Pattern and origin of stepped-bed morphology in high-gradient streams, Western Cascades, Oregon

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ABSTRACT

A general hierarchical framework for viewing stepped-bed morphology in high-gradient channels is presented. We emphasize channel units—bed features that are one or more channel widths in length—as a particularly important scale of variation. Field studies in two streams in the Cascade Range in Oregon indicated that pool, riffle, rapid, cascade, and step channel units had distinct bed slope ranges, with average slopes of 0.005, 0.011, 0.029, 0.055, and 0.173, respectively. Steeper units (rapids and cascades) are composed of step-pool sequences created by particles representing the 90th or larger percentile size fraction of bed material. Step spacing is inversely proportional to bed slope.

The distribution of channel units along a stream is influenced by bedrock and processes that introduce coarse sediment. Cascade and pool units dominate where landslide and debris-flow deposits constrict channel width and deliver large immobile boulders to the channel, whereas riffle and rapid units dominate in broad valley flats where deposition of finer sediment occurs. Markov chain analysis indicates that channel units occur in nonrandom two-unit sequences with the slope of the upstream unit inversely proportional to the slope of the next downstream unit. Pool-to-pool spacings average two to four channel widths, but variability in spacing is high, owing to uneven distribution of bedrock outcrops and boulder deposits within the channel.

Hydraulic reconstruction indicates that channel units form during high-magnitude, low-frequency events with recurrence intervals of about 50 yr. Comparison of channel-unit morphology to high-gradient flume experiments with heterogenous bedload mixtures indicated that unit morphogenesis is linked to factors that cause congestion of large particles during bedload transport events; these include local constrictions in channel width, immobile bed material, and abrupt fluctuations in velocity due to hydraulic jumps that promote deposition. Channel units appear to be a two-dimensional bar form found in streams where gradients exceed 2%, bedload is widely sorted, and width-to-depth ratios and sediment supply are low—conditions found in many mountain environments.

INTRODUCTION

Alternating steep- and gentle-gradient segments are found in a wide range of stream channels. In streams of low to moderate gradient (slope <2%), bed undulations of this type are associated with well-known pool-and-riffle sequences (Leopold and others, 1964; Yang, 1971; Richards, 1976, 1978a, 1978b; Keller and Melhorn, 1978; Milne, 1982b). Less clearly under-

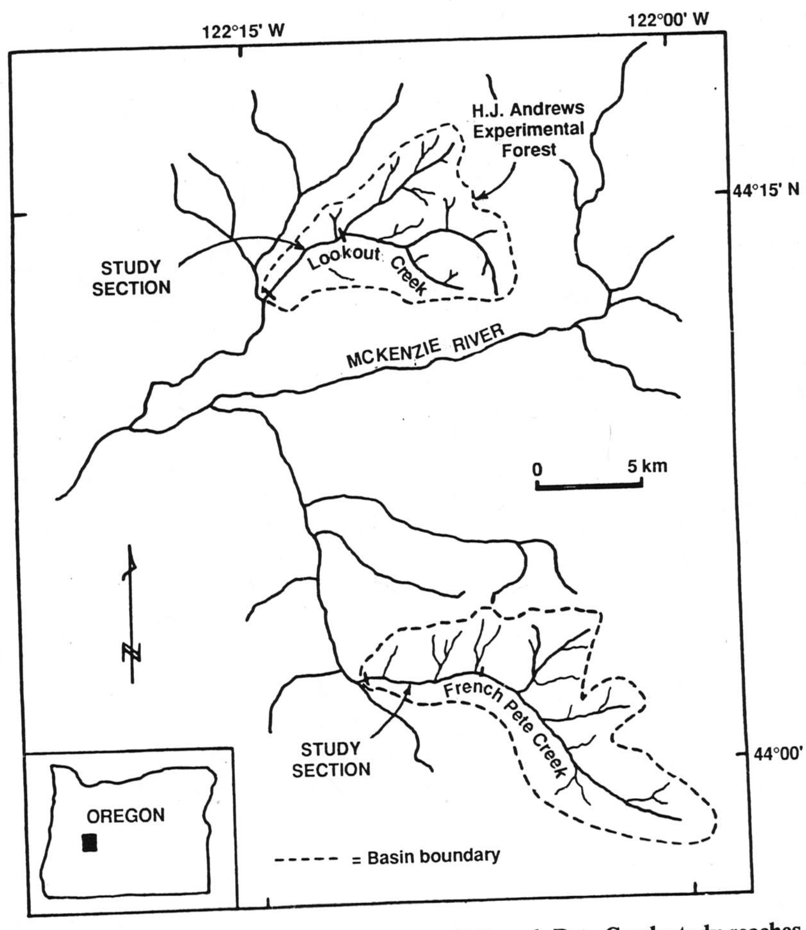

Figure 1. Locations of Lookout Creek and French Pete Creek study reaches.

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stood are variations in bed topography in high-gradient, boulder-bed mountain streams where a distinctly stepped longitudinal profile is commonly visible at several spatial scales.

Few systematic studies of bedforms in steep streams have been done. Many scientists recognize that the terms "pool" and "riffle" do not adequately distinguish the broad range of forms found in steep channels, and this results in a perplexing and imprecise nomenclature of bed features (Table 1). This wide range of terms reflects the lack of a sound conceptual framework for analyzing mountain stream channels. What is needed in part is a taxonomy of morphologic features that can be used to classify stream structure; to characterize changes in stream morphology in response to floods, debris flows, and landslides; and to analyze morphogenetic processes in steep channels. Such a framework is essential to developing theoretical and physical models of the origin of steep-channel bedforms and offers a useful heuristic device for understanding boulder-bed stream morphology.

This study focuses on the questions of whether individual bed features can be defined and discriminated in mountain streams and what processes can account for their pattern and origin. In this paper, we propose a hierarchical model of the structure of longitudinal profiles of mountain streams and examine the morphology of two steep boulder-bed channels at several scales of this hierarchy. These streams are typical of moderate-size (4th to 5th order) streams draining the western slopes of the Cascade Range in Oregon, but we have observed similar features in other places as well. Morphogenesis of bedforms in boulder-bed streams is considered in light of hydraulic reconstruction of flow conditions at incipient motion of large bed particles and by comparison with bed forms in gravel-bed channels and flumes.

Mountain streams differ from lowland streams in several important respects. Hydraulics of high-gradient streams are strongly influenced by large boulders with diameters on the same scale as channel depth or even width, which create large-scale form roughness leading to high energy losses (Bathurst, 1978), upper-regime flow, and disrupted velocity profiles (Jarrett, 1985; Wiberg and Smith, 1987). Lowland channels, in contrast, have roughness due primarily to bedforms and bars (Bathurst, 1978). Interactions between hillslopes and channels in mountain streams influence stream and valley morphology, and sediment transport is intimately linked with hillslope processes in terms of both supply rate and delivery mechanisms. Nonfluvial emplacement of bed material by landslides and debris flows results in channels containing bed particles that resist transport; consequently, geomorphically effective events for transporting sediment and restructuring channels occur infrequently (Scott and Gravlee, 1968; Hayward, 1980; Best and Keller, 1986; Grant, 1986; O'Connor and others, 1986; Nolan and others, 1987). In contrast, lowland streams are in many cases separated from valley walls by extensive flood plains and terraces, and geomorphically effective events occur relatively frequently (Pickup and Warner, 1976; Wolman and Gerson, 1978).

TABLE 1. CORRELATION OF NOMENCLATURE USED IN THIS PAPER TO DESCRIBE BED FEATURES IN BOULDER-BED STREAMS WITH THAT IN PREVIOUS WORK

Length of feature* (channel widths)	Nomenclature this paper	Other terminology	References
		Boulder clusters	Brayshaw, 1985
10^{-2}–10^{0}	Particle	Step-pool morphology	Bathurst and others, 1979; Whittaker and Jaeggi, 1982; Whittaker, 1987b
10^{-1}–10^{0}	Subunit Within-unit steps		
		Chute-and-pool topography	Sawada and others, 1983
		Transverse ribs	McDonald and Banerjee, 1971; Koster, 1978; Allen, 1982; McDonald and Day, 1978; Kishi and others, 1987
		"Minor" steps Boulder steps Rock steps	Hayward, 1980; Whittaker, 1987b
		Step-pool sequences	Bathurst and others, 1979; Whittaker and Jaeggi, 1982
10^{0}–10^{1}	Channel unit Pools Riffles Rapids Cascades Isolated steps Log steps Boulder steps Bedrock steps		
		Transverse rib sequences	Koster, 1978; Allen, 1982
		Stepped-bed morphology Regular Transitional Rapid segments	Wertz, 1966; Bowman, 1977
		Riffle steps	Hayward, 1980; Best and Keller, 1986
		"Major" steps	Whittaker, 1987a, 1987b
		Habitat units Pools Glides Riffles Cascades	Bisson and others, 1982; Sullivan, 1986
		Swells	Kishi and others, 1987
10^{2}–10^{3}	Reach Constrained Earthflow Bedrock Unconstrained		

*Measured parallel to direction of flow.

STUDY SITES

The two streams studied, Lookout Creek and French Pete Creek, are in the Cascade physiographic province, a deeply dissected terrain underlain by volcanic rocks of late Oligocene to

TABLE 2. DRAINAGE-BASIN CHARACTERISTICS FOR THE TWO STUDY BASINS

	French Pete Creek	Lookout Creek
Drainage area (km^2)	83.4	67.6
Mean basin elevation (m)	1,300	1,200
Average channel gradient		
Entire basin (%)	4.3	3.8
Study section (%)	3.8	2.2
Average unvegetated channel width (m)	18.1	18.1
Mean annual discharge (m^3/s)	3.5*	3.6
Median bed partical size (cm)	20†	13†

*Based on gauge record at South Fork McKenzie River, weighted by contributing area of French Pete Creek basin.
†Based on a sample of 750 and 1,200 particles in French Pete and Lookout Creeks, respectively, in a range of channel unit environments and weighted by the relative abundance of units.

late Pliocene age (Priest and others, 1983) (Fig. 1). Both streams flow through west-trending, steeply walled valleys (hillslope gradients >70% are common) that are densely vegetated in mature and old-growth conifers with dense stands of alder bordering the channels. French Pete Creek drains a virtually pristine basin, whereas the Lookout Creek basin has been commercially harvested for timber over the past 40 yr. Most of this activity, however, was concentrated on hillslopes away from the stream channel and has had minimal effect on stream morphology. Both streams experienced major channel changes, streamside landslides, and debris flows during the December 1964 flood, an event with roughly a 100-yr recurrence interval (Waananen and others, 1971).

The two basins are comparable in size, elevation, and mean annual discharge; however, the gradient of the study reach in French Pete Creek is 1.7 times that in Lookout Creek (Table 2). At low to moderate discharges, the most distinctive hydraulic aspect of these streams is the combination of very high bed roughness caused by large boulders protruding through the water column and occurrence of "tumbling flow" (Peterson and Mohanty, 1960) due to stretches of placid subcritical flow alternating with steep zones of supercritical flow amidst boulders. The beds of both study sections are very coarse and paved with cobbles and boulders as much as 2 m or more in diameter. Bed material is derived from alluvial fans, bedrock, glacial deposits, and colluvium. Bed material in French Pete Creek is coarser than in Lookout Creek (Table 2). Channels contain abundant coarse woody debris distributed above, within, and alongside the high-water channel (Swanson and others, 1976; Keller and Swanson, 1979; Harmon and others, 1986; Lienkaemper and Swanson, 1987), although wood plays only a minor role in controlling longitudinal profile.

A MODEL OF LONGITUDINAL PROFILE ORGANIZATION FOR MOUNTAIN STREAMS

Bedform hierarchies have been used to distinguish bedforms at different scales in streams (Allen, 1968; Jackson, 1975). The longitudinal profile of mountain streams has a staircase-like structure apparent at several different scales and conveniently expressed in terms of a hierarchy scaled by channel width (Table 1). At the finest scale, the channel is dominated by individual bed particles. Where concentrations of bed particles are high and slopes exceed 2%, bed structure is dominated by steps composed of the largest boulders in the stream interspersed with small backwater and plunge pools approximately 0.4 to 0.8 channel widths in length (Fig. 2). Taken together, the steps and intervening pools create step-pool sequences (Whittaker and Jaeggi, 1982; Ashida and others, 1984, 1986a, 1986b). We refer to this scale of variation as the "subunit" scale; it has also been called the "rib" scale (McDonald and Banerjee, 1971; Koster, 1978; Kishi and others, 1987). In forest mountain streams, individual steps can also form over large woody debris (Heede, 1972; Swanson and others, 1976; Marston, 1982) and bedrock outcrops in the channel (Hayward, 1980; Whittaker, 1987a, 1987b).

Step-pool sequences are, in turn, interspersed by larger pools, generally 10^0–10^1 channel widths in length (Fig. 2). We have termed this variation between steep and gentle bed segments the *channel unit* scale of variation; it corresponds to what Kishi and others (1987) termed "swells." Five different types of channel units can be distinguished based on their bed slopes, degree of step development, and hydraulic characteristics; these are discussed in the following section.

Lengths of stream channel 10^2 to 10^3 channel widths long are termed *reaches*. Reaches can be defined by their longitudinal profile (steep versus gentle gradient), by their planform morphology (wide or narrow valley floor in relation to channel width), or by the type of marginal constraint imposed by valley wall features (earthflow-constrained, bedrock-constrained, or unconstrained). These factors are in most cases interrelated. In our study, channel reaches were distinguished by the type and degree of constraint imposed by features exogenous to the channel, such as landslides and bedrock. These reaches generally correspond with changes in channel gradient. For example, some steeper-than-average reaches occur in Lookout Creek where active and inactive deep-seated landslides impinge on the channel, forcing it against bedrock and delivering large, immobile boulders. Along with locally steepening the channel, such mass movements also markedly constrict the width of the channel and valley (Swanson and others, 1985). The earthflow along lower Lookout Creek has constricted the unvegetated or active channel width (in the sense of Osterkamp and Hupp, 1984) to 60% of its unconstrained width upstream; total valley-floor width has been constricted from 207 to 24 m (Vest, 1988). Comparable changes in gradient and width in the vicinity of deep-seated landslides have also been reported for northern California (Kelsey, 1980, 1987).

CHARACTERISTICS OF BED MORPHOLOGY AT DIFFERENT SCALES

Viewed hierarchically, bed particles are organized into subunits, which are steps and their associated hydraulic microenvironments (small backwaters and eddies). Assemblages of sub-

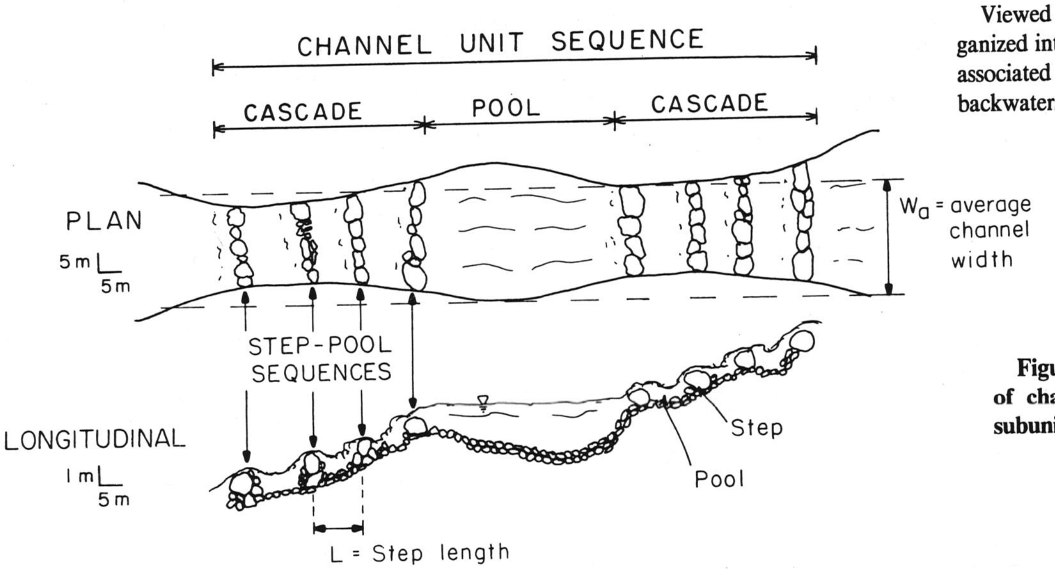


Figure 2. Schematic diagram of channel morphology at the subunit and channel-unit scales.

units make up macrobedforms, termed "channel units" (such as pools, rapids, and cascades). Sequences of channel units, in turn, make up reaches that taken collectively, define the basin longitudinal profile.

We considered some details of bed morphology at different scales in this hierarchy. Channel units were emphasized as a particularly important scale of interest for understanding stream dynamics. Bedforms at this latter scale create significant variability for flow hydraulics because rapids and riffles represent areas of macroscopically uniform flow separating regions of nonuniform flow in cascades and pools, where flow is accelerating and decelerating, respectively. Furthermore, channel units introduce an additional component of flow resistance in boulder-bed streams (Bathurst and others, 1979; Davies, 1980) and may induce nonuniformity in sediment transport rates (Whittaker, 1987a, 1987b; Hayward, 1980). Recognizing channel units is therefore extremely important for characterizing stream morphology or measuring stream processes.

Field Methods

Channel units were classified and measured along 5.5-km study sections in Lookout Creek and French Pete Creek during low-flow summer months in 1986. Discharges in the two streams during sampling were about 0.4 and 1.0 m^3/s, respectively—flows that are equaled or exceeded 95% of the time. The emphasis on low-flow forms was based on the premise that infrequent movement of large framework particles in these streams results in a bed morphology that is stable at all but the largest flows and manifest at low flow. An additional practical consideration was that only during low flow can the channel bed be seen and waded. These features are formed at high discharges, however, and their flow patterns change from low to high flow (Sullivan, 1986).

Channel units were initially classified by visual estimates of relative roughness, degree of step development, and percentage of low flow area in supercritical flow. Classification of units in French Pete Creek by one set of observers was compared with a previous classification by different observers using the same criteria and at the same discharge (Grant, 1986). The results indicated that although some disagreement was found on the precise delineation of unit boundaries, the number, sequential distribution, and relative location of units in the two surveys were virtually identical. Visual classification was corroborated by discriminant function analysis that demonstrated segregation of units by slope (discussed below). After classification, unit geometries—low flow and active (unvegetated) channel width, length, slope—were measured; presence of exogenous elements such as bedrock, large boulders, and organic debris was noted; and units were mapped.

Channel Unit Descriptions

Five distinct channel units, including four major types and one minor type, were identified (Figs. 3A–3E; Table 3). Major types included pools, riffles, rapids, and cascades and were defined as units longer than one active channel width as measured along the thalweg. Minor units were channel-spanning bedrock, boulder, or log steps less than one channel width long. Strictly speaking, these minor units represent subunits by our proposed hierarchy but were treated as channel units because they represent major breaks in the longitudinal profile. All unit descriptions are for low flow. At higher discharges, unit characteristics and boundaries become less distinct, owing to drowning of roughness elements and channel controls.

Pools are areas of slow, tranquil flow without small-scale hydraulic jumps or free-surface instabilities, and with few boulders exposed at low flow (Fig. 3A). Flow is subcritical throughout except where high-velocity chutes of water enter from upstream units and form small hydraulic jumps or standing waves. Greatest depths in pools are commonly located just downstream from entering chutes and adjacent to marginal obstructions such as bedrock (Lisle, 1986). Pools are commonly shallow at their downstream ends.

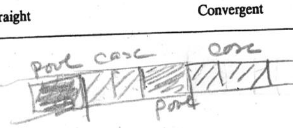
Riffles are areas of subcritical flow modified by local free-surface instabilities and small hydraulic jumps over bed roughness elements (Fig. 3B). Water surface typically has a rippled appearance; depths are shallower and velocities greater than in pools at low flow. Although individual boulders or boulder clusters (Brayshaw and others, 1983) may be present, they are not organized into ribs. Only 5%–10% of the water-surface area exhibits supercritical phenomena such as hydraulic jumps or standing waves at low flow. Both riffles and pools have flow in the tranquil regime (Peterson and Mohanty, 1960).

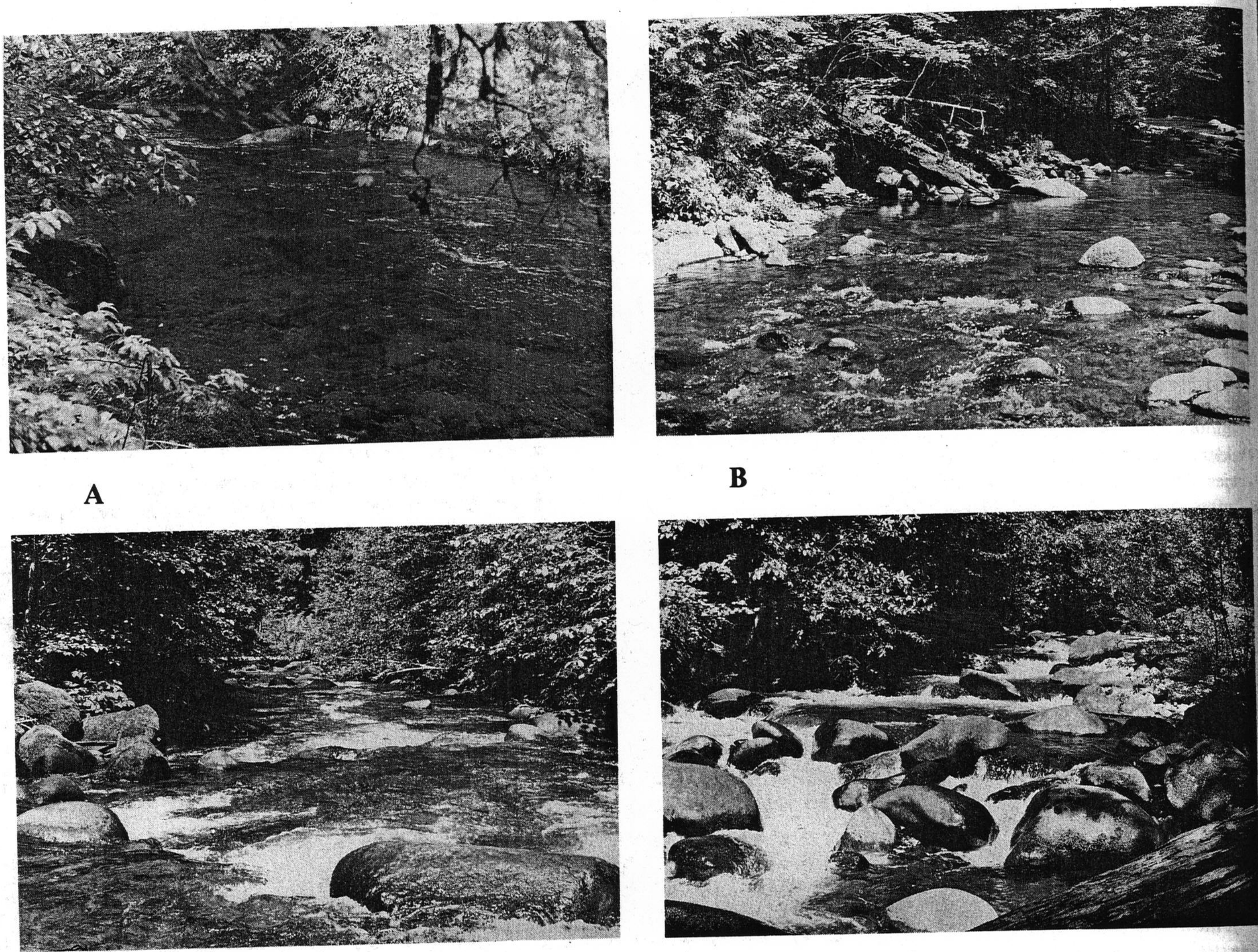
Rapids are channel units distinguished from riffles by (1) greater percentage of stream area (15%–50%) in supercritical flow and (2) organization of boulders into irregular ribs oriented more or less perpendicular to the channel and exposed at low flow; ribs partially or fully span the active channel width (Fig. 3C). Channel-spanning ribs are referred to as "steps." Pocket pools less than one channel width long separate individual ribs or steps.

Cascades are steep channel units where flow cascades over large boulders in a series of short, well-defined steps about one particle diameter (~0.2 to 1.0 m) high that are separated by areas of more tranquil flow less than one channel width in length to create a staircase appearance (Fig. 3D). Cascades have more than 50% of stream area in supercritical flow; this corresponds to the tumbling regime of Peterson and Mohanty (1960). In plan form, some cascades superficially resemble the front of transverse bars; however, no obvious bar morphology is recognized in others. Cascades typically exhibit

TABLE 3. AVERAGE CHANNEL UNIT CHARACTERISTICS FOR FRENCH PETE CREEK (FPC) AND LOOKOUT CREEK (LOC)

	Pools		Riffles		Rapids		Cascades		Steps	
	FPC	LOC	FPC	LOC	FPC	LOC	FPC	LOC	FPC	LOC
Length (active channel widths)	0.9	1.1	1.3	1.4	3.1	1.6	2.0	1.1	0.4	0.3
Slope (%)	0.6	0.4	1.2	1.0	3.0	2.4	6.4	5.2	22.4	12.2
Ratio to average long profile	0.2	0.2	0.3	0.5	0.8	1.1	0.2	0.2	0.2	0.2
Ratio to mean slope of preceding unit in classification			1.8	2.8	2.5	2.3	2.2	2.2	3.5	2.3
Unit area in supercritical flow (%)	0–5		5–15		15–50		50–100		70–100	
Relative roughness at low flow (D_{84}/R)	0.3–0.5		0.5–1.0		0.5–1.5		1.0–2.0		1.0–2.0	
Ratio of upstream to downstream width										
Low flow (m/m)	0.8	0.9	0.9	1.0	1.0	1.2	1.5	1.7	1.3	1.0
Active (m/m)	1.0	1.0	0.8	0.8	1.0	1.3	1.3	1.4	0.9	1.0
Flow pattern	Divergent		Divergent		Straight		Convergent		Straight	





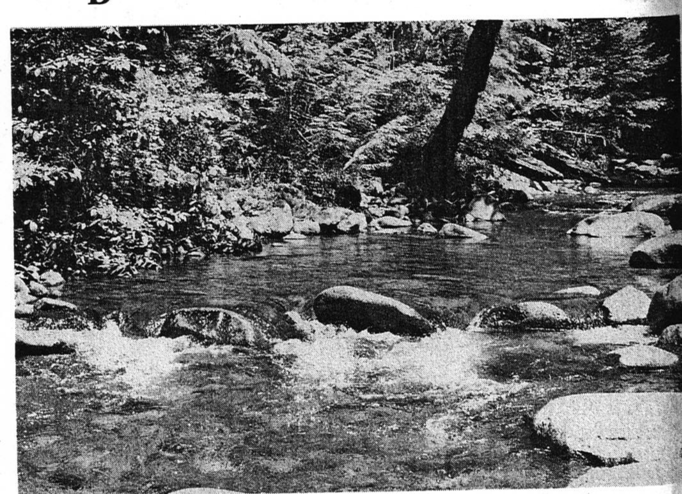


Figure 3. Channel units in French Pete Creek at summer low flow. (A) Pool: flow is tranquil and bed elements are submerged; (B) riffle: roughness is still small scale, but small hydraulic jumps form over submerged and partially exposed particles; (C) rapid: roughness is large scale with channel-spanning steps; (D) cascade: well-developed step-pool sequences and extensive supercritical flow is apparent; and (E) boulder step: channel-spanning solitary steps can be created by boulders, bedrock, or woody debris.

downstream convergence in flow (ratio of upstream to downstream unit width greater than 1.0) (Table 3).

Cascades are divided into two subtypes: (1) boulder cascades, which are composed of well-developed, closely spaced step-pool sequences created by boulders that are partially emergent at low flow (Fig. 3D) and (2) bedrock cascades where water flows directly on bedrock. Individual steps in bedrock cascades are more uniform than in boulder cascades and commonly coincide with rock structure.

Bedrock, boulder, and log steps are individual, channel-wide steps less than one channel width long that are sufficiently distinct from upstream and downstream units to be identified as separate features (Fig. 3E). Steps are in most cases short 1- to 2-m-high falls perpendicular to the channel axis and separate a backwater pool upstream from a plunge pool downstream. Steps are commonly located where immobile boulders (diameters greater than 1.5 m) and bedrock outcrops trap smaller boulders and wood.

Although channel units may describe a continuum of bed features, individual unit types represent distinct modal tendencies within this continuum that are readily recognized and classified in the field. Discriminant function analysis, a multivariate technique for evaluating the degree of overlap among populations of classified objects, was used to evaluate the distinctiveness of individual units classified in the field. Two discriminant functions were derived for each site, both statistically significant. Water-surface slope was overwhelmingly the predominant variable discriminating channel units at both sites. Correlation between individual scores on the derived discriminant functions and the original set of variables indicated overwhelmingly high correlation coefficients between slope and the discriminant scores. Overlap in fields defining pools, rapids, and cascades was relatively minor, which reflected distinctive slope ranges for each unit (Fig. 4). The field for riffles, however, somewhat overlapped with pools. Despite this overlap, the derived discriminant functions classified 22 of 31 riffles (71%) in Lookout Creek and 11 of 14 riffles in French Pete Creek (79%) in the same way as the subjective field interpretation; this indicated distinctive unit characteristics. Steps had the most variable slopes, owing for the most part to combining bedrock, boulder, and log steps together in this analysis, which we did because of small sample sizes; steps formed by these different agents are highly variable in structure and appearance.

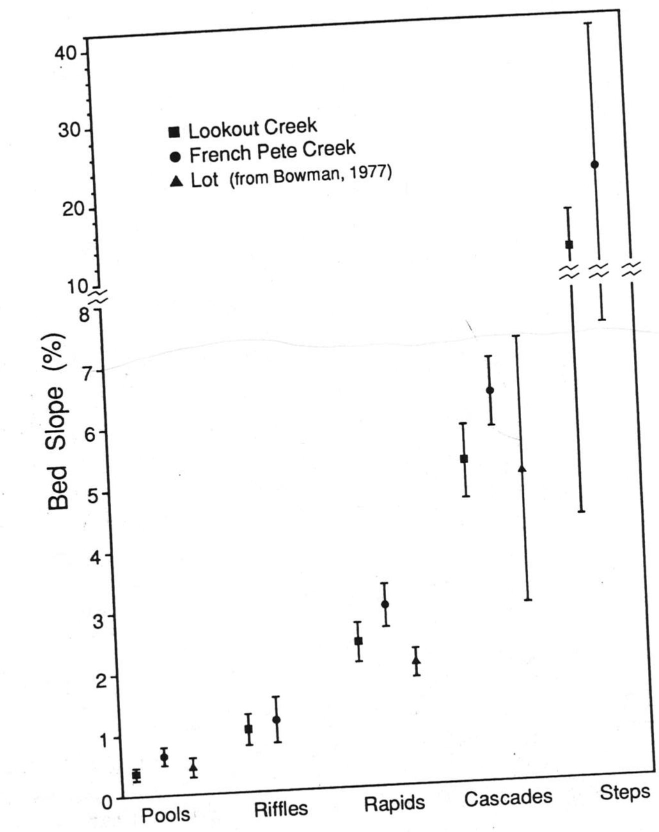


Figure 4. Bed slope with 95% confidence bars for Lookout and French Pete Creeks. Also shown are data from the Lot basin in Israel as reported by Bowman (1977), who termed units "regular," "transitional," and "rapid" in order of increasing bed slope.

Nonoverlapping slope ranges for each type of unit indicated that slope breaks occur as discrete populations in both streams (Fig. 4). Although mean slopes of pools, rapids, and cascades differ significantly by stream, 95% confidence limits for each unit type show little or no overlap between sites, suggesting that overall unit slope ranges are site independent. The ratio of each unit slope to the average longitudinal gradient is also quite consistent between sites (Table 3). On average, each unit type represents roughly a 2.5-fold increase in slope over the next-lower-gradient unit type. This suggests that although absolute slopes of channel units may differ in response to longitudinal gradient or particle size, the relative magnitudes of slope breaks between units remain constant, as does the ratio of each unit slope to the average longitudinal slope.

Average slopes for pools, rapids, and cascades are remarkably consistent with slope data for segments of ephemeral channels in the Dead Sea area as reported by Bowman (1977) (Fig. 4). He also determined that channel slopes in steep, coarse-bed stream channels occur as distinct populations, creating stepped-bed morphology.

Channel-Unit Characteristics at the Particle and Subunit Scales

Distinctiveness of channel units is also manifest at the particle and subunit scale of the long profile hierarchy. We examined differences in bed particle size and degree of step formation within the four major channel units. Differences in these characteristics contribute to units having different grain and form roughnesses, which affect velocities of flow through units.

Character of Bed Material. Particle sizes of clasts on the surface of the bed were sampled by Wolman's (1954) method in a range of channel-unit environments. Thirteen randomly chosen units, including 4 pools, 4 rapids, and 5 cascades, were sampled in French Pete Creek; 12 units, including 4 pools, 2 riffles, 3 rapids, and 3 cascades, were sampled in Lookout Creek. In each unit, the intermediate diameter (b-axis) of between 50 and 100 rocks encountered at 1-m intervals along transects spaced randomly across the active channel was measured; total numbers of rocks in each size class were summed by unit and plotted as cumulative frequency distributions (Fig. 5).

Bed material in French Pete Creek was coarser and more clearly differentiated by type of unit than that in Lookout Creek. Comparison of mean D_{50} and D_{84} size classes by one-way ANOVA using the Tukey test (Tukey, 1977) demonstrated that both mean D_{50} and D_{84} size classes for channel units in French Pete Creek came from different populations ($p < 0.01$). The D_{50} size classes for Lookout Creek pools, rapids, and cascades were also significantly different from each other. Riffles and rapids in Lookout Creek showed no significant difference in D_{50}, however, nor was the D_{84} size class different among all types of units. Pools are distinguished from other units by a higher proportion (as much as 10%) of bed area in material less than 0.5 cm; this fine fraction is presumably deposited in pools at low flows. Bed material in pools also has the poorest sorting (Fig. 5). Convergence at the upper end of the curves for all units in both creeks indicated that the largest boulders are found in all unit types.

Step Characteristics in Rapids and Cascades. Steps are absent from pools and riffles but dominate the structure of rapids and cascades. Steps bear superficial resemblance to transverse ribs described in gravel-bed streams (McDonald and Banerjee, 1971; Koster, 1978; Allen, 1982) but, unlike the ribs, display a tightly interlocking structure around a few key particles. Steps have been noted elsewhere in boulder-bed streams and represent a distinctive within-unit scale of variation (Hayward, 1980; Whittaker, 1987a, 1987b).

Risers of individual steps are generally composed of several large boulders oriented with their long axes transverse to the flow direction and intermediate axes parallel to flow or gently dipping upstream at angles of 5° or less, so that the vertical rise of the step is about equal to the short axis. Smaller boulders and cobbles are imbricated against these larger framework boulders in a manner similar to cluster bedforms (Brayshaw, 1985). Most steps are oriented perpendicular to the flow, but some steps may be oriented obliquely (70° to 80°) to flow or form broad V's pointing upstream. Steps partially or fully span the low-flow channels, and some can be traced across adjacent unvegetated surfaces as well.

Measurements of step height, percentage of

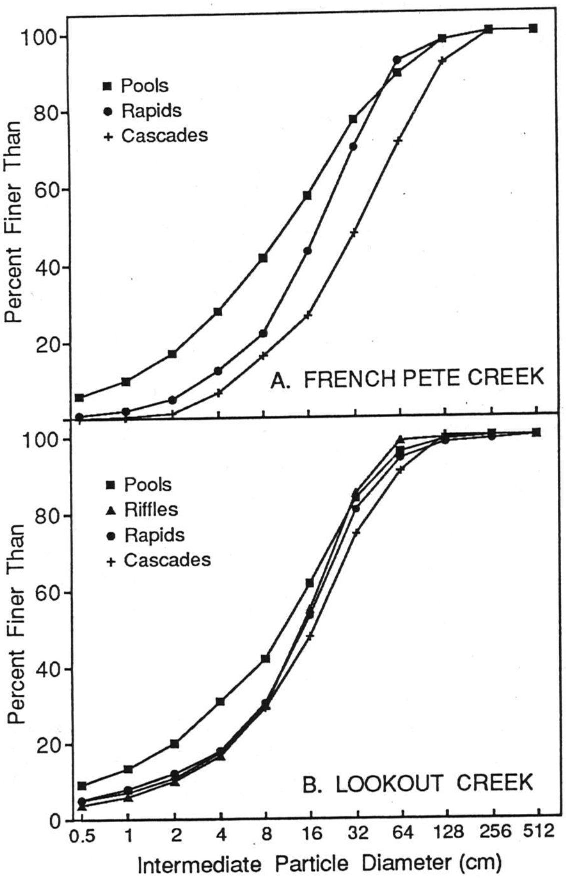


Figure 5. Particle size distribution for French Pete Creek (A) and Lookout Creek (B), based on counts of 750 and 1,200 particles, respectively.

low-flow channel spanned, interstep distance, and intermediate diameters of the five largest boulders making up the step were made for 31 steps in 4 rapids and 3 cascades in both Lookout Creek and French Pete Creek. Step height is the difference between the average of five or more measurements of bed elevation taken immediately upstream and downstream of the step; it is less than the maximum step height measured from the lip of the step.

Boulders creating steps were similar in size in all units sampled; they averaged 1.1 m, which placed them among the largest boulders in both streams (Fig. 5). No significant difference was found in the size of bed materials making up steps in rapids and cascades. Step heights were also similar for all sites: range, 0.13 to 0.29 m, average, 0.22 m. Consistency in step height seems to result from similarity in size and shape of particles forming steps.

Channel-unit gradient, measured as bed slope from upstream to downstream end of the channel unit, strongly controls step structure and spacing. Interstep spacing varied inversely with channel slope, a finding consistent with earlier work (Judd and Peterson, 1969; McDonald and Banerjee, 1971; Koster, 1978; Hayward, 1980; Whittaker, 1987b). Step spacing in French Pete Creek and Lookout Creek also paralleled the upper limb of the exponential curve presented by Whittaker (1987b) for streams in New Zealand (Fig. 6). The apparent linear trend of step spacing with slope for Lookout Creek and French Pete Creek may have resulted from the narrow range of slope values, because a lower limit of step spacing should be imposed by particle size. Control of step spacing by gradient can be explained by the similarity in size of particles creating the steps. Because step height is constant, an increase in bed slope must result in closer spaced steps over a given channel length if most of the drop is accounted for in steps.

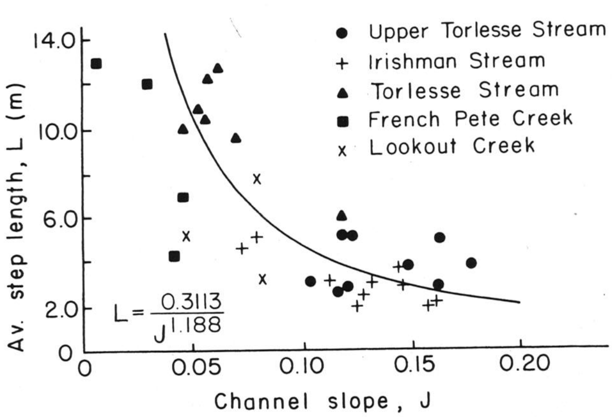


Figure 6. Average spacing between steps in rapids and cascades in relation to bed slope. Data points for French Pete and Lookout Creeks represent the average spacing of three to seven steps. Data points and curve for Torlesse and Irishman Streams (New Zealand) from Whittaker (1987a).

Percentage of low-flow width spanned by individual steps varied directly with slope (Fig. 7); this supported our observation that steps in cascades are more fully developed and more closely spaced than those in rapids. Because particles in cascades are larger than those in rapids (Fig. 5) and widths are less, the ratio of particle size to channel width is greater in cascades, which means that fewer particles are needed to form a step. Another explanation may result from the mechanism of step formation; steeper slopes may create broader hydraulic jumps that generate steps over a wider expanse of channel. No discernible relation was found between step height and unit slope or between step spacing and particle size, as is reported elsewhere (McDonald and Banerjee, 1971; Koster, 1978), perhaps because step structure is controlled by the largest particles, which in our study were uniform in size.

SPATIAL PATTERNS OF CHANNEL UNITS

Characteristics of streams by channel unit can be used to analyze and compare long lengths of channel. As an example, we compared the spatial organization of channel units in Lookout Creek and French Pete Creek by their longitudinal distribution, sequence, and spacing. Differences between creeks could be attributed to location and prevalence of exogenous features, such as landslides and bedrock.

Distribution of Channel Units

The two study sites, which are similar in length (5,770 and 5,530 m for Lookout Creek and French Pete Creek, respectively), can be characterized by the contribution of each unit type to total length and vertical drop (fall) (Figs. 8A–8D). In both streams, rapids account for the largest percentage of stream length sampled, and cascades account for most of the fall. The most striking contrast between the two creeks is that low-gradient units (pools and riffles) make up a much greater proportion of total stream length in Lookout Creek than in French Pete Creek (45% versus 18%). Given that French Pete Creek is almost twice as steep as Lookout Creek, greater abundance of steep units might be expected; however, both sites have almost identical numbers of rapids and cascades (101 in French Pete Creek versus 103 in Lookout Creek). The difference in Lookout Creek seems to be both

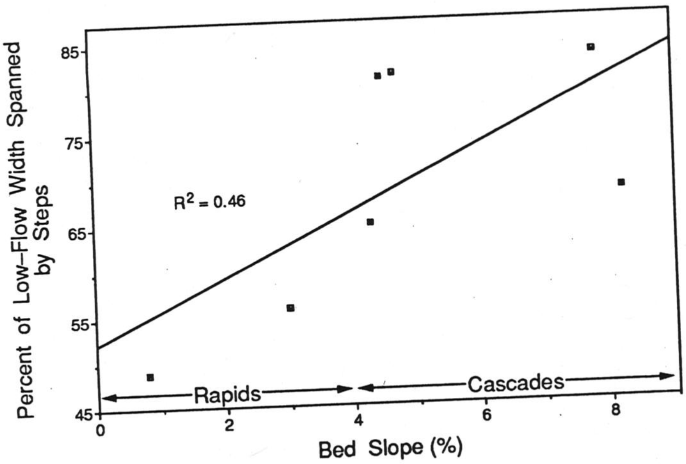


Figure 7. Percentage of low-flow channel width spanned by individual steps in relation to bed slope.

greater abundance of pool and riffle units (104 versus 56 in French Pete Creek) and longer pools and riffles (mean lengths of 22.9 and 30.1 m versus 16.4 and 23.3 m in Lookout Creek and French Pete Creek, respectively).

Units are not uniformly distributed along the creeks. At both sites, cascades and rapids do not occur simultaneously along the same stream reach, as indicated by increases in slope of the cumulative length curve for one unit corresponding to decreases in slope for the other (Figs. 8A and 8C). This suggests that local increases in channel gradient are accommodated by development of either rapids or cascades but not both.

Exogenous controls at the reach scale, such as constriction of channels by earthflows, affect distribution of channel units. For example, in Lookout Creek, the reach of channel constricted by a large earthflow has more of its length in pool and cascade units and less in rapid and riffle units (Fig. 8A). Upstream of the earthflow, more of the reach length is in riffles and rapids. Increased gradient (Fig. 2B) and frequency of large boulders and bedrock outcrops near the earthflow toe may allow cascades and pools to develop, in contrast to the lower-gradient depositional zone upstream of the earthflow. There, smaller particles, less bedrock, and fewer boulders favor riffle and rapid formation (Vest, 1988). This example suggests that different channel units may develop in response to externally imposed changes in gradient and particle size.

Unit Sequence

Little information is available in the channel morphology literature about the sequence of channel units. Where channel units are simply

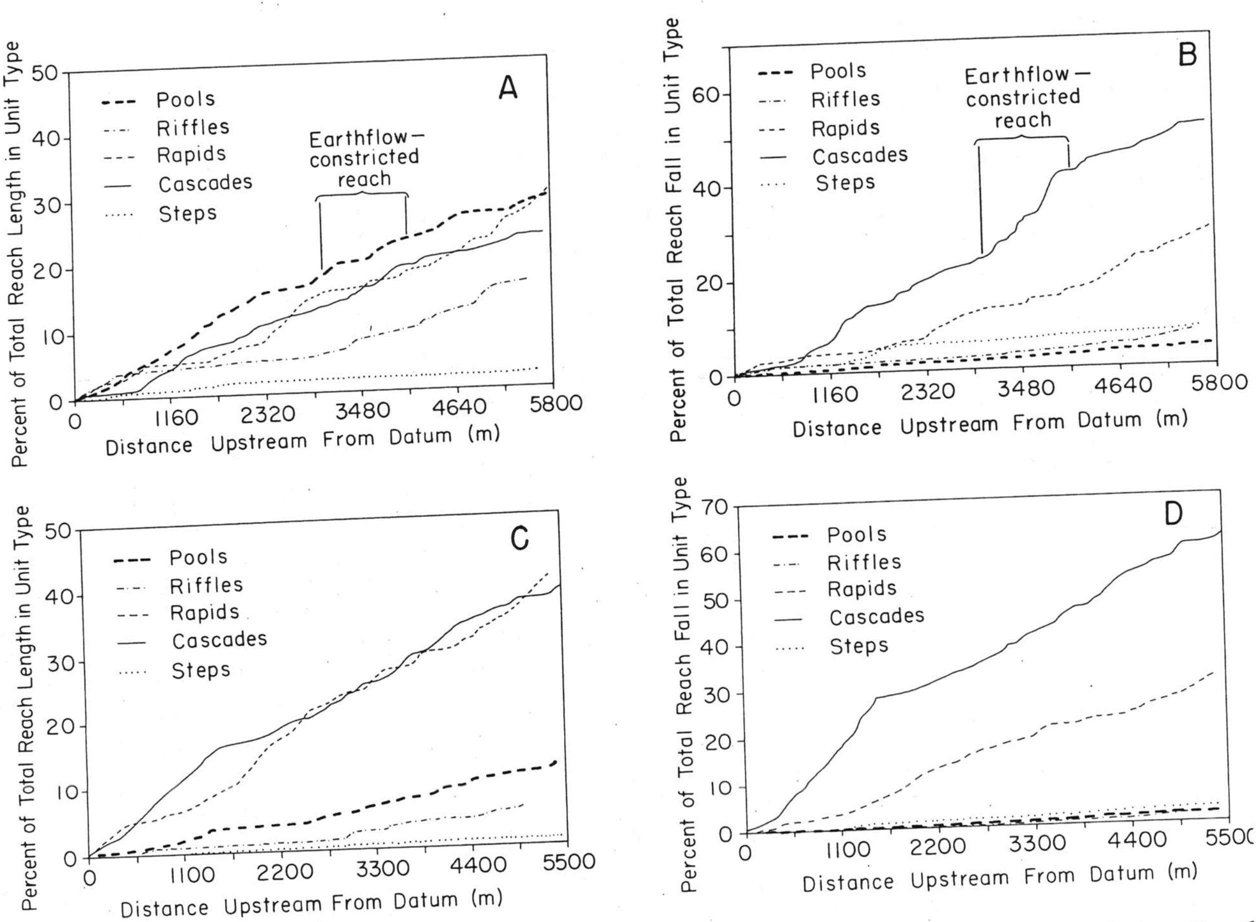


Figure 8. Distribution of units along study sites by proportion of total length and fall in each unit type. (A,B) Distribution of length and fall, Lookout Creek. The proportion of cascade units increases in the earthflow-constrained reach. (C,D) Distribution of length and fall, French Pete Creek. Steep reach in French Pete Creek is associated with large boulders deposited by debris flow.

considered to be riffles and pools, the issue of the sequence of units does not arise; pools always follow riffles and vice versa. In a system of three or more units, however, the sequence of units and the tendency for repeating series of units to develop are important properties of the channel.

Channel-unit sequences can be analyzed by using Markov chain analysis (Miall, 1973). Two-unit sequences can be described by a transition probability matrix; each cell in the matrix is the observed frequency or probability with which unit A follows (is contiguous downstream with) unit B (Table 4A). The expected transition probabilities are calculated based on a random sequence of units (Table 4B), and preferred two-unit sequences are determined as positive difference between the observed and expected values (Table 4C). Preferred sequences are shown as a sequence-relation diagram (Fig. 9) (Selley, 1969; Miall, 1973; Cant and Walker, 1976).

Our analysis indicated that channel-unit sequence is not random. Instead, the slope of the upstream unit (as inferred from unit type) is inversely correlated with the slope of the next downstream unit (Table 4C). In Lookout Creek, for example, rapids, cascades, and steps preferentially terminate in pools (Fig. 9); a similar pattern of pools below steep units is also seen in French Pete Creek. This suggests that pool formation may result from acceleration and convergence of flow in channel units immediately upstream. Flowlines through cascades tend to converge downstream; thus, high-velocity flow is concentrated and, where focused toward the channel bed or resistant channel margins, promotes scour (Lisle, 1986). Flow in steps or rapids, although generally neither converging nor diverging, accelerates owing to locally steepened bed slope. Low slopes and absence of converging flowlines in riffles reduces the likelihood that pools will be created by scour downstream.

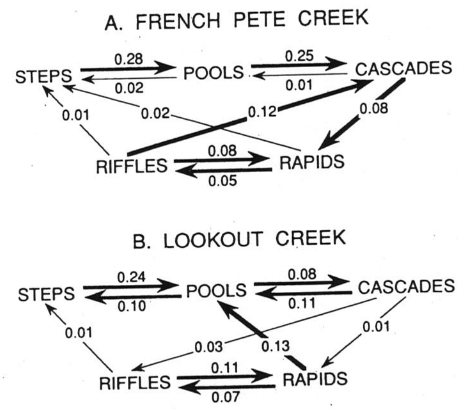


Figure 9. Sequence-relation diagrams for French Pete Creek (A) and Lookout Creek (B). Numbers shown are differences between observed and random transitional probabilities (see Table 4). Bolder arrows indicate transitional probabilities >0.05.

TABLE 4. TWO-UNIT TRANSITION PROBABILITY MATRICES FOR LOOKOUT CREEK CHANNEL UNITS

A. Observed transition probabilities

Downstream unit	Upstream unit				
	Pools	Riffles	Rapids	Cascades	Steps
Pools	0.00	0.26	0.54	0.51	0.60
Riffles	0.06	0.00	0.25	0.21	0.20
Rapids	0.25	0.35	0.00	0.28	0.15
Cascades	0.46	0.32	0.19	0.00	0.05
Steps	0.24	0.06	0.02	0.00	0.00
Total	1.00	1.00	1.00	1.00	1.00

B. Transition probabilities, assuming random sequence

Downstream unit	Upstream unit				
	Pools	Riffles	Rapids	Cascades	Steps
Pools	0.00	0.38	0.41	0.43	0.36
Riffles	0.20	0.00	0.18	0.18	0.15
Rapids	0.31	0.24	0.00	0.27	0.23
Cascades	0.35	0.27	0.30	0.00	0.26
Steps	0.13	0.10	0.11	0.12	0.00
Total*	0.99	1.00	1.01	1.00	1.00

C. Observed minus random transition probabilities

Downstream unit	Upstream unit				
	Pools	Riffles	Rapids	Cascades	Steps
Pools	0.00	−0.12	0.13	0.08	0.24
Riffles	−0.15	0.00	0.07	0.03	0.05
Rapids	−0.06	0.11	0.00	0.01	−0.08
Cascades	0.11	0.05	−0.11	0.00	−0.21
Steps	0.10	−0.04	−0.09	−0.12	0.00

*Column totals do not sum to 1.00 owing to rounding errors.

Pools, on the other hand, preferentially terminate in cascades or steps. This suggests an alternate mechanism of pool formation. Cascades and steps are sufficiently steep to act as critical overfall weirs during low to moderate discharges (Kellerhals, 1970, 1972, 1973). Pool formation upstream from these units may be enhanced by backwater behind these natural rock weirs.

Strong "nonpreferences," indicated by large negative values in Table 4C, reinforce this picture. Pools rarely end in riffles or rapids, riffles rarely end in pools, and rapids rarely end in cascades. This may be partly an artifact of the classification process because contiguous units with strongly contrasting slopes are easier to identify in the field. High frequency of cascade-to-rapid or riffle-to-rapid sequences in both creeks indicates, however, that sharp slope breaks are not necessary for unit identification.

Unit Spacing

Spacing of successive channel units has received considerable attention over the past 30 yr. Straight channels characteristically form alternating pools and riffles spaced at distances of five to seven channel widths; this may represent a tendency toward meandering, which is expressed in the third dimension (Leopold and others, 1964, p. 203). Keller and Melhorn (1978) showed that rhythmic spacing of pools occurs in bedrock and ice channels as well as in alluvial channels, and they confirmed Leopold and Wolman's (1957) conclusion that pool-to-pool spacing is a function of channel width. This finding is also corroborated by Richards (1978a, 1978b) and Milne (1982a).

Pool-to-pool spacing in Lookout Creek and French Pete Creek was examined to determine whether units were similarly spaced in these boulder-bed streams. Successive units of any type could be analyzed; pool-to-pool spacing was used for comparison with earlier studies. The data generally support the hypothesis of a tendency toward regular spacing, although spacing is less than that reported elsewhere (Keller and Melhorn, 1978). Frequency distributions of pool spacing in Lookout Creek, for example, peak between two and four active channel widths (mean = 4.0) (Fig. 10A). Pool spacings are more irregular in French Pete Creek; frequency distributions are bimodal with a primary peak at 3 and a secondary peak at 5–7 channel widths, but interpool distances range as high as 45 channel widths.

These results are consistent with the observation of Church and Gilbert (1975) that very small streams and boulder torrents seem to have predominant wavelengths about 2–3.5 times the channel width. Bathurst and others (1983) demonstrated in flume studies that bar frequency varies directly with channel slope, and so bedform spacing in steep, boulder channels might be expected to be less than in gravel-bed streams.

Although distributions of pool spacings show distinct peaks, substantial variability occurs around mean values (Fig. 10B). Some of this variability may result from uneven distribution of large roughness elements, such as logs, bedrock, and boulders. Long distances between pools in Lookout Creek seem to be due to absence of bedrock; only 8% of the units separating pools with spacings greater than 6 channel widths had bedrock along their margins, compared to 59% of other units (Fig. 10B). Absence of bedrock exposures in the channel may limit opportunities for development of helicoidal secondary circulation cells, which promote pool formation (Lisle, 1986).

Pool spacings in French Pete Creek are inversely related to the density of large boulders in the channel, which is expressed as the number of boulders greater than 1.5 m per 100 m of channel. In the 1-km reach of stream where pool-to-pool spacing is greatest (mean spacing of 32 channel widths), boulder densities average 20 boulders/100 m, which contrasts with 30 boulders/100 m in the 1-km reach immediately downstream.

In both Lookout Creek and French Pete Creek, variance in pool spacing seems to be linked to frequency of occurrence of nonalluvial, pool-forming features along the channel margin, which interferes with the tendency toward regular spacing in two ways. First, these factors in many cases have lengths and diameters on the same scale as channel width and can thus restrict or induce unit formation at irregular intervals (Lisle, 1986). Second, large boulders and wood can trap smaller particles, thereby reducing particle transport rates. Milne (1982a) noted "bed form spacings can be easily upset by variation in sediment mixtures and the presence of 'residual' bedload . . . which disallow the high bed-transport rates that produce regular repeating distances."

MORPHOGENESIS OF CHANNEL UNITS

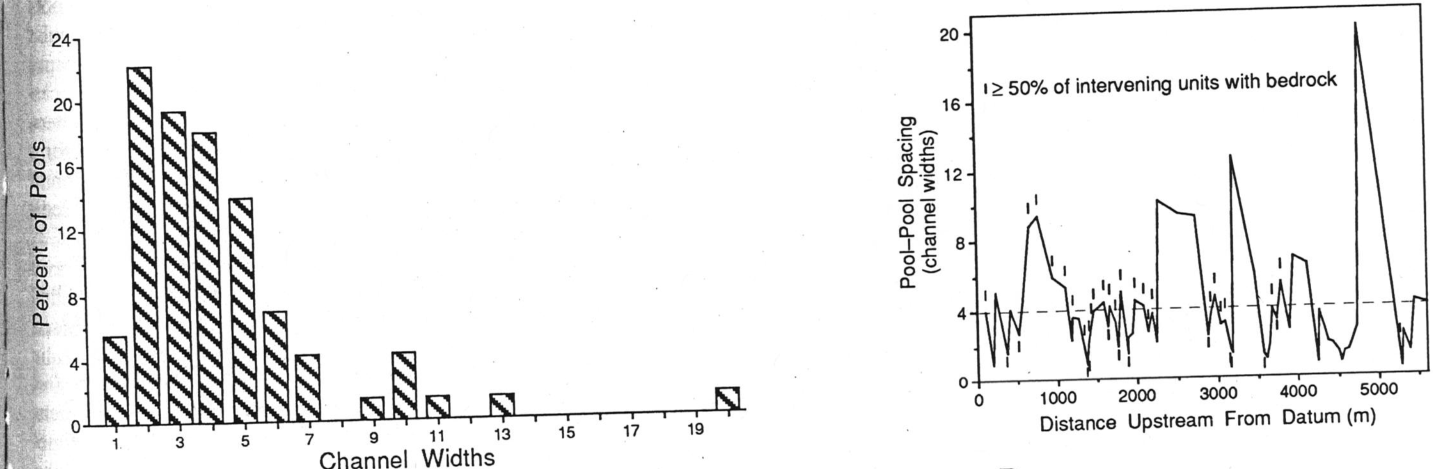
Characteristic morphology, bed-material sorting, sequence, and spacing of channel units suggest that development of these features is induced by interactions among the flow, bedload, channel boundary, and bed. The origin of channel units is poorly understood, however, and a full treatment is beyond the scope of this paper. Our analysis, nevertheless, would be incomplete without some consideration of hydraulic and geomorphic conditions promoting unit formation, and this discussion is intended to lay the foundation for future laboratory and field investigations. Three aspects of unit morphogenesis are developed here: (1) hydraulic conditions required for entrainment of large particles, (2) comparison with flume experiments, and (3) contrast with channel bars and associated riffles and pools in gravel-bed streams.

Flow Conditions at Particle Entrainment

Formation of rapid, cascade, and step channel units requires movement of large framework particles to form the steps. Studies of bedload transport in gravel-bed streams have documented that bed shear stresses in pools commonly equal or exceed shear stresses in riffles when riffle material is transported (Keller, 1971; Lisle, 1979; Jackson and Beschta, 1982). If the same holds for boulder-bed streams, competence calculations in rapids and cascades represent a conservative estimate of flow conditions required to form channel units.

Reconstruction of flow conditions at entrainment of framework particles (D_{84} size class) in rapid and cascade units indicates that these units are formed during infrequent, high-magnitude flows. Relations of stage versus discharge were calculated for seven surveyed cross sections in French Pete Creek (Table 5); for this purpose, velocities and other hydraulic data were calculated by using resistance equations developed for mountain streams that gave the best agreement with field data (Thorne and Zevenbergen, 1986). Because the effect of form drag on individual particles is an appreciable component of the resistance in mountain streams (Bathurst and others, 1979), relative submergence of particles was explicitly included in the equations. Where $D_{84}/R \geqslant 1.0$, Bathurst's (1978) equation was used; where $D_{84}/R < 1$, an equation developed by Hey (1979) was used. The maximum particle size moved at a given depth was calculated using Costa's (1983) method. Flow depths and discharges reconstructed by this method were field checked against heights of cutbanks and boulder deposits interpreted as resulting from the December 1964 flood. The 1964 discharge for French Pete Creek was estimated as 100 m^3/s, based on regional relations between drainage area and discharge (Harris and others, 1979). Agreement between predicted flood depths and preserved 1964 flood scars and deposits was generally good.

From this analysis, it seems that bedload transport events capable of restructuring channel units occur every 25–50 yr in French Pete Creek (Table 5). Approximate recurrence intervals were calculated by using regional flood frequency relations (Harris and others, 1979), because French Pete Creek has no gauges. The method used to calculate critical discharges for channel-unit formation may underestimate flow



A B

Figure 10. Pool-to-pool spacing along the Lookout Creek study reach. Spacing is measured as the distance from center to center of successive pools and is expressed as the average active channel width separating the pools. (A) Frequency distribution of pool spacings. (B) Spatial distribution of spacings along the study reach; location of bedrock in intervening units is noted.

TABLE 5. CALCULATED HYDRAULIC VARIABLES AT INCIPIENT MOTION OF THE SURVEYED CROSS SECTIONS, FRENCH PETE CREEK

Unit type	D_{84} (m)	D_{max} (m)	R (m)	V_{avg} (m/s)	Q_{crit} (m^3/s)	Recurrence interval (yr)	Froude number*
Cascade	0.9	2.4	1.6	3.6	250	>100	0.9
Cascade	0.3	2.2	0.7	3.4	60	26	1.3
Pool	0.6	1.2	1.1	3.0	80	52	0.9
Rapid	0.5	2.1	1.0	3.1	90	68	1.0
Rapid	0.3	1.2	0.6	2.7	30	5	1.1
Rapid	0.5	1.2	1.0	3.1	110	>100	1.0
Rapid	0.6	2.2	1.1	3.2	70	38	1.0

Note: abbreviations are D_{84}, size fraction for which 84% of bed particles are finer; D_{max}, size of maximum particle sampled; R, calculated hydraulic radius at incipient motion of bed; V_{avg}, calculated average velocity at incipient motion of bed; Q_{crit}, calculated critcal discharge at incipient motion of bed.
*Froude number calculated as $V_{avg}/(gR)$, where g is gravitational constant.

conditions because the method is based on entrainment of individual particles and does not take into account imbrication or packing of particles. Arrangement of particles in stable step structures may increase particle entrainment thresholds (Brayshaw and others, 1983; Brayshaw, 1985), and use of the upper range estimate of a 50-yr return period flow to form units appears reasonable.

We conclude, contrary to Miller (1958), that development of channel units reflects adjustment to a current discharge regime. Units are stable under most discharges but can be reformed when events with return periods of about 50 yr or greater occur. This frequency of particle movement compared favorably with similar analyses for boulder-bed streams in southern California (Best and Keller, 1986), New Zealand (Hayward, 1980), and Israel (Bowman, 1977). Time-lapse photographs of a tributary to Lookout Creek during a 15–20 yr storm in February 1986 clearly show movement of boulders 0.5–1.0 m in diameter. Field observations by Sawada and others (1983) of bed topography of high-mountain streams in Japan before and after debris-flow passage indicate that large floods and debris flows destroy low-flow channel form, but re-establishment of what they termed "chute-and-pool" bed topography occurs rapidly (within 10 days) during more moderate events.

Comparison with Flume Experiments. Development of step-pool morphology has been studied in laboratory flumes, where it has been shown that steps form where flow conditions are critical to supercritical (Froude number $\geqslant$ 1.0), bedload is heterogenous, and diameters of the largest-size particles are the same order of magnitude as the depth of competent flows (Koster, 1978; McDonald and Day, 1978; Whittaker and Jaeggi, 1982; Ashida and others, 1984, 1985, 1986a, 1986b; Kishi and others, 1987; Hasegawa, 1988). Steps form where large particles come to rest under hydraulic jumps and antidunes and trap smaller particles. Both physical obstruction and the abrupt decrease in velocity that occur near a jump promote deposition of step-forming particles.

flows in French Pete Creek was compatible with these observations; during discharges when channel units form, the flow regime is at or above critical across much of the bed, and calculated flow depths are less than or equal to D_{max} (Table 5). Similar findings are reported by Bowman (1977). Under these conditions, boulders protruding above the bed or contractions in channel width from marginal boulders or bedrock favor hydraulic jump formation (Bathurst and others, 1979; Kieffer, 1985). Jarrett and Costa (1986) attributed step formation after a dam-break flood to a similar mechanism.

Step-pool morphology occurs at the subunit scale (Table 1). Few mechanisms have been proposed, however, to explain development of regular alternating steep and gentle channel units. Iseya and Ikeda (1987) demonstrated in flume experiments that when bedload is widely graded, longitudinal sorting of sediments into alternating "smooth" and "congested" zones can occur from particle interactions alone. Smooth zones are low-gradient reaches that had high concentrations of fines and few coarse particles, whereas congested zones are steep reaches of closely packed coarse particles and few fines. A transitional zone between the two extremes was also described. Sediments segregate into these zones because high concentrations of fines increase local bedload transport rates of coarse particles relative to fines by reducing grain roughness and providing a smooth transport surface. Mobilized coarse particles are transported until they encounter other coarse particles, where increased grain roughness and friction cause transport to slow, forming a gravel jam. A similar mechanism for movement of bedload sheets is described by Whiting and others (1988). In essense, both mechanisms are refinements of the kinematic wave originally proposed by Langbein and Leopold (1968).

Although untested in natural channels, Iseya and Ikeda's model of longitudinal sediment sorting is an attractive mechanism for producing channel units because it explains many of the features seen in boulder-bed channels. By analogy, pools and riffles represent smooth zones, rapids transitional zones, and cascades congested

proximately five channel widths long, comparable to lengths of channel units (Table 3) (although flume width may have constrained zone width), and included bed profile undulations (Iseya and Ikeda, 1987; Fig. 7) corresponding to subunit- or step-scale features, which the authors attributed to formation of gravel jams under antidunes. Preferred sequences seen in the flume were similar to those observed in the field (Fig. 9); congested to smooth (cascade to pool) and smooth to congested (pool to cascade) were observed, as well as congested to transitional to smooth (cascade to rapid to pool). This model also corresponds to particle size distributions observed in boulder-bed streams (Fig. 5), with much higher concentrations of fines in pools. A key implication of the longitudinal sorting model, however, is that smooth and congested zones migrate downstream through time. This has not been observed in the two study sites; a 10–15 yr storm in French Pete Creek in 1986 did not appreciably change unit location. Repeat mapping of stream reaches following larger storms should permit further testing of this hypothesis.

Contrast with Channel Bars, Riffles, and Pools. Channel units can be compared with features that create stepped profiles in gravel-bed streams; that is, channel bars. Channel bars are macroform channel features with lengths on the same order as channel width and with heights comparable to the depth of the generating flow (American Society of Civil Engineers, 1966); they are closely associated with riffles and pools that give rise to vertical oscillations in longitudinal profiles of gravel-bed streams.

Channel units differ from bars and associated features in several important respects, however, and do not fit neatly into any of the proposed classification systems for bar types (Krigström, 1962; Church and Jones, 1982). Channel-unit sequences do not follow regular bar-riffle-pool pattern, and their spacings are more irregular than pool-pool spacings in gravel-bed streams. Although channel units such as rapids and cascades have the same length dimensions as bars, they do not have a three-dimensional bar form but represent a two-dimensional classification of the bed surface. In contrast to bars, little sediment is stored in steep channel units.

In characterizing macrobedforms in gravel streams, Church and Jones (1982) distinguished between framework riffles, which are composed of the coarsest bed fraction and offer hydraulic resistance but do not store much sediment, and superposed bars, which store transient sediment finer than the framework cobbles. Steep channel units may represent boulder-bed analogs of the former. By this view, steep channel units represent skeletal bars and will occur only where sediment transport rates are low and competence to move framework particles is exceeded only infrequently, conditions prevailing in many mountain streams. This hypothesis is supported by the observation that distinct channel units apparently do not form in steep, coarse-bed streams with high sediment-transport rates such as glacial outwash streams. Instead, braiding and development of medial bars is the preferred bedform type (Fahnestock, 1963). Absence of width constraint in these latter streams may also inhibit unit formation.

Some cascades or boulder steps in Lookout Creek and French Pete Creek may represent avalanche faces of poorly developed diagonal or transverse bars, particularly in low-gradient reaches (S < 2%) of the channel. These are the exception rather than the rule, however. The maps show that only 3 of 165 and 10 of 237 of the units of French Pete Creek and Lookout Creek, respectively, could be interpreted as slip faces associated with bars.

Bars and associated features generally are not observed in the field where the channel gradient exceeds 2% (Florshein, 1985), although Bathurst and others (1983) reported alternate bar formation in flume experiments at slopes as high as 9%. Bar formation is suppressed in steep, narrow channels where width-to-depth ratios are low and bed particle diameters are on the same order as flow depth during competent flows (Table 5). Low ratios of depth to particle size apparently inhibit bar formation because particles cannot be vertically accreted but instead form tightly locking step structures interspersed with pools (Church and Jones, 1982). In some steep channels, therefore, bar resistance is apparently replaced by form resistance around individual bed elements, steps, and step sequences.

SUMMARY AND CONCLUSIONS

A hierarchical framework is useful for viewing structure of bedforms in boulder-bed streams. Longitudinal profiles of many boulder-bed channels are stepped at spatial scales ranging from less than a channel width to hundreds of channel widths. Steps form at the subunit scale where they increase form resistance by creating rib structures transverse to flow; stream energy is expended both as form drag on the rib and as a result of spill resistance caused by hydraulic jumps formed at low to moderate discharges (Whittaker and Jaeggi, 1982). Steps at this scale are thus analogous to bedforms, such as dunes and antidunes in sand-bed streams, and represent a bed deformation in response to increasing discharge, which offsets reduced particle resistance as the ratio of particle size to depth decreases (Morris, 1968; Davies, 1980).

Channel units represent a distinct scale of variation within the hierarchy, as macrobedforms that can be easily classified in the field and discriminated by well-defined slope populations, particle size distributions, morphologies, and hydraulics. Units differ in abundance of subunit types, including individual steps, and display distinctive and nonrandom sequences and spacings. Location and spacing of channel units is strongly influenced by occurrence of exogenous features such as bedrock and boulders along the channel margin. The distribution of channel units provides a way to characterize longer reaches of channel and may be useful for comparing channels with different disturbance histories.

Formation of channel units requires (1) widely graded bedload, including large boulders that are immobile under low to moderate discharges; (2) a discharge regime capable of moving even the largest particles occasionally under near-critical flow conditions; (3) low sediment supply; and (4) channels with small width-to-depth ratios and irregular, resistant boundaries. Field observations suggest that distinct channel units do not form where sediment supply is high and channels are wide. Instead, braiding occurs and channel bed morphology is characterized by long, featureless rapids (Fahnestock, 1963). We have not observed well-developed channel-unit sequences in streams with average bed gradients of less than 2%, and they are also difficult to distinguish at bed gradients above 10% where the entire channel becomes one long cascade or a series of falls over boulders separated by pools less than a channel width long.

Stepped beds at different scales represent distinctive morphologic and hydraulic environments, and their identification must precede measurement of flow parameters or sediment transport. Step-pools, for example, are important from the standpoint of both flow resistance and sediment transport. Higher drag forces over stepped beds results in greater rate of energy expenditure per unit channel length than in unstepped beds (Peterson and Mohanty, 1960; Bowman, 1977; Bathurst and others, 1983; Khashab, 1986). Sediment transport rates also differ between stepped and unstepped beds. The small pools between steps provide storage sites for fine sediment transported during low to moderate discharges. Sediment transport rates during a particular storm event are therefore dependent on the available storage capacity of these pools as well as on the absolute magnitude of the discharge. Antecedent storage volume in pools has been shown to influence sediment rating curves in both field studies (Ashida and others, 1976; Sawada and others, 1983, 1985) and flume experiments (Ashida and others, 1986; Whittaker, 1987a, 1987b).

At this stage of our understanding of dynamics of water and sediment movement through steep channels, unit formation cannot be attributed to a single cause. On balance, the linear scale and spacing of channel units supports the interpretation of units as a type of two-dimensional bar formed during infrequent bedload transport events, possibly in response to differential transport of coarse- and fine-grained particles. Hillslope processes that deliver large particles to the channel also promote formation of alternating steep and gentle (cascade-pool) sequences, creating a stair-stepped channel. In the absence of a source for large particles, a more uniform bed characterized by riffles and rapids results. Unit formation is linked to critical flow phenomena, including development of hydraulic jumps, and may be a longitudinal profile adjustment reflecting a dynamic equilibrium between hydraulic processes promoting critical flow and energy dissipation in a highly irregular channel.

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