# On the Stability of Step-Pool Mountain Streams[1]

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## ABSTRACT

Although step-pools are generally considered to be stable bedforms, stability is not absolute, but depends on size, scale, and perspective. Hydraulic analysis of the stability of step-pool sequences in the Santa Monica Mountains, California, indicates that they are active channel features that are generally restructured within 5 to 100 years. The degree of mobility depends on step particle size. Steps are stable within small temporal and spatial scales, where they function as independent variables that dissipate stream energy and regulate channel hydraulics, but stability decreases at larger scales, where step pools become dependent variables that respond to discharge and sediment load. Hence the role of step-pools changes from energy dissipation to one of channel adjustment. These results underscore the need to consider larger spatial and temporal scales in order to reveal the complete function and significance of step-pools in mountain fluvial systems.

## Introduction

Mountain streams are characterized by alternating sequences of steps and pools. There are rock steps composed of bedrock, riffle steps that steepen the profile, and log steps that are found in forested areas (Marston 1982). Most steps, however, are accumulations of cobbles and boulders transverse to the channel (Hayward 1980). Finer sediments fill the pool areas between steps to produce a striking, repetitive sequence of bedforms with a stepped longitudinal profile resembling a staircase (figure 1). Despite their ubiquity in a wide range of high-gradient environments, step-pools have until recently been relatively neglected in fluvial geomorphological research. Recent work has brought considerable attention to these bedforms (Chin 1989; Grant et al. 1990; Wohl and Grodek 1994), but their formation remains an issue for debate (Grant and Mizuyama 1991; Abrahams et al. 1995), and their function and significance in the mountain fluvial system have not yet been fully articulated. Because the step-pool morphology characterizes mountain areas which cover a sizable portion of the earth's surface (Graf 1988, p. 175), and because mountain areas are sources for the water and sediment of large downstream basins, an enhanced understanding is critical in explaining the operation of the general fluvial system.

This paper addresses the fundamental question of stability for step-pool sequences in mountain streams. Although workers have generally considered step-pools to be stable bedforms, (i.e., O'Loughlin 1969; Whittaker 1987), the issue of stability has not been investigated in a comprehensive way, and its implications for landform development have not been explored. Step-pool stability is not absolute but is intricately linked to scale with important implications for the role of step-pools in the fluvial system. Scale is particularly relevant in the definition of step-pool stability, because it is during low flow when steps behave as stable structures that dissipate stream energy and regulate channel hydraulics. When the entire spectrum of possible flows are considered, however, steps have a greater potential of becoming destabilized. Once mobile, they respond to prevailing flow and channel conditions and become dependent variables in the evolution of the fluvial system. Therefore, knowledge of the timescales at which step-pools are restructured, and the intervening time span during which they remain stable, would allow greater understanding of their role as gravel bedforms in the larger fluvial system.

This paper seeks to answer three specific research questions. First, are step-pool sequences adjustable features controlled by fluvial processes under the present hydrologic regime? Second, how stable is the step-pool channel over a range of space and time scales? Third, what are the implications

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**Figure 1.** Step-pool sequences in the Santa Monica Mountains, California.

for the role of step-pools in the larger mountain fluvial system? The answers to these questions shed light on the function and significance of step-pools, and on interactions between form and process and between cause and effect, in the evolution of the mountain fluvial system. They also provide insights to identifying the step-pool generating mechanism, as some disagreement exists concerning the nature of hydraulic control on step-pool formation (Miller 1958; Newson and Harrison 1978; Mosley 1987; Grant et al. 1990).

## Study Area

The Santa Monica Mountains of southern California (figure 2) were selected as the field laboratory for this study because the steep channels contain prototype steps and pools, and because the rugged canyons are accessible through numerous state parks and natural reserves. In addition, there are sufficient undisturbed stream segments with adequate length and range of slopes for testing morphological relationships (for different components of the study to be reported elsewhere). The Santa Monica Mountains are ideal in that the small rugged basins are representative of many steep, low-altitude mountain watersheds in the southwestern part of the United States, allowing generalizations to be made.

The southernmost of California's E-W trending Transverse Ranges, the Santa Monica Mountains are a relatively young mountain range that has a

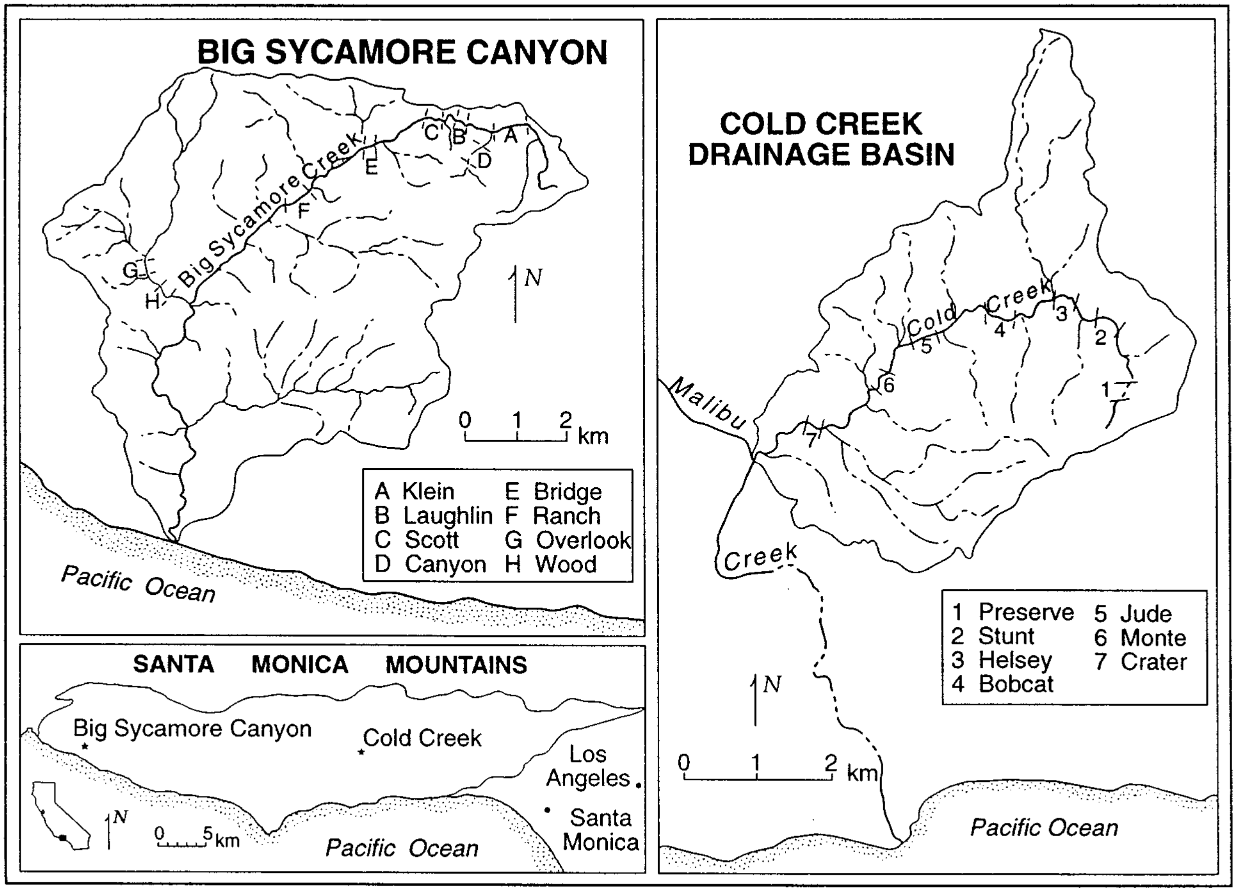

**Figure 2.** Study reaches in the Santa Monica Mountains, California.

complex geology and a varied physical geography. The mountains are composed of primarily Tertiary age sedimentary rocks (shales, sandstones, and conglomerates), although scattered patches of igneous rocks are also found (Wilson 1955; Bass 1960; Yerkes and Campbell 1980). The Mediterranean climate is characterized by warm, dry summers and mild, rainy winters, with some 85% of the rainfall occurring between November and April. Chaparral dominates the vegetation above elevations of about 250 m, whereas coastal sage scrub is the typical community at lower elevations (O'Leary 1981).

The study focuses on two small basins that drain eventually to the Pacific Ocean: Cold Creek and Big Sycamore Canyon (figure 2). Cold Creek is a perennial stream with a drainage area of approximately 25 km$^2$, ranging in elevation from 855 m to 134 m where it joins Malibu Creek. Seven study reaches along Cold Creek were examined, ranging in length from 169 m to 273 m and in slope from 0.014 to 0.115 (figure 2; table 1). Similarly, the eight study reaches in Big Sycamore Canyon range from 125 m to 270 m in length, and from 0.013 to 0.096 in slope. At the westernmost end of the Santa Monica Mountains, the seasonally wet watershed of Big Sycamore Creek drains some 55 km$^2$ of rugged terrain from a peak elevation of 846 m to sea level at the outlet to the Pacific Ocean. Overall, the Cold Creek and Big Sycamore Creek study reaches are comparable in size, elevation, slope, channel width, and bed material size. The two basins are also representative of other watersheds in the Santa Monica Mountains in terms of geology, climate, and vegetation. They provided a sample of 360 step-pool sequences for this investigation (166 from Cold Creek and 194 from Big Sycamore Canyon). The rhythmic nature of these sequences suggests fluvial transport (figure 1), particularly as there is no clear evidence of debris flows or structural control in the channels.

## Methods

Because step-pools are generally formed by high-magnitude, low-frequency floods that are difficult to observe (Whittaker and Jaeggi 1982; Grant et al. 1990), the analysis relied on hydraulic calculations to recreate mathematically the flow conditions nec-

**Table 1.** Characteristics of Study Reaches

| | Reach | Length (m) | Slope ($mm^{-1}$) | Channel Width (m) | Rock Size[a] (mm) | Drainage Area ($km^2$) |
|---|---|---|---|---|---|---|
| Cold Creek | Preserve | 186 | .115 | 2.5 | 490 | .52 |
| | Stunt | 169 | .063 | 2.5 | 417 | 2.47 |
| | Helsley | 198 | .038 | 2.9 | 313 | 4.19 |
| | Bobcat | 221 | .019 | 3.2 | 365 | 10.48 |
| | Jude | 225 | .033 | 5.6 | 550 | 13.13 |
| | Monte | 218 | .022 | 6.6 | 403 | 14.93 |
| | Crater | 273 | .014 | 6.6 | 208 | 21.62 |
| Big Sycamore Creek | Canyon | 210 | .096 | 3.5 | 493 | 1.24 |
| | Klein | 170 | .050 | 2.2 | 380 | 2.56 |
| | Laughlin | 160 | .047 | 2.4 | 405 | 4.68 |
| | Scott | 270 | .061 | 3.6 | 519 | 5.19 |
| | Bridge | 190 | .036 | 5.5 | 461 | 7.67 |
| | Ranch | 194 | .013 | 5.5 | 290 | 14.06 |
| | Overlook | 125 | .024 | 3.6 | 294 | 8.30 |
| | Wood | 193 | .017 | 4.7 | 305 | 9.48 |

[a] Rock size is the mean representative step particle size in the reach. Representative step particle size is calculated by averaging the b-axis of the five largest rocks comprising each step.

essary for their movement. These calculations determined the threshold of particle mobility in order to assess whether step-pool sequences are products of hydraulic processes under the present flow regime, or relicts of a more intense climatic/hydrologic regime in the past.

Several studies have focused on estimating the critical shear stress needed for particle entrainment in gravel-bed streams using the standard Shields (1936) equation (Baker and Ritter 1975; Church 1978; Carling 1983; Wiberg and Smith 1987). The general conclusion from these studies, however, is that the Shields relationship, designed for uniform sand-sized particles, does not yield good estimates of initial motion for coarse, heterogeneous materials found in gravel- and boulder-bed streams. In these situations, the hiding of small particles and the high exposure of large ones cause heterogeneous particle sizes to have nearly equal mobility (Parker and Klingeman 1982; Andrews 1983; Bathurst 1987). An alternative approach is to use velocity to determine competence, based on the principle that the particle weight or size is proportional to some power of the velocity (Leliavsky 1955). Velocity can be estimated with resistance equations developed for mountain streams (Thorne and Zevenbergen 1986), or by empirical relationships derived from field data. Bradley and Mears (1980) and Costa (1983) provide more detailed background information on theoretical and empirical methods using this approach.

The specific algorithm selected for this study was developed by Costa (1983) for small, steep mountain streams. The methodology retains a physical basis while combining both theoretical equations and empirical relationships by an arithmetic average, resulting in average equations that may be more accurate than any single procedure. A series of computations uses particle size as the independent variable to determine the velocity and depth of flow necessary to initiate movement of step particles: $v = 0.18\, d^{0.487}$, where $d$ = particle size (mm), $v$ = velocity ($msec^{-1}$); depth from family of equations that defines figure 7 in Costa (1983) (i.e., for slope 0.005, $D = 0.012\, d^{0.872}$ where $D$ = average depth (m); for slope 0.010, $D = 0.005\, d^{0.788}$). From these depth and velocity estimates, discharge is calculated by computing cross-sectional area: Q = AV. Following Costa's (1983) recommendation, these procedures were performed for two surveyed cross sections in each study reach to yield an average discharge value.

Once critical discharge was calculated, the final issue in determining step-pool stability was to relate the discharge to a flow frequency. Because neither Cold Creek nor Big Sycamore Creek has stream gauges, the study used regional relationships (Young and Cruff 1967) to obtain an estimation of the frequency of discharges sufficient to initiate movement of particles comprising steps. Flood frequency-magnitude in the Santa Monica Mountains is a function of drainage area, altitude, and mean annual precipitation.

Field measurements of particle size, cross-sectional dimensions, and average bed slope yielded data for the paleohydraulic computations. The b-axes of the five largest rocks at each step were measured, and the average was used in the analysis to represent step particle size. This value approximates a particle size of $d_{84}$ (84th percentile) or $d_{90}$ (90th percentile) (Costa 1983) and is generally assumed to be the framework particles that must move to mobilize coarse bedload channels (Jackson and Beschta 1982; Reid and Frostick 1984). Standard surveying techniques provided channel dimensions; the average bed slope was used to approximate the energy slope at high flow.

The three stated research questions will be addressed. First, results of the paleohydraulic analysis are presented to answer the basic question of whether step-pools are formed by flows under the present hydrologic regime. Second, these results are interpreted over a range of space and time scales to define the stability of step-pools. Statements on step-pool stability provide insights on their role and function in the fluvial system, which are discussed in the last portion of the paper.

## Results of Hydraulic Calculations

Tables 2 and 3 present results of the paleohydraulic analysis for particle sizes ranging from 100 to 1000 mm in each study reach. The sizes of 100–1000 mm essentially cover the entire range of representative particles comprising steps in all the study reaches, except in several cases where boulders averaged more than 1 m (figure 3). The tables show that in Cold Creek, flows ranging from 0.6 to 295.5 $m^3sec^{-1}$ are capable of moving step boulders of up to 1 m diameter. Similarly, the Big Sycamore reaches require critical flows of 1.3 to 284.9 $m^3sec^{-1}$ for bed motion to occur. These values correspond to recurrence intervals of 2 to 192 years in Cold Creek, and 2 to 200 years in Big Sycamore Creek (Young and Cruff 1967). Thus, movement of steps in the study reaches is possible within 200 year periods, the frequency depending on the sizes of particles comprising steps.

Because the range of recurrence intervals computed for both Cold Creek and Big Sycamore Creek is similar (2 to 200 years), bed motion in the two creeks, and thus for the Santa Monica Mountains, can be generalized by describing the range of recurrence intervals associated with critical flow causing movement of each step particle size (figure 4). Thus, for steps comprised of 200 mm rocks, movement occurs on the order of 5 to 15 years, the variations caused by differences between channel reaches. Steps with the median rock size or smaller (about 400 mm for the two creeks; figure 3) are restructured every 15 to 50 years. Only the smallest steps (those comprised of particles smaller than 200 mm, representing <5% of all steps in study reaches [figure 3]) are expected to move more frequently than every 5 years. On the other hand, only the largest steps composed of 1 m boulders or larger remain stable for long periods of 100–200 years. Because these large steps comprise <5% of the study sample (figure 3), one can further conclude from the previous analysis that step-pool sequences in Cold and Big Sycamore Creeks are generally restructured within 5–100 years. Figure 5 further illustrates the point that steps in the Santa Monica Mountains are likely to be restructured by relatively frequent flows.

These results are compatible with those reported by Hayward (1980), Best and Keller (1985), Whittaker (1987), and Grant et al. (1990). They are also supported by field observations in the Santa Monica Mountains and elsewhere, where small steps have been observed to break down during floods (Hayward 1980; Gintz et al. 1996). Therefore, contrary to Miller (1958), and despite skepticism by Mosley (1987), these results strongly suggest that step-pools are adjustable features formed under the present hydrologic regime.

## On the Stability of Step-Pool Channels

Given that movement of step particles generally occurs within the wide range of 5 to 100 years, the step-pool channel can be considered stable or unstable depending on the distribution of step particle sizes in the study reaches. The channel may be extremely stable if large steps on the order of 1 m dominate, or relatively unstable if steps are composed of rocks primarily in the 200–300 mm range. Because the largest rocks are generally found in the steep headwaters, Preserve and Canyon reaches in Cold Creek and Big Sycamore Creek, respectively, are among the most stable reaches, with movement expected to occur on the order of 30 to 80 years (figures 2, 4). On the other hand, channel restructuring is possible as frequently as every 4 or 5 years in the lower reaches of Crater and Ranch, where step particle sizes are generally smaller. To the extent that average step-particle size decreases in a downstream direction (table 1), one can expect the frequency of channel restructuring to increase correspondingly.

While the frequency of bed motion for an entire channel can be described in a general or probabilistic way, a more detailed scenario is that, within a given study reach, a variation of step particle sizes exists and there is differential movement that results in both stability and instability within a particular reach. In the extreme case, stable locations are those where bedrock and relatively immobile

**Table 2.** Calculated Hydraulic Variables at Incipient Motion, Cold Creek

| Reach | Part Size (mm) | Velocity (msec$^{-1}$) | Depth (m) | Qcrit (m$^3$sec$^{-1}$) | R.I. (year) | Reach | Part Size (mm) | Velocity (msec$^{-1}$) | Depth (m) | Qcrit (m$^3$sec$^{-1}$) | R.I. (year) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Preserve | 100 | 1.70 | .19 | .6 | 3 | Bobcat | 600 | 4.06 | 1.58 | 97.6 | 67 |
| | 200 | 2.38 | .33 | 1.6 | 7 | (cont'd) | 700 | 4.37 | 1.79 | 120.1 | 91 |
| | 300 | 2.90 | .45 | 4.0 | 19 | | 800 | 4.67 | 2.00 | 143.9 | 100 |
| | 400 | 3.33 | .56 | 7.2 | 31 | | 900 | 4.94 | 2.20 | 168.8 | 125 |
| | 500 | 3.71 | .67 | 10.5 | 40 | | 1000 | 5.20 | 2.41 | 194.8 | 141 |
| | 600 | 4.06 | .77 | 14.3 | 53 | Jude | 100 | 1.70 | .31 | 2.6 | 2 |
| | 700 | 4.37 | .87 | 18.7 | 63 | | 200 | 2.38 | .55 | 13.7 | 7 |
| | 800 | 4.67 | .97 | 23.4 | 77 | | 300 | 2.90 | .76 | 32.5 | 19 |
| | 900 | 4.94 | 1.06 | 28.8 | 83 | | 400 | 3.33 | .96 | 48.9 | 29 |
| | 1000 | 5.20 | 1.16 | 34.5 | 100 | | 500 | 3.71 | 1.16 | 66.5 | 40 |
| Stunt | 100 | 1.70 | .21 | 1.0 | 2 | | 600 | 4.06 | 1.35 | 85.8 | 53 |
| | 200 | 2.38 | .36 | 3.0 | 2 | | 700 | 4.37 | 1.53 | 106.5 | 63 |
| | 300 | 2.90 | .50 | 7.1 | 11 | | 800 | 4.67 | 1.70 | 128.7 | 77 |
| | 400 | 3.33 | .63 | 14.6 | 26 | | 900 | 4.94 | 1.88 | 152.2 | 93 |
| | 500 | 3.71 | .75 | 20.9 | 35 | | 1000 | 5.20 | 2.05 | 176.9 | 106 |
| | 600 | 4.06 | .87 | 28.6 | 46 | Monte | 100 | 1.70 | .36 | 4.9 | 3 |
| | 700 | 4.37 | .98 | 36.7 | 56 | | 200 | 2.38 | .64 | 18.8 | 8 |
| | 800 | 4.67 | 1.09 | 44.1 | 63 | | 300 | 2.90 | .89 | 40.4 | 26 |
| | 900 | 4.94 | 1.20 | 51.6 | 72 | | 400 | 3.33 | 1.13 | 60.5 | 39 |
| | 1000 | 5.20 | 1.31 | 59.4 | 83 | | 500 | 3.71 | 1.36 | 83.2 | 50 |
| Helsley | 100 | 1.70 | .26 | 1.4 | 2 | | 600 | 4.06 | 1.58 | 108.3 | 67 |
| | 200 | 2.38 | .46 | 6.9 | 8 | | 700 | 4.37 | 1.79 | 135.1 | 84 |
| | 300 | 2.90 | .64 | 14.9 | 19 | | 800 | 4.67 | 2.00 | 162.2 | 105 |
| | 400 | 3.33 | .81 | 25.7 | 33 | | 900 | 4.94 | 2.20 | 190.2 | 127 |
| | 500 | 3.71 | .97 | 37.4 | 46 | | 1000 | 5.20 | 2.41 | 219.4 | 145 |
| | 600 | 4.06 | 1.12 | 47.9 | 56 | Crater | 100 | 1.70 | .49 | 9.5 | 3 |
| | 700 | 4.37 | 1.28 | 58.9 | 67 | | 200 | 2.38 | .88 | 32.7 | 13 |
| | 800 | 4.67 | 1.42 | 70.6 | 80 | | 300 | 2.90 | 1.25 | 57.2 | 27 |
| | 900 | 4.94 | 1.57 | 82.8 | 91 | | 400 | 3.33 | 1.59 | 85.2 | 40 |
| | 1000 | 5.20 | 1.71 | 95.5 | 103 | | 500 | 3.71 | 1.92 | 116.2 | 63 |
| Bobcat | 100 | 1.70 | .36 | 3.6 | 2 | | 600 | 4.06 | 2.24 | 148.5 | 81 |
| | 200 | 2.38 | .64 | 12.1 | 7 | | 700 | 4.37 | 2.55 | 182.7 | 101 |
| | 300 | 2.90 | .89 | 24.4 | 17 | | 800 | 4.67 | 2.86 | 218.7 | 125 |
| | 400 | 3.33 | 1.13 | 45.0 | 36 | | 900 | 4.94 | 3.16 | 256.4 | 161 |
| | 500 | 3.71 | 1.36 | 73.6 | 53 | | 1000 | 5.20 | 3.45 | 295.5 | 192 |

large boulders control channel morphology, as illustrated in a portion of Preserve Reach in Cold Creek (figure 6). These rock steps and large boulder steps are essentially permanent features in the stream channel, which apparently do not respond to hydraulic influences. In between these control points are smaller and less stable steps that move with higher frequency; they represent adjustments to flow and channel conditions.

These results support observations noted earlier by Hayward (1980) who described major and minor patterns of steps and pools. Hayward defined major patterns as those rock steps and riffle steps that control the large-scale channel morphology. Although he did not perform quantitative analyses in this regard, Hayward suggested that these major patterns are stable for periods of 50–100 years. Minor patterns, on the other hand, are composed of boulder steps that Hayward observed to break down every 2–5 years. The unstable minor patterns are superimposed on the major, more permanent ones. Therefore, to the extent that step sizes vary within a channel reach, there will be local spatial patterns of channel stability and instability.

These results suggest that step-pool channels can be either stable or unstable depending on the spatial and temporal scales considered. At a small spatial scale of one step-pool unit, the step is stable within short time spans between critical flows, because stability is entirely determined by the mobility of the rocks that comprise that step. At the larger spatial scale of an entire channel reach, however, both stability and instability exist because of variations in step sizes and frequencies of critical flows. Also, over time, unstable situations result when high-magnitude flows restructure the step-

**Table 3.** Calculated Hydraulic Variables at Incipient Motion, Big Sycamore Creek

| Reach | Part Size (mm) | Velocity (msec$^{-1}$) | Depth (m) | Qcrit (m$^3$sec$^{-1}$) | R.I. (year) | Reach | Part Size (mm) | Velocity (msec$^{-1}$) | Depth (m) | Qcrit (m$^3$sec$^{-1}$) | R.I. (year) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Klein/ Laughlin | 100 | 1.70 | .91 | 1.5 | 3 | Bridge | 100 | 1.70 | .26 | 2.5 | 5 |
| | 200 | 2.38 | .44 | 4.2 | 7 | | 200 | 2.38 | .46 | 6.8 | 11 |
| | 300 | 2.90 | .61 | 7.7 | 18 | | 300 | 2.90 | .64 | 15.8 | 22 |
| | 400 | 3.33 | .77 | 11.8 | 22 | | 400 | 3.33 | .81 | 28.1 | 39 |
| | 500 | 3.71 | .92 | 16.8 | 30 | | 500 | 3.71 | .97 | 43.4 | 56 |
| | 600 | 4.06 | 1.07 | 22.9 | 35 | | 600 | 4.06 | 1.12 | 57.8 | 71 |
| | 700 | 4.37 | 1.21 | 31.5 | 44 | | 700 | 4.37 | 1.28 | 75.1 | 91 |
| | 800 | 4.67 | 1.35 | 45.1 | 56 | | 800 | 4.67 | 1.42 | 91.2 | 101 |
| | 900 | 4.94 | 1.48 | 53.7 | 63 | | 900 | 4.94 | 1.57 | 108.2 | 111 |
| | 1000 | 5.20 | 1.62 | 63.0 | 67 | | 1000 | 5.20 | 1.71 | 126.3 | 122 |
| Scott | 100 | 1.70 | .21 | 1.4 | 2 | Ranch | 100 | 1.70 | .49 | 5.3 | 4 |
| | 200 | 2.38 | .36 | 3.8 | 5 | | 200 | 2.38 | .88 | 24.8 | 19 |
| | 300 | 2.90 | .50 | 7.1 | 8 | | 300 | 2.90 | 1.25 | 48.0 | 35 |
| | 400 | 3.33 | .63 | 16.3 | 22 | | 400 | 3.33 | 1.59 | 74.2 | 53 |
| | 500 | 3.71 | .75 | 25.2 | 31 | | 500 | 3.71 | 1.92 | 103.9 | 72 |
| | 600 | 4.06 | .87 | 36.9 | 46 | | 600 | 4.06 | 2.24 | 136.9 | 94 |
| | 700 | 4.37 | .98 | 46.8 | 56 | | 700 | 4.37 | 2.55 | 173.2 | 111 |
| | 800 | 4.67 | 1.09 | 58.4 | 67 | | 800 | 4.67 | 2.86 | 208.7 | 143 |
| | 900 | 4.94 | 1.20 | 71.4 | 77 | | 900 | 4.94 | 3.16 | 246.0 | 182 |
| | 1000 | 5.20 | 1.31 | 83.0 | 91 | | 1000 | 5.20 | 3.45 | 284.9 | 200 |
| Canyon | 100 | 1.70 | .19 | 1.3 | 5 | Wood/ Overlook | 100 | 1.70 | .36 | 3.7 | 3 |
| | 200 | 2.38 | .33 | 3.4 | 11 | | 200 | 2.38 | .64 | 13.3 | 11 |
| | 300 | 2.90 | .45 | 6.2 | 22 | | 300 | 2.90 | .89 | 26.6 | 27 |
| | 400 | 3.33 | .56 | 12.6 | 39 | | 400 | 3.33 | 1.13 | 41.1 | 39 |
| | 500 | 3.71 | .67 | 20.8 | 56 | | 500 | 3.71 | 1.36 | 58.2 | 53 |
| | 600 | 4.06 | .77 | 29.9 | 71 | | 600 | 4.06 | 1.58 | 77.5 | 71 |
| | 700 | 4.37 | .87 | 40.1 | 91 | | 700 | 4.37 | 1.79 | 95.2 | 91 |
| | 800 | 4.67 | .97 | 49.1 | 101 | | 800 | 4.67 | 2.00 | 113.8 | 102 |
| | 900 | 4.94 | 1.06 | 59.3 | 111 | | 900 | 4.94 | 2.20 | 133.3 | 118 |
| | 1000 | 5.20 | 1.16 | 70.9 | 133 | | 1000 | 5.20 | 2.41 | 153.6 | 135 |

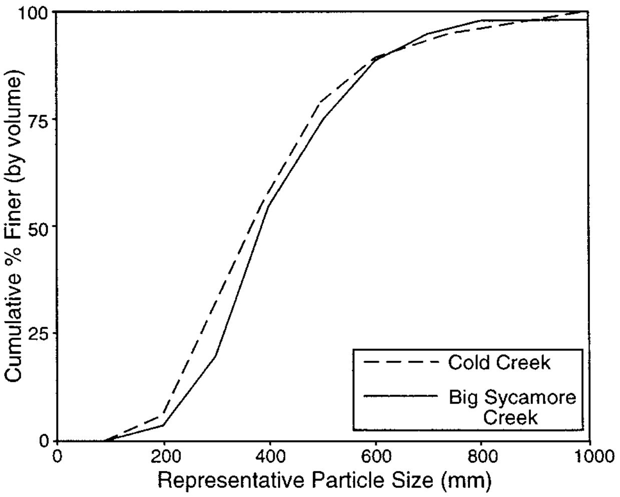

**Figure 3.** Size distribution of representative particles comprising steps. The representative particle size of each step is the average of the five largest rocks (b-axis) comprising the step.

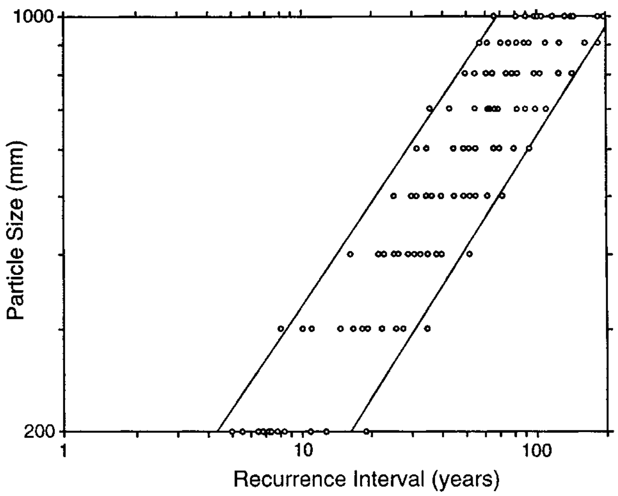

**Figure 4.** Critical flow frequency corresponding to initiation of motion for each particle size. Lower and upper limits determined by regression through lowest and highest points.

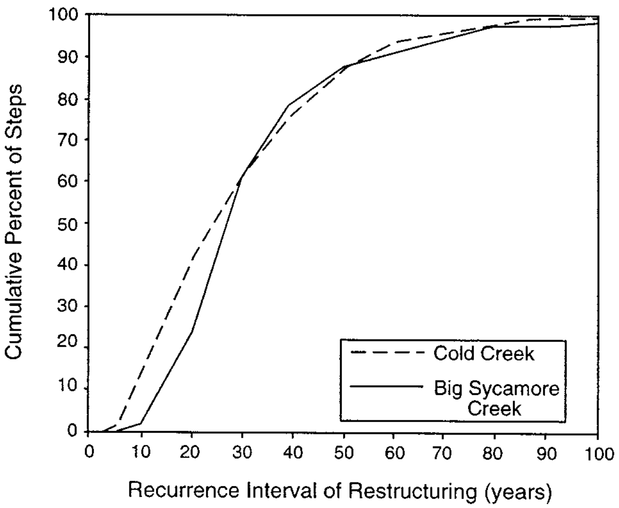

**Figure 5.** Cumulative percent of steps capable of being restructured.

pool channel. Because high-magnitude flows occur at low frequencies, the likelihood of instability increases with increasing timescales.

## On the Significance of Spatial and Temporal Scales

Considerations of step-pool stability over time and space are significant in defining their role in the fluvial system, in linking form and process, and in identifying cause and effect in the development of landforms. The importance of time and space in explaining the behavior of geomorphic systems has been well documented in the seminal paper by Schumm and Lichty (1965), which showed that the distinction between cause and effect depends on the span of time involved and on the size of the system under study. As the dimensions of time and space change, cause and effect relationships may be obscured or even reversed. Dependent variables at one scale may become independent variables at a different scale.

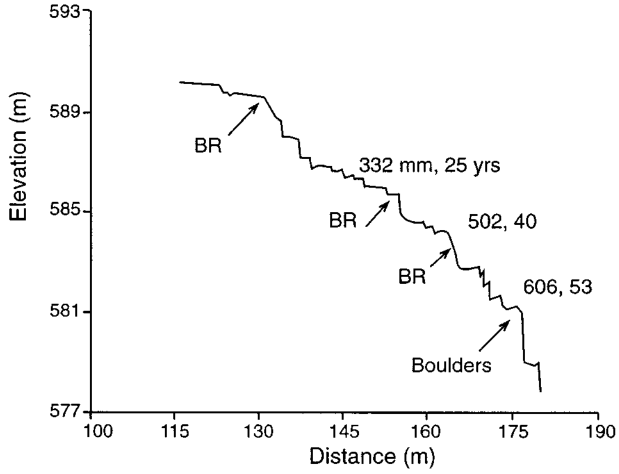

**Figure 6.** Relative channel stability and instability, Preserve Subreach. Arrows indicate bedrock (BR) or 1–2 m boulders. Numbers show mean step particle size (mm) in between control points and frequency of movement of these steps (yrs).

In this context, step-pools are channel morphological variables that act as both dependent and independent variables depending on the time scale of inquiry. At low flow, during short spans of time, the step-pool morphology assumes an independent status that regulates channel hydraulics. As the time scale increases and high-magnitude flows are included, step pools become a dependent variable that responds to discharge and sediment load. Therefore, definition of the time scale at which step-pools are mobilized, and the intervening period during which they remain stable, clarifies their role as independent or dependent variables, and thus the causal relationship between form and process, in the broader context of the evolution of the geomorphic system.

Figure 7 summarizes the role of step-pool bedforms over several temporal and spatial scales, with particular reference to the three time scales defined by Schumm and Lichty (1965). The figure points to the present and modern time scales as having particular relevance for step pools and illustrates the shift from independence to dependence with increasing scales. As independent variables during the short present time of one year or less, step-pools are stable structures that serve the primary function of energy dissipation (Heede 1981; Chin 1989). As dependent variables over the longer portion of modern time from 100–1000 years, when step-pools in the Santa Monica Mtns. are restructured by high-magnitude flows, step-pools are adjustable gravel bedforms that resemble pools and riffles in lower gradient channels. With increasing scales and dependence, therefore, the role of step-pools changes from energy dissipation to one of channel adjustment.

It is during the shorter portion of modern time, between 1–100 years, where a shifting independence and dependence occurs that complicates form and process relationships. Here, the status of independency/dependency depends on step particle size and its frequency of motion: the smaller the step, the higher the likelihood of dependence, the more important the role of channel adjustment. Only the largest steps are capable of maintaining

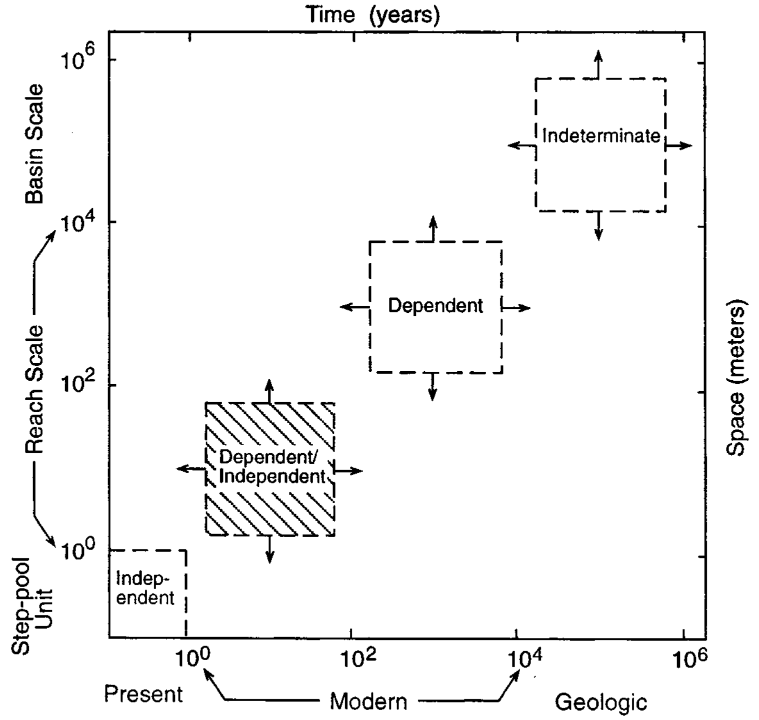

**Figure 7.** Changing role of step pools over space and time.

an independent status through this time span, dissipating stream energy and regulating flow and channel hydraulics. Because stability regime shifts on 1–100 year scales, flow and particle size relationships must be assessed on a case-by-case basis during this time. These results suggest important implications for management and engineering problems in steep mountain areas.

## Conclusions

Analysis of the stability of step-pool sequences in the Santa Monica Mountains, California, indicates that they are generally restructured within 5 to 100 years. While small steps in the lower reaches may have a life-span of only 5 years or less, even the most stable reaches (except bedrock) can be restructured under extreme high flows. Therefore, step-pools are active channel features that are products of the modern hydrologic regime, rather than relicts of a historical past. They are fundamental and adjustable aspects of channel morphology in steep mountain streams, similar in this regard to log steps in forested areas (Marston, 1982). The degree of adjustability in this case depends on the size of the step particles.

Step-pool stability depends on scale and perspective. Steps in the Santa Monica Mountains can be immobile during the present and modern time scales (up to 100 years), confirming Church and Jones's (1982) statement that they are stable for periods comparable to "regime" time. Because field observations have been made within short time spans and over small spatial scales, workers have generally emphasized the stability of step-pools (i.e., O'Loughlin 1969; Whittaker 1987; Schmidt and Ergenzinger 1992) and the primary function of energy dissipation (Heede 1981; Chin 1989). However, instability increases with increasing scales, and their role as bedforms that respond to discharge and sediment load becomes increasingly important at increasing timescales. Therefore, larger spatial and temporal scales are needed to reveal the complete function and significance of step-pools in mountain fluvial systems.

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