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The geomorphic significance of step–pools in mountain streams

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Abstract

This paper develops a conceptual model to define the changing role and significance of step–pools as energy dissipators in steep mountain channels. Although energy dissipation is a significant function of step–pools, this role changes over time with variations in discharge. Steps are effective in reducing stream energy at low flows, but their effectiveness diminishes with increasing stage. Accordingly, the manner in which energy dissipation occurs also varies. With increasing flows, spill resistance gives way to a dominance in form and grain resistance. The conceptual model for the changing role of step–pools is illustrated with data from hydraulic analysis and modeling of step–pools in the Santa Monica Mountains of California. The model points to the importance of the size of steps in determining their role in energy dissipation and in their interactions with channel hydraulics. The model offers a new articulation for the geomorphic significance of step–pools in mountain streams, and it serves as a useful template for a more complete understanding of step–pools over a longer time scale.

Keywords: Step–pool; Energy dissipation; Mountain stream geomorphology

1. Introduction

Steps and pools are ubiquitous bed forms in mountain stream channels, occurring where gradients exceed ~ 2% and materials are in the gravel to boulder size range (Grant et al., 1990; Montgomery and Buffington, 1997; Wohl, 2000a). Coarse particles spanning the channel width create steps (Hayward, 1980), which alternate with finer sediments in pools to produce a characteristic, repetitive sequence of bed forms (Chin, 2002) (Fig. 1) with a stepped longitudinal profile resembling a staircase. The step–pool morphology similarly develops in bedrock channels (Duckson and Duckson, 1995, 2001; Wohl, 2000b). In forested streams, steps are commonly composed of logs mixed with vegetative debris (Marston, 1982; Curran and Wohl, in press).

Step–pools serve a fundamental role in river systems because they provide hydraulic resistance (Abrahams et al., 1995). Steps induce water to flow over and through the large roughness elements and plunge into the pool below, promoting tumbling flow (Peterson and Mohanty, 1960) where much of the flow's kinetic energy is dissipated by roller eddies. Steps also cause a distinct vertical drop in the water surface elevation as water flows from step to pool. Through vertical fall, steps decrease the amount of potential energy that otherwise would be available for conversion to a longitudinal component of kinetic energy used for erosion and sediment transport (Ashida et al., 1976; Marston, 1982). In these ways, steps provide the ability

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Fig. 1. Step–pool sequences in the Santa Monica Mountains, California.

to counterbalance steep gradients, thereby preventing excessive erosion and channel degradation (Heede, 1981). The role of step–pools is especially important in confined mountain streams that prohibit lateral adjustments and energy dissipation by meandering and braiding (Chin, 1989, 2002).

Despite their common occurrence and functional importance, step–pools have received little attention in fluvial geomorphological research compared to riffle–pools. Recent work has generated important new data from around the world (e.g., Chartrand and Whiting, 2000; Wohl and Thompson, 2000; Lenzi, 2001; Zimmermann and Church, 2001; Lee and Ferguson, 2002), but the specific formative processes are not completely understood, and the significance of step–pools in the broader fluvial system has not been fully articulated. Because upland step–pool channels are linked to fluvial responses in large downstream basins (Montgomery and Buffington, 1997) and because step–pool units are important riparian ecosystems (Scheuerlein, 1999), increased knowledge of step–pools is critical to the understanding of the overall functioning of the river system. As urbanization increasingly encroaches upon mountain fronts in response to population growth (Chin and Gregory, 2001), improved understanding of step–pools could also contribute to approaches to the design and management of steep channels.

This paper develops a conceptual model for the changing role and significance of step–pools as energy-dissipating features in the fluvial system. Although early work has recognized step–pools as important energy-dissipating mechanisms in steep slopes (i.e., Heede, 1972; Church and Jones, 1982; Chin, 1989), this issue could be investigated explicitly, and the implications for the changing role of step–pools in the evolution of the fluvial system could be explored. The role of step–pools changes over time because the effectiveness of fall obstructions varies with river stage. Steps are most effective in reducing stream energy at low flows when vertical fall is most pronounced. For example, steps account for 40–100% of the total drop in water surface elevation in channels of Colorado, Arizona, and Washington (Heede, 1972, 1981; Curran and Wohl, in press). However, the effectiveness of energy reduction by steps is greatly impaired at increasingly high flows (Heede, 1972; Hayward, 1980; Marston, 1982; Whittaker and Davies, 1982). Energy loss due to individual steps is diminished at high flows because the water surface profile and energy line flatten (Stuve, 1990; Leopold, 1994; Zimmermann and Church, 2001) and flow resistance decreases correspondingly (Beven et al., 1979; Lee and Ferguson, 2002). However, although the importance of documenting energy dissipation at higher stages has been recognized (Marston, 1982), critical data have been lacking to enable a more complete picture of energy dissipation by step–pools, owing to the difficulties of making process measurements in rugged and often densely vegetated terrains (Chin, 1989).

The role of step–pools also changes over time because the manner in which flow resistance is imparted by steps varies with stage. At low flows, when the staircase-like step structure is most pronounced and water plunges from step to pool, spill resistance is the dominant energy-dissipating mechanism in step–pool channels (Abrahams et al., 1995), approaching as much as 80–90% (Curran and Wohl, in press). However, as stage increases and the step–pool shape becomes increasingly hidden, spill resistance gives way to a dominance in form resistance and then to grain resistance. Thus, the relative dominance of the energy-dissipating mechanism by steps changes when considered over time with variations in discharge. Although the stage-dependency nature of roughness conditions has been noted (Ergenzinger, 1992; de Jong and Ergenzinger, 1998; Lee and Ferguson, 2002) and attempts at partitioning flow resistance in step–pool channels during low flow have been made (Curran and Wohl, in press), further consideration of energy dissipation over a range of flows would reveal additional insights for step–pools over a longer time scale.

Herein, I outline a conceptual model to define the changing role and significance of step–pools as energy dissipators in the fluvial system. The model is built upon answering four specific research questions. First, how stable are step–pool sequences? Second, how effective are step–pools in reducing potential energy through vertical falls? Third, how does potential energy dissipation vary with increasing flow? Fourth, at what stage do step–pools become submerged?

Identifying the points of instability and submergence are key to the development of the conceptual model. The point of instability is important because it marks a change in the fundamental role of steps in the river system (Chin, 1998). When steps are stable, they are independent variables that regulate surrounding flow, channel hydraulics, and energy dissipation; once steps are mobilized, they become a dependent variable that adjusts to prevailing flow and energy conditions. Similarly, the point of submergence marks a major shift in the dominant role of step–pools in the channel system, from functioning as fall obstructions that induce spill resistance, to behaving more like other bed forms and roughness elements that impart form and grain resistance. Thus, defining these two points would form the basis for a model of the changing role and significance of step–pools in the fluvial system over a longer time scale. Such a model acknowledges the progressive development of step–pools in between large, channel-forming events that break down the sequences (Lenzi, 2001). This model therefore applies to step–pool systems that are hydraulically controlled and capable of being submerged and restructured at high flows. Examples include the Rio Cordon of Italy (Lenzi et al., 1997; Lenzi, 2001), the Lainbach River of Germany (Ergenzinger, 1992; Gintz et al., 1996), and streams in the Santa Monica Mountains of the United States (Chin, 1998, 1999a) where large floods have been observed to submerge and mobilize steps.

For the remainder of the paper, the term “energy dissipator” is used as in an engineering sense (Vischer, 1995), in that when a step functions like a baffle or fall obstruction and induces free water fall, it is an energy dissipator. However, when a step is submerged and vertical fall is no longer present, I will refer to it as a “roughness element” (Bathurst, 1987). Using this terminology, submergence represents a point when steps cease to function as energy dissipators and behave simply as roughness elements in the stream channel, like any other.

2. Study area and methods

2.1. Theoretical structure

This investigation considers the low flow step–pool form and process as a middle member of the range of possible spectrum of states in the evolution of the fluvial system (Fig. 2). By working backward and forward from this central state, the channel-forming flow can be inferred and the effects of the step–pool morphology on stream energy dissipation can be determined. Hydraulic reconstructions estimate the threshold of step–pool mobility; direct field measurements and hydraulic modeling allow energy dissipation to be evaluated. Energy dissipation with increasing flow permits identification of the threshold discharge at which step–pools become ineffective energy-dissipating features. Although this threshold

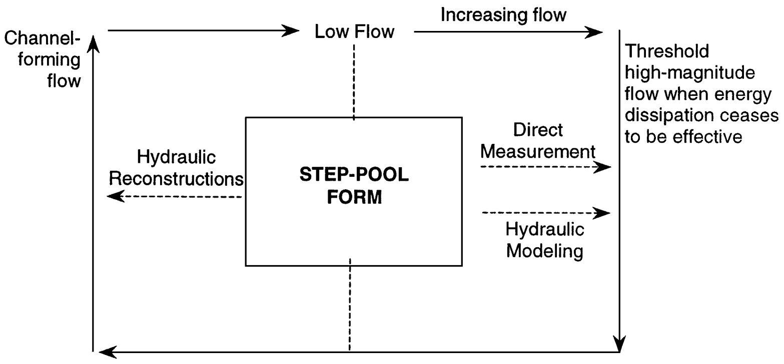

Fig. 2. Theoretical structure for investigating step–pools. Low flow represents a middle member of the range of possible spectrum of states in the evolution of the fluvial system.

discharge does not necessarily have to equal the channel-forming flow, presumably, at some high-magnitude flow, the step breaks down and channel adjustment occurs. Therefore, this theoretical diagram represents one complete life cycle of a step–pool sequence, and the task is to define the dimensions of the diagram.

2.2. Field sites from Santa Monica Mountains

Streams from the Santa Monica Mountains of southern California are used to define the frequency–magnitude dimensions of the conceptual model for the changing role of step–pools. The Santa Monica Mountains were the site of previous studies on the stability (Chin, 1998), origin (Chin, 1999a), morphology (Chin, 1999b), and periodicity (Chin, 2002) of step–pool systems. This analysis uses data from the hydraulic reconstructions of step–pool mobility reported in Chin (1998). Thirteen of the original 15 study reaches from Big Sycamore Creek and Cold Creek are selected for further analysis. These reaches contain well-developed step–pools. They vary from 0.02 to 0.12 in slope and from 125 to 270 m in length (Table 1). For more descriptions of the study reaches and the Santa Monica Mountains, see Chin (1998, 1999a,b, 2002).

2.3. Hydraulic reconstructions

Working backwards from the low-flow state (Fig. 2), hydraulic reconstructions were used to estimate the high-magnitude flow needed to mobilize steps in the study reaches. The specific algorithm used was developed by Costa (1983) for small, steep mountain streams. A series of computations uses particle size as the independent variable to determine the velocity and flow depth necessary to mobilize coarse step particles:

$$v = 0.18\, d^{\,0.487} \qquad (1)$$

where d is the average size of the five largest particles (mm) and v is the average velocity (m s^{-1}). Depth is determined from a family of equations that defines Fig. 7 in Costa (1983) (i.e., for

Table 1
Study reaches in the Santa Monica Mountains

	Reach	Step–pool sequences	Length (m)	Slope (m/m)	Channel width (m)	Step size[a] (mm)
Cold Creek	Preserve	48	186	0.115	2.5	490
	Stunt	42	169	0.063	2.5	417
	Helsley	45	198	0.038	2.9	313
	Bobcat	39	221	0.019	3.2	365
	Jude	30	225	0.033	5.6	550
	Monte	27	218	0.022	6.6	403
Big Sycamore Creek	Canyon	37	210	0.096	3.5	493
	Klein	33	170	0.050	2.2	380
	Laughlin	29	160	0.047	2.4	405
	Scott	38	270	0.061	3.6	519
	Bridge	40	190	0.036	5.5	461
	Overlook	28	125	0.024	3.6	294
	Wood	28	193	0.017	4.7	305

[a] Calculated by averaging the *b*-axis of the five largest rocks comprising each step.

slope 0.005, $D = 0.012d^{0.872}$ where D is the average depth (m); for slope 0.010, $D = 0.005d^{0.788}$). Computed flow depths were evaluated in the field against high water marks and flood debris, visible at about half of the study reaches, which suggested that such depths were reasonable estimates for the Santa Monica Mountains (Chin, 1999a). Discharge was computed from cross-sectional surveys and then related to a flow frequency based on regional relationships (Young and Cruff, 1967). More background for this methodology is detailed in Chin (1998), which also contains the complete set of data and results for the 15 study reaches in the Santa Monica Mountains. Threshold discharges computed with this method are conservative estimates (Grant et al., 1990; Scheuerlein, 1999; Zimmermann and Church, 2001) because such factors as particle imbrication and interaction are unaccounted for.

2.4. Energy dissipation

An assessment of the significance of step–pools in stream energy dissipation is to consider potential energy in a channel reach:

$$\mathrm{PE} = mgh \qquad (2)$$

where PE is potential energy; m is mass; g is acceleration of gravity; and h is height (or elevation) above a horizontal datum. Thus, PE per unit mass is directly proportional to height or elevation:

$$\mathrm{PE}/m\alpha h \qquad (3)$$

Potential energy dissipation caused by steps is the ratio of the cumulative change of water surface elevation in vertical falls (h) to the total stream relief, or change in water surface elevation (Fig. 3):

$$\mathrm{PE\ loss}_{\mathrm{steps}} = h/\mathrm{total\ stream\ relief} \qquad (4)$$

This ratio, commonly used for log steps and organic debris (e.g., Heede, 1972, 1981; Keller and Swanson, 1979), expresses the potential energy reduced by steps that otherwise would be available for conversion to kinetic energy and sediment transport. Marston (1982) provides more details of energy transformations in stream channels.

To evaluate potential energy dissipation by step–pools over a range of flows, the approach was to work forward from the central low-flow state to the high-magnitude discharge where steps are submerged and are no longer effective as energy dissipators (Fig. 2). This threshold marks the shift from the role of steps in inducing free water fall to form roughness taking a greater importance. A series of water surface profiles were constructed in order to evaluate energy dissipation and to identify the point of submergence. Field surveys provided data for the low-flow profile, but similar data could not be obtained at higher flows.

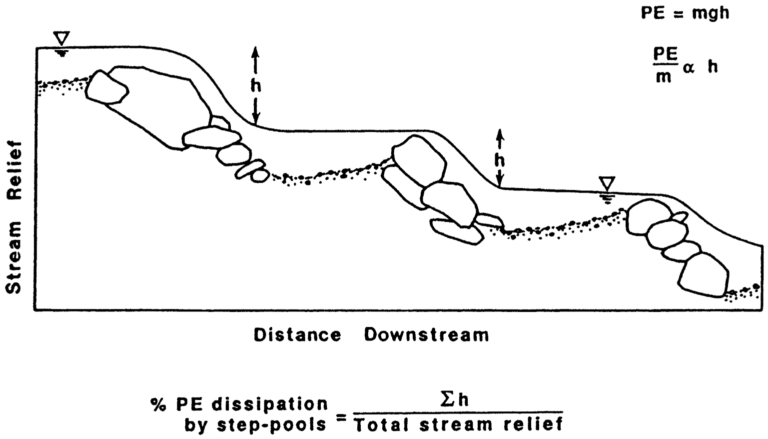

Fig. 3. Potential energy dissipation by steps.

Instead, water surface profiles were modeled for higher flows using the step-backwater HEC-2 program of the U.S. Army Corps of Engineers (1990).

2.5. Hydraulic modeling

The HEC-2 model calculates water surface profiles based on the solution of the one-dimensional energy equation. It is the original version of HEC-RAS, the River Analysis System program (U.S. Army Corps of Engineers, 1998). The newer HEC-RAS model provides several improved hydraulic features over HEC-2 (Brunner and Piper, 1994), such as alternative channel subdivision for conveyance calculations and mixed flow regime calculations, but the two programs are fundamentally the same. For example, comparison of water surface elevations calculated with HEC-2 and those with HEC-RAS at ~ 2000 cross sections showed that, for the 10% chance flood, 73.1% of the cross sections had identical water surface elevations and 96.9% were within ± 0.006 m (Bonner et al., 1994). Similarly, for the 1% chance flood, 70.1% of the cross sections showed no difference and 95.8% were within ± 0.006 m.

Because HEC-2 is a one-dimensional model for steady, gradually varied flow, the assumptions are difficult to meet for mountain streams. Even so, the focus on modeling higher flows with HEC-2 in this application makes the program a reasonable choice. For example, although HEC-2 often gives inaccurate predictions of hydraulic parameters during low flows (Miller and Wenzel, 1985), these errors decline with increasing stage (Carling and Wood, 1994; Keller and Florsheim, 1993) because bed-generated turbulence tends to be less important at higher flows (Jarrett, 1984). Also, although numerous local supercritical transitions probably occur in step–pool channels, modeling flow as subcritical nevertheless gives good results (O'Connor and Webb, 1988) because subcritical flow has been largely reported for mountain streams owing to extreme turbulence (Heede, 1972; Jarrett, 1984; Lopez and Falcon, 1999). Therefore, because the complex hydraulics associated with mountain channels are not likely to be represented fully by any model currently available, simple hydraulic programs provide useful approximations for these environments (Lopez and Falcon, 1999). As a first attempt to model flow through step–pool channels, HEC-2 allowed another glimpse of high-magnitude flow conditions where field measurements were nearly impossible (Keller and Florsheim, 1993; Carling and Wood, 1994). Similar applications to pool–riffle reaches (Keller and Florsheim, 1993) and bedrock channels (Wohl et al., 1999) yielded good results.

The modeling was performed for a 30-m portion of Stunt Reach in Cold Creek, 1 of the 13 study reaches (Fig. 1; Table 1). Seven step–pool sequences comprise this reach, named Stunt Subreach. The reach is comparatively simple hydraulically, a desirable trait for modeling (O'Connor and Webb, 1988). The accessibility of the reach also facilitates data gathering for model calibration and verification. Basic input data for HEC-2 are surveyed channel geometry (cross sections and length of channel between consecutive cross sections), initial stage and discharge, flow regime, and the energy loss coefficients (Manning's n and expansion/contraction coefficients). A total of 24 surveyed channel cross sections represented Stunt Subreach; these were taken at every major break in slope. Five flow profiles were generated; these served as starting points for indicating trends in energy loss by steps at higher flows.

The remainder of the paper addresses the four stated research questions. I then explore the implications of these findings for the changing role of step–pools, followed by the development of the conceptual model outlining the significance of step–pools as energy dissipators in mountain streams.

3. Mobility, energy dissipation, and the changing role of step–pools

3.1. Threshold of step mobility

As reported in Chin (1998), results of the hydraulic calculations indicate that step–pools in the study reaches of the Santa Monica Mountains are mobilized by discharges ranging from 0.6 to 295.5 m^3 s^{-1}, depending on the size of the particles comprising the steps. The larger the particle sizes, the greater the flows required. The calculated discharge values correspond to recurrence intervals of about 2 to 200 years. Thus, for steps consisting of 100- to 200-mm rocks, movement occurs on the order of 2 to 15 years.

On the other hand, only the largest steps, composed of 1-m boulders or larger, remain stable for periods of 100 to 200 years. Most steps (median rock size of about 400 mm) restructure every 15 to 50 years on average.

These results are applied to Stunt Subreach for developing the conceptual model for step–pools. Steps in Stunt Subreach are composed of clast sizes ranging from 300- to 792-mm. Thus, they are mobilized by flows with magnitudes ranging from ~ 7.1 to 43.5 $m^3 s^{-1}$ (Fig. 4), depending on the particle sizes comprising each step. These critical discharges correspond to frequencies of about 11 to 62 years in the Santa Monica Mountains (Chin, 1998). In Fig. 4, the smallest step (Step A, average 300-mm rocks) and the largest step (Step B, average 792-mm rocks) are highlighted for the purpose of illustrating the conceptual model that follows.

3.2. Energy dissipation at low flow

Potential energy dissipation by step–pools in the study reaches of the Santa Monica Mountain streams is nearly complete at low flow (Table 2). In Cold Creek, steps account for 82–98% of the total elevation loss in the study reaches (90% for all reaches combined). Similarly, the cumulative height of steps nearly equals the total drop in elevation in the Big Sycamore Creek reaches (ratio = 80–100%; 97% for all reaches combined). These values indicate that, through vertical fall, steps are effective in reducing flow energy that otherwise might be available for bed and bank erosion.

Table 2
Potential energy dissipation at low flow

	Reach	Total relief (m)	Cumulative height of steps (m)	PE dissipation (%)
Cold Creek	Preserve	20.88	18.63	89
	Stunt	10.43	10.21	98
	Helsley	6.63	5.65	85
	Bobcat	4.27	3.79	89
	Jude	7.35	6.74	92
	Monte	4.21	3.47	82
	All reaches	53.77	48.49	90
Big Sycamore Creek	Canyon	8.81	7.82	89
	Klein	7.55	7.38	98
	Laughlin	16.02	16.02	100
	Scott	20.32	20.12	99
	Bridge	6.98	6.83	98
	Overlook	2.74	2.19	80
	Wood	2.85	2.70	95
	All reaches	65.27	63.25	97

Although as a group, steps are effective in reducing nearly all the elevation losses in study reaches, a large proportion of the losses are accomplished by relatively few individuals. For example, for Stunt Subreach (Fig. 4), Step B alone accounts for 17.8% of the elevation drops in this reach, compared to only 1.6% for Step A. Thus, to the extent that step sizes vary within a given reach, large steps in the Santa Monica Mountains play more prominently in potential energy dissipation. Because in hydraulically controlled reaches such as those in the Santa Monica Mountains, step height is dependent upon the particle sizes comprising the step (Egashira and Ashida, 1991; Chin, 1999b; Chartrand and Whiting, 2000), potential energy

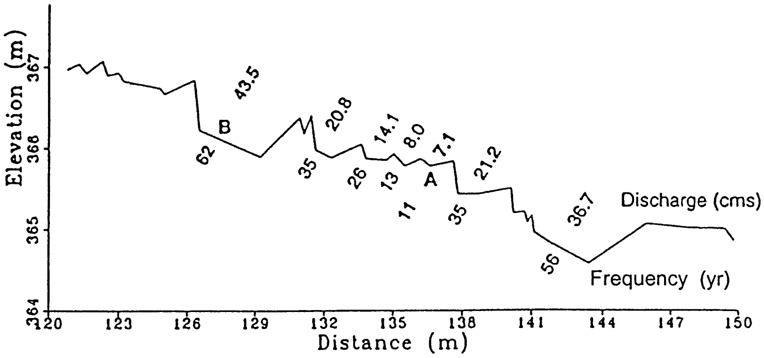

Fig. 4. Critical flow for initiating motion of step particles, Stunt Subreach, Cold Creek.

reduction is expected to vary with step particle size accordingly.

3.3. Dissipation with increasing flows

Field survey and hydraulic modeling generated five water surface profiles for Stunt Subreach (Fig. 5). They included the range of flows capable of mobilizing steps in this reach: 0.05, 0.3, 2.5, 17.63, and 51.93 $m^3\ s^{-1}$. These discharges correspond to flow frequencies ranging from <1 to about 72 years in the Santa Monica Mountains (Chin, 1998). Visual inspection indicates that the low-flow profile follows the step–pool bed configuration closely, but the profiles depart with increasing high flows. The profiles for the two highest flows (17.63 and 51.93 cm) show evidence of the two large pools only, as the intervening smaller ones are entirely submerged. This submergence is analogous to the drowning out of weirs or log jams.

Table 3
Energy dissipation with increasing flows, Stunt Subreach

Discharge[a] (cm)	Total drop of water surface elevation (m)	Cumulative drop of water surface elevation at steps (m)	PE reduction by steps (%)
0.05	1.85	1.66	90
0.30	1.66	1.35	81
2.50	1.51	1.01	67
17.63	1.39	0.37	27

[a] The discharge of 51.93 cm is not included because a flow of that magnitude is expected to break down the series of steps in this reach.

Analysis of the reconstructed water surface profiles (Fig. 5) shows a trend of decreasing energy losses with increasing discharge (Table 3). At the low flow of 0.05 $m^3 s^{-1}$, because the water surface profile follows the staircase-like bed configuration closely and creates a dominant vertical component to the flow, potential energy dissipation by steps is nearly complete at 90%. At a flow of 0.30 $m^3\ s^{-1}$, as two of the smallest steps are drowned out, the remaining steps are left to account for 81% of the total drop in water surface elevation in the reach. At 2.5 $m^3\ s^{-1}$, because submergence occurs for the entire series of small steps in the central portion of Stunt Subreach, potential energy dissipation by steps reduces to 67% (Table 3), attributable to the larger steps only. The smaller steps, when submerged, therefore become ineffective as energy dissipators at higher flows.

At the two highest flows, it is unclear whether vertical drops in the water surface profiles are caused directly by the steps underneath. This is probably the case for the discharge of 17.63 cm because flow is contained within the channel and is insufficient to mobilize the larger steps in Stunt Subreach (Fig. 4). The bed profile remains largely intact. However, the individual large steps contribute to only 27% of the total loss in water elevation at this flow (Table 3). On the other hand, the high-magnitude flow of 51.93 cm is best interpreted as flood waves because of the large depths and flow that spill overbank. According to the hydraulic calculations (Chin, 1998), a flow of this magnitude is expected to break down this series of step–pools in Stunt Subreach (Fig. 4). Thus, not only are these steps ineffective in energy dissipation at this discharge, the entire channel bed becomes a

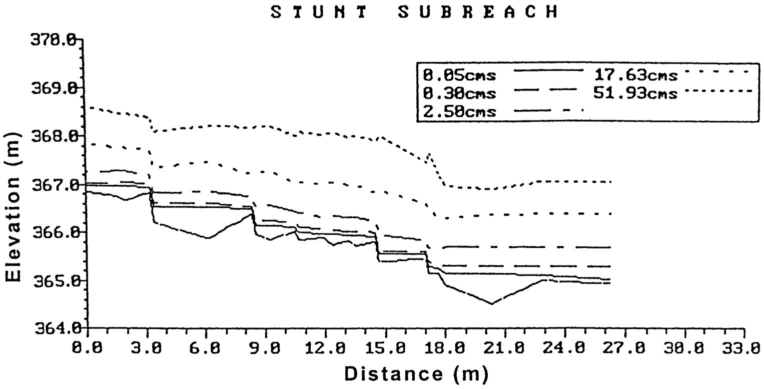

Fig. 5. Water surface profiles from hydraulic modeling.

dependent variable that adjusts to flow and energy conditions.

3.4. *Point of submergence—defining the changing role of step–pools*

When steps are submerged, they lose their distinct property of inducing vertical fall. More potential energy is then available for conversion to kinetic energy and sediment transport; spill resistance gives way to a dominance in form and grain roughness in energy dissipation. Thus, at the point of submergence, steps no longer function as energy dissipators; they become more like other bed forms and roughness elements in the channel system. They are analogous to pool–riffle sequences when submerged.

In Stunt Subreach (Fig. 5), the point of submergence varies for each individual step because of variations in their sizes. At the low flow, each of the seven steps contributes to the total elevation loss in this reach. Therefore, all individual steps participate as energy dissipators that induce spill resistance, even though the extent varies between individual steps because of varying sizes. As steps become increasingly drowned at higher flows, an increasing number of steps cease to function as energy dissipators, and they increasingly become more like other bed forms in stream channels. Thus, at the 2.50 cm flow, three of the smaller steps in the central portion of the reach become bed forms that impart form and grain roughness. At the highest flows, only the largest individual steps remain as energy dissipators. Because large steps are submerged less frequently, they serve more prominent roles as energy dissipators over a longer time scale. For small steps, their role changes readily when they are drowned during smaller floods.

4. A conceptual model for step–pools

4.1. *Toward a general model for step–pools*

The point of submergence defined above can be connected with the channel-forming flow determined by the hydraulic analysis to develop a conceptual model describing the function of step–pool systems. It was originally suggested (Fig. 2) that, as flow increases and energy dissipation ceases to be effective, channel restructuring occurs. This general idea can be refined to consider the two energy-dissipating mechanisms by steps: potential energy loss through vertical falls, which approximates spill resistance, and kinetic energy dissipation by form and grain roughness. As potential energy reduction diminishes at high flows (Table 3), energy is available for conversion to kinetic energy and sediment transport, which become more important, until flows are sufficient to move boulders and reform the channel. Thus, a general model for the significance of step–pools needs to incorporate the relative dominance of potential and kinetic energy dissipation. Fig. 6 illustrates this model, which is an expansion of the right side of the theoretical diagram of Fig. 2.

4.2. *Application to specific test cases*

To define its dimensions, the general model is applied to the two steps highlighted earlier in Stunt Subreach, Step A and Step B (Fig. 4). They are the smallest and largest steps in the reach, respectively, offering greatest contrast. Step A and Step B are composed of 300- and 793-mm particles, respectively.

Working backward from the low-flow form (Fig. 7A), hydraulic calculations showed that a step of this size (300-mm) would require flows of about 7.1 m^3 s^{-1} to mobilize. This represents the channel-forming flow and corresponds to a recurrence interval of about 11 years in Stunt Subreach. Working forward with increasing discharge, analysis of water surface profiles indicated that this small step would become submerged and cease functioning as an energy dissipator

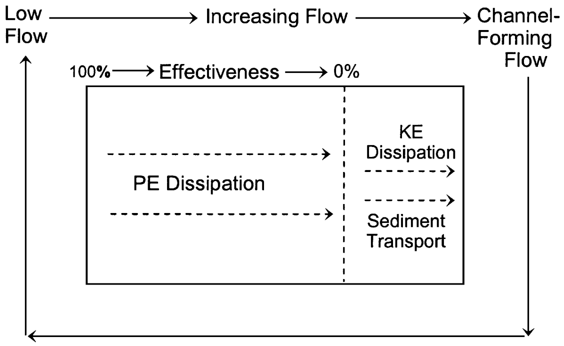

Fig. 6. A general model for energy dissipation by step–pools.

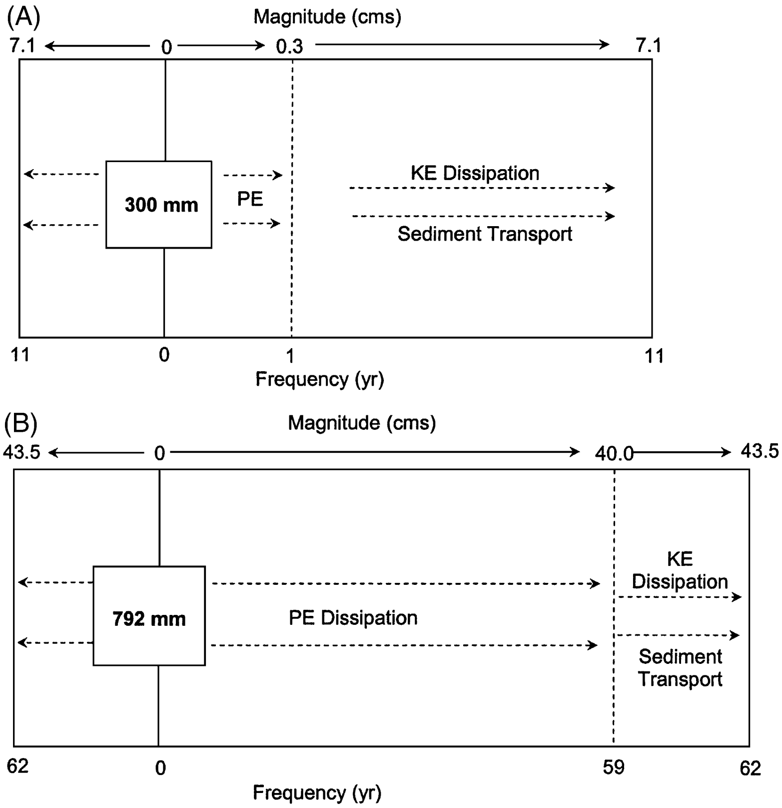

Fig. 7. Conceptual model for step–pools, Stunt Subreach. (A) 300-mm rocks; (B) 792-mm rocks.

at a flow of about 0.3 $m^3 s^{-1}$, or every year on average. Therefore, when flow exceeds 0.3 $m^3\ s^{-1}$, the step behaves more like a roughness element. Channel hydraulics are analogous to those of pool–riffle channels and include kinetic energy dissipation and sediment transport, until flow reaches a critical magnitude of about 7.1 $m^3\ s^{-1}$. Presumably, at this point, the step breaks down and reforms, and the whole cycle begins again.

The same explanation applies for the larger step, composed of 792-mm rocks (Fig. 7B). The difference is the relative dominance of potential versus kinetic energy dissipation. In this case, the larger step has a longer life span, with restructuring expected to occur once every 62 years on average in Stunt Subreach. Because submergence occurs at relatively high flows, the step behaves as an energy dissipator over a much larger range of flows and as a roughness element relatively seldom. Thus, the zone dominated by kinetic energy dissipation is much smaller.

4.3. A conceptual model for steps of varying sizes

A series of nested diagrams for varying step sizes results in a conceptual model defining the changing role of step–pools as energy dissipators (Fig. 8). Each of the boxes represents a step of a certain size, arbitrarily chosen from 300- to 800-mm. The time scale is linear in the diagram, so the length of the box indicates the average life span for each step. The vertical dashed lines separate the zones characterized by potential and kinetic energy dissipation. Therefore, it identifies the point at which a step makes that transition, or shift, from functioning as an energy dissipator to behaving like a roughness element in the river system.

A point that emerges clearly is how the size of a step dictates its stability and its role in energy dissipation. First, the stability of steps obviously depends on their size as well as flow conditions. Small steps composed of 300-mm rocks are unstable in comparison, breaking

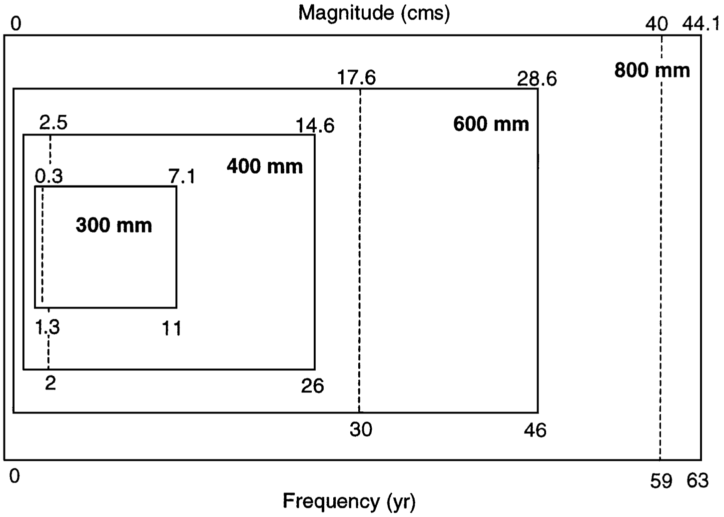

Fig. 8. Conceptual model for steps of varying sizes.

down every 11 years on average in Stunt Subreach. On the other hand, large steps on the order of 800 mm are structures that remain in place for periods of over 60 years. Second, the role of steps in energy dissipation also changes according to their size. Within their life spans, the relative dominance of potential energy dissipation increases with increasing size of the step. This is clearly shown by the shifting of the dashed lines to the right within the boxes in Fig. 8, so that large steps would function as energy dissipators through a large proportion of the time, whereas small steps would behave more as roughness elements much of the time.

5. Summary and conclusions

Analysis of step–pools in streams in the Santa Monica Mountains of California yields answers to the four stated research questions for this paper and insights into the significance of step–pools as energy dissipators in the fluvial system. First, step–pools in streams in the Santa Monica Mountains are adjustable bed forms that are capable of being restructured. The flows required to destabilize step–pool sequences depend on the particle sizes comprising steps. For steps in Stunt Subreach, with clast sizes ranging from 300 to 800 mm, these flows have recurrence intervals of about 11 to 62 years. Second, steps are effective energy dissipators at low flows. Steps account for 80–100% of the elevation losses in the study reaches in the Santa Monica Mountains. Through vertical falls, steps reduce the potential energy that otherwise might be available for conversion into a longitudinal component of work, thereby offsetting steep gradients. Third, energy dissipation by steps diminishes at increasing flows. As step–pools become increasingly drowned at high flows, spill resistance gives way to a dominance in form resistance and, to a lesser extent, grain resistance. Thus, the manner in which energy dissipation occurs varies with discharge. Fourth, the point at which steps become submerged marks a transition in their role as energy dissipators to roughness elements in the fluvial system. Because submergence occurs more readily for small steps, these steps function more as roughness elements over a longer time scale, whereas large steps serve more prominent roles as energy dissipators.

These findings permit the development of a conceptual model that defines the changing role and significance of step–pools in the larger fluvial system. The model articulates how the function of step–pools changes over time with variations in discharge. It also points to the importance of the step size in determining its role in energy dissipation and in its interactions with channel hydraulics. Small steps often function as roughness elements that impart form and grain roughness, rather than as energy dissipators that induce spill resistance. These steps regulate channel hydraulics comparatively seldom, but they are important as dependent variables that adjust to the prevailing flow and energy conditions. On the other hand, the role of energy dissipation becomes primary for large steps. These steps function predominantly as energy dissipators during the evolution of the fluvial system. Therefore, they maintain an independent status throughout much of the time, regulating and controlling flow and channel hydraulics.

The model developed in this paper has flow magnitudes and time dimensions that apply to Stunt Reach in Cold Creek. However, the model is generally applicable if frequency–magnitude relations are defined for other areas and if the boxes and separations in the model are interpreted as zones rather than clear boundaries. The model offers a new articulation for the geomorphic significance of step–pools in mountain streams, and it serves as a useful template for a more complete understanding of step–pools over a longer time scale. Because step–pools characterize mountain areas that cover a sizable portion of the earth surface, increased knowledge of step–pools is important in the broader understanding of mountain geomorphology and earth surface systems.

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