-pool channels, likely because the step-debris interaction effects described above are not accounted for. This contrasts with successful applications of the cylinder drag approach in lower-gradient rivers [*Shields and Gippel*, 1995; *Manga and Kirchner*, 2000].

[50] Although our results suggested that calculated values of spill and debris resistance are sensitive to the partitioning methods employed and that delineation and quantification of f_{spill} is problematic, the general conclusion that form resistance, incorporating both LWD and spill, is dominant in step-pool channels was universal to all the methods we tested. In addition, the importance of spill resistance documented here suggests a key difference in resistance dynamics between step-pool and lower-gradient systems, in which spill resistance is essentially absent.

[51] Further, we found that grain roughness produced by bed sediments on step treads was a small component of total resistance when steps and/or debris were present. This result partly reflects simplifications in our treatment of grain roughness, which was represented here by grains with a relatively homogenous size distribution compared to bed sediments in natural step-pool channels and only by grains on step treads. This approach therefore did not model the form and spill resistance from large, step-forming particles, which are undoubtedly important in natural channels. Although these simplifications suggest limitations on the applicability of our findings regarding grain resistance to

field settings, field studies also have found that f_{grain} only contributes a small fraction of f_{total} in step-pool channels [*Curran and Wohl*, 2003; *MacFarlane and Wohl*, 2003]. In contrast, grain resistance can be the dominant source of resistance in lower gradient gravel and cobble bed channels [*Bray*, 1982; *Knighton*, 1998].

[52] Errors in grain resistance estimates can introduce error into additive partitioning approaches in which grain resistance values are used to indirectly quantify unmeasurable components. The comparison between our f_{grain} values and those derived from other equations [*Parker and Peterson*, 1980; *Bathurst*, 2002] illustrates that f_{grain} values are sensitive to the form of equation used (e.g., logarithmic versus power law) and to the choice of characteristic grain size and/or roughness height in these equations. Whereas we found that Keulegan-type equations based on the D_{84} of material on the step treads produced f_{grain} values that were only a small fraction of f_{total}, *Lee and Ferguson* [2002] indicated that Keulegan-type equations in which k_s was scaled to step D_{84} performed well in predicting total resistance in step-pool channels without woody debris.

[53] Errors in f_{grain} values for flume runs with steps also may have resulted from the transfer of roughness height (k_s) values derived for specific Q-S combinations using plane-bed runs to step runs. Such errors are unlikely to have affected overall partitioning results, however, given the small magnitude of f_{grain} values compared to f_{total} when steps and LWD were present.

[54] Partitioning between grains, steps, and LWD was strongly influenced by discharge. For example, as discharge increases and steps are drowned out, spill resistance and its fractional contribution to f_{total} declines. The reduction in spill resistance with discharge can be conceptualized in terms of the transition from nappe flow to skimming flow [*Chanson*, 1994]. At lower flows, steps produce nappe flow, where flow tumbles over each step as a succession of overfalls, resulting in a high f_{spill} contribution. At higher flows, the water surface profile flattens and a transition toward skimming flow occurs, reducing the f_{spill} contribution. Procedures developed for calculating the discharge at which the onset of skimming flow occurs in stepped spillways [*Chanson*, 1996; *Boes and Hager*, 2003] suggest that with the flume dimensions and step geometry employed here, this transition should occur between approximately 50 and 60 L/s. This is slightly less than the highest discharge we modeled (64 L/s), although we did not observe fully developed skimming flow with a uniform water surface, perhaps because these methods were developed for somewhat different conditions than those in our flume. Transitions toward skimming flow were evident, however, providing conceptual support for the above explanation of reduced f_{spill} contributions at high discharges.

[55] Whereas the contribution of f_{spill} to f_{total} was found to decrease with Q, the relative contribution of f_{grain} increased with Q. Because grain resistance is calculated as a function of relative submergence of bed particles, its magnitude decreases with increasing depth or discharge. The proportion of total resistance attributable to grain resistance, however, may increase with increasing stage as form resistance components are drowned out, particularly where those components are calculated as leftover values, as observed here and by *Parker and Peterson* [1980].

[56] Discharge also influenced the magnitude of deviations between various methods of calculating resistance components, including the comparison of the sum of separately measured components to f_{total} (Figure 4) and the comparison of cylinder drag estimates of f_{debris} with those based on additive methods (Figure 10). These analyses showed that deviations were greatest at low discharges and smallest at high discharges, when overall f_{total} values were small and synergistic effects of combinations of resistance components were limited.

5. Conclusions

[57] This study has illustrated patterns of flow resistance partitioning between LWD, spill over steps, and grains in step-pool channels. The combined effect of LWD and spill over steps dominates flow resistance in these channels, and grain resistance along step treads is only a small component of total resistance. Resistance from spill and LWD therefore substantially reduce the shear stress applied to the bed and available for sediment transport in step-pool channels. The relative contributions of different sources of resistance are mediated by discharge, because steps and associated spill resistance are drowned out at high discharges, and, to a lesser extent, by LWD density.

[58] Flow resistance partitioning in step-pool channels is complicated by the substantial interaction effects that occur between roughness variables. Momentum extraction associated with LWD, steps, and grains varies depending on the presence of other roughness variables, and the flow resistance created by these features cannot always be delineated into a clear category such as spill resistance. Interaction effects between roughness components therefore can create error in additive approaches to resistance partitioning that attempt to quantify unmeasurable resistance components by subtraction from measured components. Such approaches, which are commonly used in partitioning analyses, assign interaction effects to unmeasurable components, thereby inflating these leftover values. Furthermore, methods developed for lower-gradient channels, including cylinder-drag-based approaches for calculating debris resistance, are unreliable in step-pool channels because they do not capture interaction effects.

[59] Several avenues of future research could build on the flume study described here. For example, field studies entailing manipulation of roughness variables (e.g., addition of LWD to clast-formed step-pool sequences), investigations linking hydraulics and roughness partitioning to sediment transport dynamics and/or aquatic habitat characteristics, and exploration of methods for quantifying spill resistance would further enrich understanding of mountain stream channels.

Notation

f_{total} total flow resistance, represented here by Darcy-Weisbach friction factor.

f_{grain} component of Darcy-Weisbach friction factor associated with grains.

f_{form} component of Darcy-Weisbach friction factor associated with flow resistance created by bed forms or other sources of form drag.

g gravitational acceleration.
R hydraulic radius.
S_f friction slope.
V flow velocity.
d flow depth.
k_s roughness height.
m coefficient used for scaling characteristic grain size in roughness height calculations.
D_x grain size for which $x\%$ of particles are finer.
d/D_x relative submergence of bed particles.
f_{spill} component of Darcy-Weisbach friction factor associated with spill over steps into pools.
f_{debris} component of Darcy-Weisbach friction factor associated with large woody debris (LWD).
H step height.
L step length.
S bed slope.
Q water discharge.
$H/L/S$ step height-step length-bed slope ratio.
$f_{measurable}$ component of flow resistance that can be measured directly or calculated using existing methods.
$f_{unmeasurable}$ component of flow resistance that is difficult to measure directly.
F_d drag force acting on LWD piece.
ρ density of water.
C_d^{app} apparent drag coefficient (i.e., drag coefficient measured for a specific set of geometric and hydraulic conditions and corrected for the blockage effect of LWD).
$\bar{u}$ depth-averaged approach velocity.
A submerged cross-sectional area of LWD piece.
θ angle of LWD piece relative to downstream.
C_d drag coefficient in flow without boundary effects (i.e., in an infinitely large volume of fluid under steady conditions).
a experimentally determined coefficient for converting C_d to C_d^{app}.
b experimentally determined coefficient for converting C_d to C_d^{app}.
B blockage ratio; ratio of the frontal area of an object to the cross-sectional flow area.
L' LWD piece length.
d_{LWD} cylinder diameter.
A_{flow} cross-sectional area of the flow.
τ_{debris} shear stress associated with LWD.
X distance between LWD pieces.

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