

THE PERIODIC NATURE OF STEP-POOL MOUNTAIN STREAMS

ANNE CHIN

Department of Geography, College of Geosciences, Texas A&M University,
College Station, Texas 77843-3147

ABSTRACT. Rhythmic sequences of steps and pools in steep mountain streams have captured the attention of numerous workers, but whether periodicities exist in the occurrence of step-pools has not been investigated in a comprehensive way, and the implications for such periodicities have not been explored. Spectral analysis was applied to bed elevation data from streams in the Santa Monica Mountains of southern California to investigate periodicity in the occurrence of step-pools. Results indicate significant step-pool periodicities, confirmed by independent field measurements, that vary from 0.43 channel widths to 2.40 channel widths. Spectral analysis of channels affected by external influences tends to indicate multiple significant peaks that reflect higher variance in step-pool spacing. Underlying periodicities are nevertheless detected, suggesting that external factors obscure but do not destroy the effects of more general internal mechanisms.

Periodicity in the occurrence of step-pools suggests that step-pools are bedforms that represent a fundamental mutual adjustment between flow, channel morphology, and energy expenditure. A rhythmic channel thalweg supports the notion that step-pools are analogous to meandering in the vertical dimension, and implies that, because step-pool channels are not able to adjust energy expenditure in the plane dimension, they instead adjust boundary roughness in the vertical dimension. A continuum of rhythmic gravel bedforms that displays the results of such adjustments, and that shows how step-pools merge into pools and riffles in the stream channel system, is discussed and illustrated with empirical data from the Santa Monica Mountains. Although many differences exist between steep mountain streams and broad alluvial rivers, the findings of this study suggest that generalized principles of uniform energy expenditure may also apply to rhythmic step-pool streams. These findings are potentially valuable in the management and design of steep channels.

INTRODUCTION

Steps and pools are fundamental components of channel morphology in high-gradient mountain streams. Step-pools commonly form in channels with slopes exceeding 2 percent and material size in the gravel to boulder range (Grant and others, 1990; Montgomery and Buffington, 1997; Chin, 1999a). Cobbles and boulders generally compose the steps, which alternate with finer sediments in pools to produce a repetitive, staircase-like longitudinal profile in the stream channel (fig. 1). Despite their striking appearance and common occurrence in a wide range of high-gradient environments (Chin, 1989), step-pools have been relatively neglected in fluvial geomorphological research compared to pools and riffles in lower gradient rivers. Recent efforts have provided insights on morphological relationships (Wohl and others, 1997; Chin, 1999a; Chartrand and Whiting, 2000), velocity characteristics (Wohl and Thompson, 2000), step-pool stability (Chin, 1998), and the origin of step-pool sequences (Grant and Mizuyama, 1991; Abrahams and others, 1995; Chin 1999b; Chartrand and Whiting, 2000). However, a complete explanation of step-pool sequences has not yet been achieved, and the significance of the step-pool system in the broader context of stream behavior has not been fully articulated. Because the step-pool morphology dominates 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, a better understanding of steps and pools is critical in explaining the inner workings of the general fluvial system. As development and land use pressures increase in mountainous areas, improved understanding of the step-pool

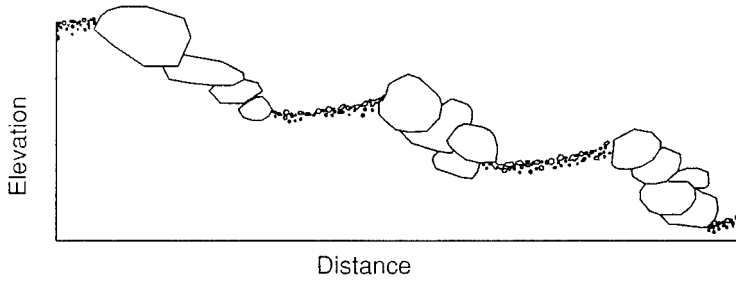


Fig. 1. Longitudinal profile of step-pool sequences (after Chin, 1989).

bedform would also facilitate more effective management of high-gradient stream environments.

This paper addresses the fundamental question of periodicity in the occurrence of steps and pools in high-gradient channels. The striking, rhythmic character of the step-pool streambed has long captured the attention of previous workers (for example, Judd, 1964; Wertz, 1966; Newson and Harrison, 1978), but whether step-pools are truly periodic bedforms has not been investigated in a comprehensive way, and the implications for such periodicities have not been explored. The identification of a step-pool periodicity has important implications for the nature of fluvial adjustments in steep mountain drainage basins. Mountain channels are strongly coupled to adjacent hillslopes and are prone to external forcings such as bedrock, debris, and vegetation (Miller, 1958; Furbish, 1985, 1998; Lisle, 1986; Nakamura and Swanson, 1993; Montgomery and others, 1995; Montgomery and Buffington, 1997; Wohl, 2000a). Internal mutual adjustments are difficult to achieve, as cobbles and boulders that comprise the mountain streambed are infrequently mobilized (Grant and others, 1990; Chin, 1998), and sediment transport is episodic owing to limited sediment supply (Schmidt and Ergenzinger, 1992; Whittaker, 1987). Nevertheless, despite possible external influences, the detection of an underlying periodicity in step-pools would suggest that step-pools are bedforms that represent a fundamental mutual adjustment between flow and channel morphology. Periodicity implies a strong internal mechanism that is not entirely masked by external influences, and a regularity that reflects a spatial organization in coarse-grained alluvial channels.

The existence of a step-pool periodicity is also of considerable interest in regards to general river behavior because the development of rhythmic thalweg morphology in steep channels would suggest that meandering in the third, or vertical, dimension also operates in these streams. Many authors have suggested that the development of pools and riffles represents a tendency toward third-dimension meandering that is analogous to horizontal meandering (Leopold and others, 1964; Richards, 1976; Keller and Melhorn, 1978). Keller and Melhorn (1978) further suggested that vertical meanders may be manifested in diverse examples in addition to pools and riffles, including undulating bottom topography in supraglacial streams, and even stepped topography in glacial valleys, reflecting a more general phenomenon when one material flows differentially over another. In this regard, step-pool sequences may be an equivalent of third-dimension meandering because flow and streambed oscillations are primarily vertical in such channels. As confined mountain valleys prohibit horizontal meandering and braiding, the role of step-pools is analogous to the energy dissipation associated with lateral adjustments in alluvial, low-gradient streams (Chin, 1989). Thus, demonstrating that the step-pool channel thalweg is rhythmic would support the view that step-pools, like other rhythmic bedforms, are analogous to meandering in the

vertical dimension. Because meandering is considered to be a fundamental style of behavior of natural streams (Leopold and others, 1964), understanding the periodic nature of step-pool channels would add considerably to our knowledge of mountain streams in fluvial geomorphology. Improved understanding of step-pool periodicities would also be potentially valuable in the management and design of steep channels.

The existence of a possible periodicity in the occurrence of step-pool sequences was first suggested by Wertz (1966) in a study of ephemeral mountain streams in the southwestern United States. Wertz (1966) described the characteristic pattern of desert mountain streams as composed of alternating rugged segments with large boulders and flat, horizontal segments covered with sand, a sequence he termed "stepping". He recognized possible spatial relationships between such steps and pools and performed non-parametric statistical tests to investigate periodicity. However, Wertz (1966) did not obtain statistically significant results, and suggested that numerous external factors, such as vegetation, bedrock outcrops, and channel bends would probably inhibit step-pools from occupying an ideal sequence in the natural environment.

Although numerous workers have since documented the role of external local controls on channel morphology (Zimmerman and others, 1967; Best and Keller, 1985; Grant and others, 1990), including cases where such influences have promoted the formation of randomly spaced pools (Meyer and Swanson, 1994, 1996; Keller and Swanson, 1979; Lisle, 1986; Gregory and others, 1994; Montgomery and others, 1995; Wood-Smith and Buffington, 1996), recent work has also given reason to believe that the probability for step-pool periodicities would be high. Hydraulic calculations (Grant and others, 1990; Wohl and others, 1997; Chin, 1998) and field observations (Hayward, 1980; Gintz and others, 1996) have clearly shown that step-pools are theoretically capable of being mobilized by flows as frequently as every 2-5 years. Therefore, except for systems that are relicts of past glacial processes (for example, Miller, 1958; Furbish, 1985; Trayler and Wohl, 2000), step-pools are adjustable bedforms under the present hydrologic regime. Detailed field measurements have also yielded morphological relationships with slope that show step-pools as an integral part of the hydraulic geometry of mountain streams (Hayward, 1981; Heede, 1981; Wohl and Grodek, 1994; Wohl and others, 1997). Furthermore, although step-pool spacing is not invariant, data from step-pool streams in Oregon (Grant and others, 1990), Alaska and Washington (Montgomery and others, 1995), and California (Chin, 1989, 1999a), have suggested a tendency toward systematically regular step-pool spacing, ranging from less than one to four channel widths. These findings provide ample indication that the spatial organization of step-pools is not random, and that, given the tendency for regular spacing, the probability for periodicities is high. This paper therefore re-examines the question of periodicity in step-pool sequences. This investigation utilizes spectral analysis, a powerful statistical technique that has been successful in the detection of periodicities in pools and riffles (Richards, 1976) and meanders (for example, Hooke, 1984), to test for periodicity in step-pools. Spectral analysis represents a new approach to characterizing the step-pool geometry at the reach scale, and it has the potential of generating new insights into the nature of channel adjustments in the broader context of stream behavior.

This paper addresses three research questions. First, do step-pools exhibit a periodicity that can be detected by spectral analysis? The tendency toward regular spacing suggests so, but, does step-pool spacing manifest itself in a periodic trend in bed elevation? Second, how may external factors such as boulders and vegetation affect step-pool periodicity? Specifically, are the internal signals sufficiently strong in step-pool sequences to be detected despite external influences? Third, what are the implications of a step-pool periodicity with regard to more general river behavior?

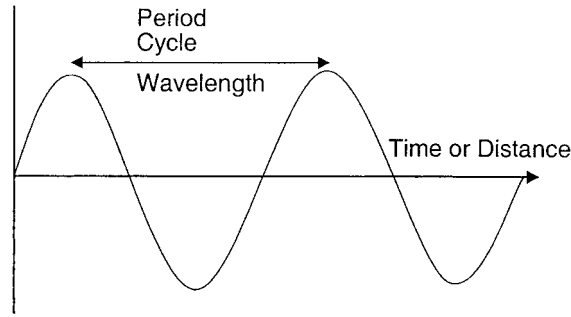


Fig. 2. Terminology.

This analysis adopts the standard terminology used to describe sinusoidal curves (Rayner, 1971). The term wavelength refers to the distance between similar points on the curve (for example, from crest to crest or trough to trough) (fig. 2). Therefore, applied to step-pool sequences, the wavelength is the distance between successive steps or successive pools. Where the horizontal axis is time, the terms period and cycle are usually used in place of wavelength. For the purposes of the following discussion, the terms period (periodicity) and cycle (cyclicity) are used interchangeably with wavelength as applied to successive steps and pools. The periodicity (cyclicity) of steps would be the same as the periodicity of pools in a given reach, since the distance between successive steps would be the same as that between successive pools. Although this definition of periodicity (wavelength) differs somewhat from those used by some workers to describe step-pool spacing (for example, Grant and others, 1990; Wohl and others, 1997), it is consistent with Chin (1989, 1999a) and Abrahams and others (1995), as well as with definitions for pool-riffle (Keller and Melhorn, 1978) and sand bedform spacing (Allen, 1982). This definition thus facilitates interpretation in the larger context of fluvial bedforms as well as application of spectral analysis. Although differing slightly in absolute values, these definitions should not affect the general conclusions of this study or hinder cumulative generalizations concerning the nature of step-pool bedforms.

STUDY AREA

This investigation was conducted in the Santa Monica Mountains of southern California (fig. 3). Part of the east-west trending Transverse Ranges, the Santa Monica Mountains had the advantage of relatively easy access to the steep rugged basins through numerous state parks and natural preserves. The steep channels contain well-developed steps and pools, and there are sufficient undisturbed stream segments with adequate length for spectral analysis (10 to 20 times the mean step-pool wavelength (Nordin, 1971). The Santa Monica Mountains were also the site of previous step-pool studies that evaluated the stability (Chin, 1998), morphological relationships (Chin, 1999a), and step-pool origin (Chin, 1999b). These studies therefore provided useful background to the present analysis; more descriptions of the general geology and physical geography of the Santa Monica Mountains are also found therein.

This study focuses on two small basins that drain into the Pacific Ocean: Cold Creek and Big Sycamore Creek (drainage areas $\sim 25 \text{ km}^2$ and $\sim 55 \text{ km}^2$, respectively) (fig. 3). Seven study reaches within the Cold Creek basin were examined, ranging from 169 to 273 m in length and 0.014 to 0.115 m/m in slope (table 1). All contain clearly identifiable steps and pools except Crater Reach where riffle-pools are the dominant form. Crater Reach was nevertheless included to enable a sampling of the

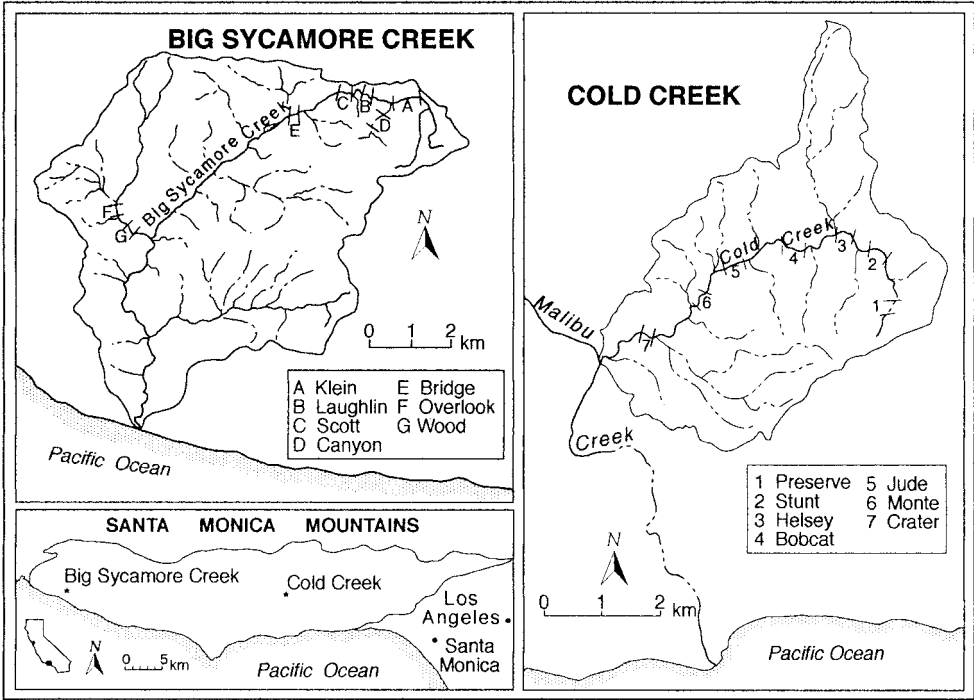


Fig. 3. Study reaches in Study Creek and Big Sycamore Creek.

TABLE 1
Characteristics of study reaches

	Reach	Length (m)	Slope (m/m)	Channel Width (m)	Rock Size* (mm)	Drainage Area (km ²)
COLD CREEK	Preserve	186	0.115	2.5	490	0.52
	Stunt	169	0.063	2.5	417	2.47
	Helsley	198	0.038	2.9	313	4.19
	Bobcat	221	0.019	3.2	365	10.48
	Jude	225	0.033	5.6	550	13.13
	Monte	218	0.022	6.6	403	14.93
	Crater	273	0.014	6.6	208	21.62
BIG SYCAMORE CREEK	Canyon	210	0.096	3.5	493	1.24
	Klein	170	0.050	2.2	380	2.56
	Laughlin	160	0.047	2.4	405	4.68
	Scott	270	0.061	3.6	519	5.19
	Bridge	190	0.036	5.5	461	7.67
	Overlook	125	0.024	3.6	294	8.30
	Wood	193	0.017	4.7	305	9.48

*Calculated by averaging the b-axis of the five largest rocks at each step.

entire downstream length of Cold Creek for comparison. In Big Sycamore Creek, the study focused on five channel reaches in the steep upper watershed exhibiting characteristic step-pool morphology, with two additional tributary reaches contributing data for the analysis. The seven Big Sycamore reaches range from 125 to 270 m in length and 0.017 to 0.096 m/m in slope (table 1). 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 others in the Santa Monica Mountains in terms of geology, hydrology, climate, and vegetation.

The Santa Monica Mountains are similar to many low-altitude mountain basins in the southwestern United States, but they differ from other mountain watersheds in the western United States in two notable aspects. First, unlike high-altitude mountains such as the Colorado Front Range and the Sierra Nevada Mountains, the Santa Monica Mountains had not been affected by past glaciation. Second, different from other forested basins, such as those in the Pacific Northwest, channels in the Santa Monica Mountains are for the most part devoid of large woody debris, because of the nature of the chaparral vegetation that is present (O'Leary, 1981). Therefore, as fluvial processes are not masked by prior glacial signatures or obscured by coarse woody debris, except in the most remote headwaters in some cases, these channels potentially enable internal fluvial mechanisms to be more easily detected than those in other environments.

METHODS

The approach in this study was to apply spectral analysis, a powerful tool to examine periodicity in natural phenomena, to test for periodicities in step-pool sequences. Spectral analysis belongs to a family of time series analytic techniques whose aim is to uncover trends or patterns in a sequence of data over time. By extending the temporal methods and substituting space for time, one dimensional spatial data can also be analyzed by these techniques (Granger, 1969; Bennett, 1979; Richards, 1981). Examples of this application are the determination of objective wavelengths in meanders (Speight, 1965, 1967; Chang and Toebes, 1970; Ferguson, 1975; Hooke, 1984), pools and riffles (Richards, 1976), gravel bedforms (Naden, 1987), and pools caused by coarse woody debris (Nakamura and Swanson, 1993). These successful applications suggest that spectral analysis may be a useful test for periodicity in step-pool sequences as well. Spectral analysis also provides a method of extracting the step-pool wavelength objectively from systematic measurements of bed elevation, as an alternative to the common procedure of measuring step-pool spacing with a tape.

Spectral analysis partitions the variation in a time (or spatial) series into components according to the duration or length of the intervals within which the variation occurs. The analysis is based on the Fourier theory that almost any function of a real variable can be represented as the sum of sines and cosines. Any wave form, regardless of how complex, can be described by an expression of the Fourier relationship:

$$Y = a[k] \cos(k\theta) + b[k] \sin(k\theta) \quad (1)$$

where $a[k]$ is the amplitude, k is the phase angle, θ is the angle, and $b[k]$ is the harmonic number, or number of cycles per basic interval. Since the sum of all the sinusoids is equal to the original time (or spatial) series, the sum of the variation in all of the sinusoids represents the total variation in the series. Spectral analysis isolates the harmonics present and partitions the variance according to frequency. The results are summarized in a power spectrum (spectral density function) which indicates the variance accounted for by fluctuations at the different frequencies. Rayner (1971) and Davis (1986) provide more detailed explanations of spectral analysis for geologic research.

This study considered bed elevation as a function of distance along a channel. To obtain the necessary data, longitudinal profiles of the study reaches were surveyed in the field with an automatic level and stadia rod. Four important requirements for spectral analysis guided field measurements and data preparation. First, the sampling interval had to be carefully chosen for proper resolution because an interval that is too close or too far apart can result in wasting frequency bands on frequencies that exhibit negligible oscillation intensity (Speight, 1965; Bennett, 1979). Bennett (1979) suggested an appropriate data interval to be one with at least three but preferably six samples per period, while Nordin and Algert (1966) recommended 10 to 12 observations per bedform wavelength with a minimum of 50 total observations. Based on these guidelines, along with field observations of the step-pool spacing in the Santa Monica Mountains (Chin, 1989, 1999a), an initial sampling interval of 0.5 m was chosen at which elevation was measured along the channel thalweg. Second, because it was important to document the profiles accurately, especially at steps and pools, additional elevation points were measured at step crests and at the deepest parts of the pools, and at other breaks in slopes, if these locations did not coincide with the 0.5 m intervals. Third, spectral analysis requires equally spaced data. Therefore, by interpolation, equally spaced data were extracted from the surveyed profiles. Because the closest two original measured elevation points were 0.2 m apart, the interpolation procedure yielded final data sets at an interval of 0.2 m. Initial trial runs were performed for reaches in Big Sycamore Creek with data at both the interpolated 0.2 m interval and the original 0.5 m interval to check for consistency. The same statistical results were obtained in all cases.

Finally, detrending the longitudinal profiles was necessary in order to satisfy the stationarity assumption for spectral analysis. According to Granger (1969), stationarity means that the data mean and variance are constant over the distance series, and the covariance between any two terms depends only on the spacing between them and not on absolute distance. For stream channels, this assumption is invariably violated because elevation points do not fluctuate around a constant mean over a given reach, but decreases downstream. The decreasing downstream slope therefore must be removed prior to analysis. Several methods have successfully removed non-stationarity in stream channels, including polynomial regression and subtraction where regression residuals (from distance and elevation data) are used rather than original elevation data points (Chang and Toebe, 1969; Squarer, 1970; Church, 1972; Mulla, 1988; Brook and Hanson, 1991). Granger and Hatanaka (1964) have shown that this method does not significantly affect the spectral estimates of frequency bands. In light of successful applications to similar pool-riffle streams (Richards, 1976), the regression and subtraction method was used in this study. In most cases, simple linear downstream slopes in the study reaches were successfully removed, although difficulties with eliminating non-stationarity in long series (Speight, 1965) limited the lengths of some of the reaches in this analysis.

To confirm that the dominant periodicities detected by spectral analysis are associated with step-pool sequences, the spectral peak wavelengths were compared with wavelengths obtained by independent field measurements in the Santa Monica Mountains. Such data were available from a previous analysis of step-pool characteristics, in which Chin (1999a) measured the pool-to-pool wavelengths of 464 sequences (each composed of one step and pool) in the Cold Creek and Big Sycamore Creek study reaches (table 2). These data allowed an evaluation of whether spectral peak wavelengths correspond to those of step-pool sequences. They were also useful in assessing the role of external factors in affecting a possible step-pool periodicity.

The results are discussed in three parts. First, results of the spectral analysis are presented to address the basic questions of whether a periodicity exists in step-pool

TABLE 2
*Pool-to-Pool Wavelengths**

	Reach	Avg.	Std. Dev.	Coeff.Var.	n
COLD CREEK	Preserve	3.87	4.19	1.08	48
	Stunt	3.95	3.33	0.84	42
	Helsley	4.23	2.05	0.48	45
	Bobcat	5.20	2.77	0.53	39
	Jude	7.45	7.63	1.02	30
	Monte	6.86	8.58	1.25	27
BIG	Canyon	5.19	3.48	0.87	37
SYCAMORE	Klein	4.38	2.05	0.39	33
CREEK	Laughlin	5.03	1.81	0.36	29
	Scott	5.77	2.71	0.47	38
	Bridge	4.81	2.63	0.55	40
	Overlook	4.99	3.30	0.66	28
	Wood	6.99	5.15	0.74	28

*Original data from Chin (1999a).

sequences and whether spectral analysis is capable of detecting such a periodicity. Second, these results are interpreted in light of the role of external factors in affecting the step-pool periodicity. The last portion of the paper explores the implications of a step-pool periodicity for fluvial geomorphology, and includes discussions on rhythmic bedforms and fluvial adjustments in the context of general stream behavior.

RESULTS OF SPECTRAL ANALYSIS

Results of the spectral analysis show a distinct periodic character in the longitudinal bed profiles of the study reaches (fig. 4; table 3). Statistically significant spectral peaks (at 0.05 level) are detected in all but one of the thirteen step-pool reaches; several reaches exhibit more than one significant peak. Dominant frequencies range in Cold Creek from 0.15 cycles/m (Jude Reach) to 0.36 cycles/m (Preserve Reach), whereas they vary from 0.14 cycles/m (Scott Reach) to 0.47 cycles/m (Canyon Reach) in Big Sycamore Canyon. These frequencies correspond to wavelengths (1/frequency) ranging in Cold Creek from 2.8 to 6.9 m, and from 2.1 to 7.1 m in Big Sycamore Canyon. When these spectral peak wavelengths are standardized by the average active channel width, table 3 further shows that the periodic spacing ranges from 0.43 channel widths (Monte) to 2.16 channel widths (Helsley) in Cold Creek, and from 0.60 channel widths (Canyon) to 2.40 channel widths (Laughlin) in Big Sycamore Creek. As these values are generally compatible with previous reports that step-pool spacing is of the order of one to two channel widths (Bowman, 1977; Whittaker and Jaeggi, 1982; Whittaker 1987; Montgomery and others, 1995; Chin, 1989, 1999a), they suggest, at least initially, that the periodicities detected by spectral analysis reflect those of step-pool oscillations in the streambed.

To confirm that dominant periodicities detected by spectral analysis are associated with step-pools, the spectral peak wavelengths are compared to those previously obtained by independent field surveys in the Santa Monica Mountains (table 2). The

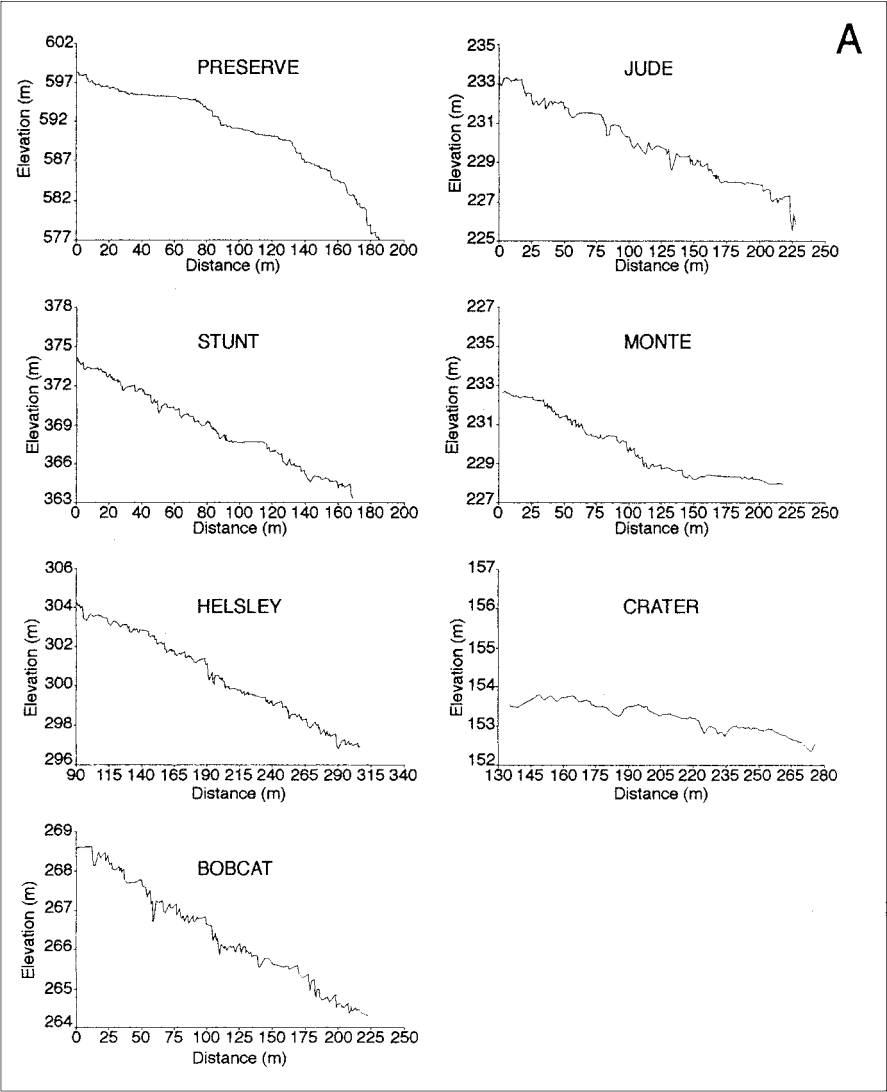


Fig. 4. Longitudinal profile of study reaches. A. Cold Creek; B. Big Sycamore Creek.

following discussion refers to the wavelength extracted by spectral analysis as “spectral wavelength,” while the average step-pool wavelength obtained from field measurements is designated “average wavelength.” “Average wavelength” or “average spacing” are terms that have been used in previous studies to refer to the average separation distance between step-pool features (Hayward, 1980; Heede, 1981; Whittaker, 1987; Grant and others, 1990; Chin, 1989; Abrahams and others, 1995). Here, the average wavelength represents the sloped distance between two successive trough points (pool-to-pool), as measured in the field (Chin, 1999a).

Theoretically, one would expect the spectral wavelength to vary somewhat from the average wavelength because they represent slightly different measures. Spectral analysis detects the underlying dominant wave form existing in a sequence of data.

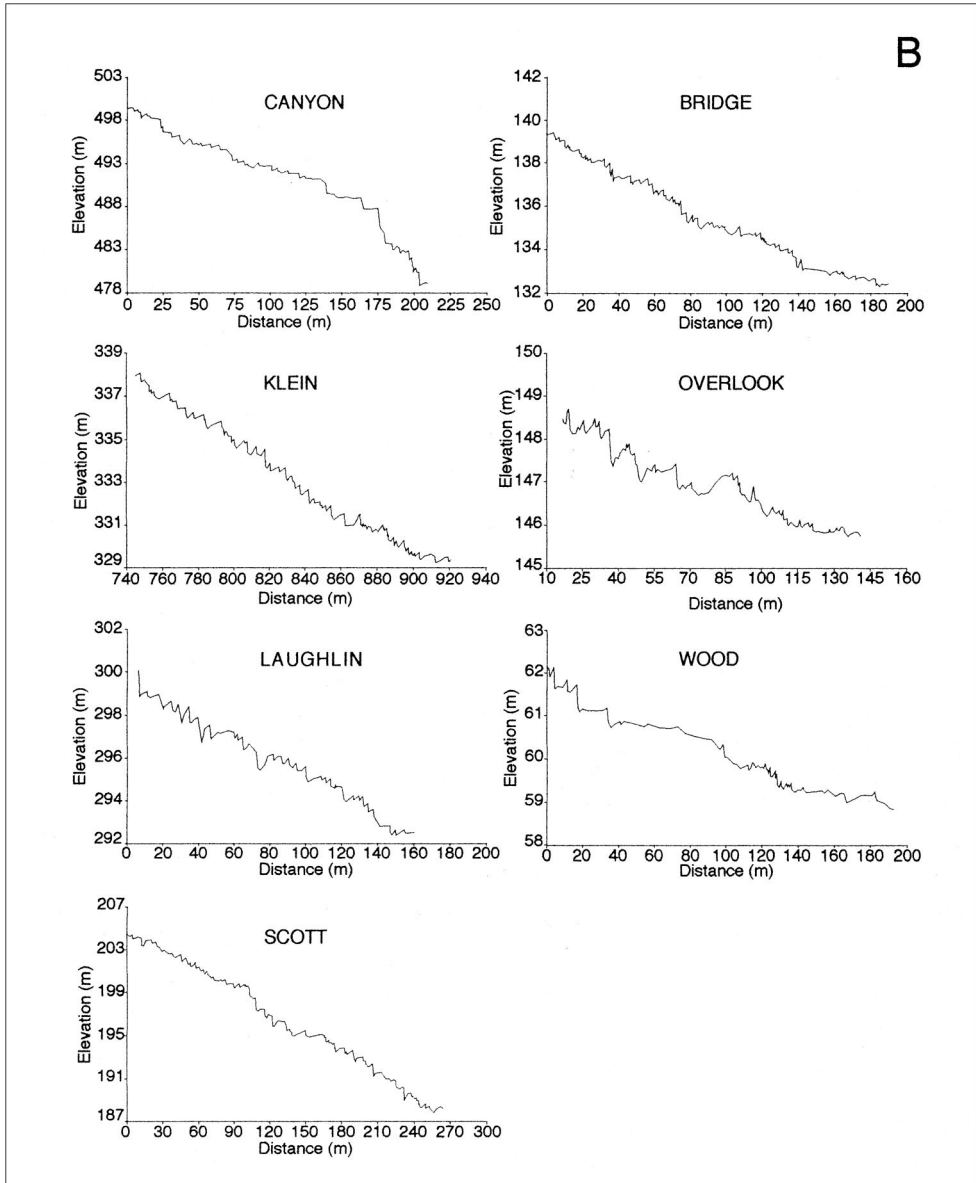


Fig. 4. (continued)

Therefore, any detected periodicity would reflect the dominant wavelength, one that occurs most frequently within the data set. Thus, spectral wavelength may be more similar to the mode of the distribution, as opposed to the mean or average wavelength value of all the members of the sequence. To the extent that the distribution of step-pool wavelength typically skews to the right (Ashida and others, 1984; Grant and others, 1990; Chin, 1999a), mean values would be greater than the mode, and one might expect the average wavelength to be longer than the spectral wavelength.

TABLE 3
Spectral Density Peaks

	Reach	Frequency (cycles/m)	Wavelength (m)	Width (m)	Wavelength (widths)
COLD	Preserve	0.36*	2.82	2.5	1.13
CREEK	Stunt	0.24*	4.21	2.5	1.68
	Helsley	0.16*	6.26	2.9	2.16
	Bobcat	0.22*	4.57	3.2	1.43
	Jude	0.15*	6.85	5.6	1.22
		0.20*	5.04	5.6	0.90
		0.16*	6.22	6.6	0.94
	Monte	0.35*	2.85	6.6	0.43
BIG	Canyon	0.16*	6.30	3.5	1.80
SYCAMORE		0.47*	2.10	3.5	0.60
CREEK	Klein	0.25*	4.06	2.2	1.85
	Laughlin	0.17*	5.76	2.4	2.40
	Scott	0.14*	7.07	3.6	1.97
		0.19*	5.38	3.6	1.49
	Bridge	0.31*	3.34	5.5	0.61
	Overlook	0.18*	5.37	3.6	1.49
	Wood	0.32	3.12	4.7	0.66

*Significant at 0.05 level.

Step-pool wavelengths are compared to test the null hypothesis that there is no significant difference between the spectral wavelength and the average field-measured wavelengths (table 4). In the case of multiple spectral peaks, the wavelength with the highest power was used because it represents the most dominant oscillation in the streambed. Results show that the two measures of wavelength are very similar in some reaches, such as Stunt Reach (Cold Creek) and Klein Reach (Big Sycamore Creek) where the differences are 0.26 m and 0.32 m, respectively. Although other reaches have values that are farther apart, such as Helsley Reach in Cold Creek and Canyon Reach in Big Sycamore Creek, a matched pair *t* test indicates no statistically significant difference (at the 0.05 level) between spectral and average wavelengths. There is also no clear pattern for the direction of the difference between spectral and average wavelength. About half of the reaches have spectral wavelengths that are shorter than the average wavelength, the other half longer. Thus, the two measures of wavelength do not reflect a notable difference that can be generalized, and the null hypothesis of no difference cannot be rejected.

These results confirm that dominant periodicities detected by spectral analysis are those of step-pool undulations in the streambed. The relatively similar values between spectral and average wavelengths also confirm the utility of spectral analysis as an alternative and objective means of determining step-pool wavelengths, similar to the case of riffle-pool (Richards, 1976) and meander (Speight, 1965, 1967; Hooke, 1984)

TABLE 4
Spectral and average wavelength comparisons

	Reach	Spectral Wavelength		Average Wavelength*		Difference	
		(m)	(widths)	(m)	(widths)	(m)	(widths)
COLD CREEK	Preserve	2.82	1.13	3.87	1.61	-1.05	-0.48
	Stunt	4.21	1.68	3.95	1.58	0.26	0.10
	Helsley	6.26	2.16	4.23	1.46	2.03	0.70
	Bobcat	4.57	1.43	5.20	1.63	-0.63	-0.20
	Jude	6.85	1.22	7.45	1.33	-0.60	-0.11
	Monte	6.22	0.94	6.86	1.04	-0.64	-0.10
BIG SYCAMORE CREEK	Canyon	6.3	1.80	5.19	1.68	1.11	0.12
	Klein	4.06	1.85	4.38	2.05	-0.32	-0.20
	Laughlin	5.76	2.40	5.03	2.18	0.73	0.22
	Scott	5.38	1.49	5.77	1.84	-0.39	-0.35
	Bridge	3.34	0.61	4.81	0.91	-1.47	-0.30
	Overlook	5.37	1.49	4.99	1.49	0.38	0.00

*Defined as the average sloped distance between successive trough points (pool-to-pool). Data from Chin (1999a).

wavelengths. When expressed in units of channel width, the two measures become even more similar. The average difference is ± 0.28 channel widths for Cold Creek and ± 0.20 channel widths for Big Sycamore Creek. Because the unit of channel width expresses wavelength in more general terms than the measure of absolute distance, it is not surprising that the relationship between spectral and average wavelengths is better defined in units of widths rather than meters. Figure 5 illustrates this tentative relationship, which can be further sharpened with a larger data set.

PERIODICITY OF STEP-POOL SEQUENCES

Given that a step-pool periodicity was successfully detected by spectral analysis, results are discussed in greater detail in order to assess the character of the underlying periodicity and to explore the possible role of external factors. The discussion focuses first on six study reaches that contain the most developed and most regular step-pool sequences, identified in Chin (1999a) as Stunt, Helsley, and Bobcat in Cold Creek, and Klein, Laughlin, and Bridge reaches in Big Sycamore Canyon (fig. 3). They contain some of the best examples of step-pool sequences in the Santa Monica Mountains (fig. 6). Analysis of the field-measured wavelengths also indicated the lowest variability in these reaches (table 2).

The spectral density functions for these six reaches reveal single, significant frequencies at the 0.05 level (fig. 7). Dominant wavelengths occur at 4.2, 6.3, and 4.6 m for Stunt, Helsley, and Bobcat reaches in Cold Creek, respectively, and 4.1, 5.8, and 3.3 m for Klein, Laughlin, and Bridge reaches in Big Sycamore Canyon (table 3). These significant results indicate that, in channels with well-developed step-pool morphologies, the sequences occur with sufficient regularity to produce single, dominant periodicities. These results clearly suggest that an underlying periodicity characterizes well-developed step-pool sequences in alluvial reaches, reflecting a strong internal

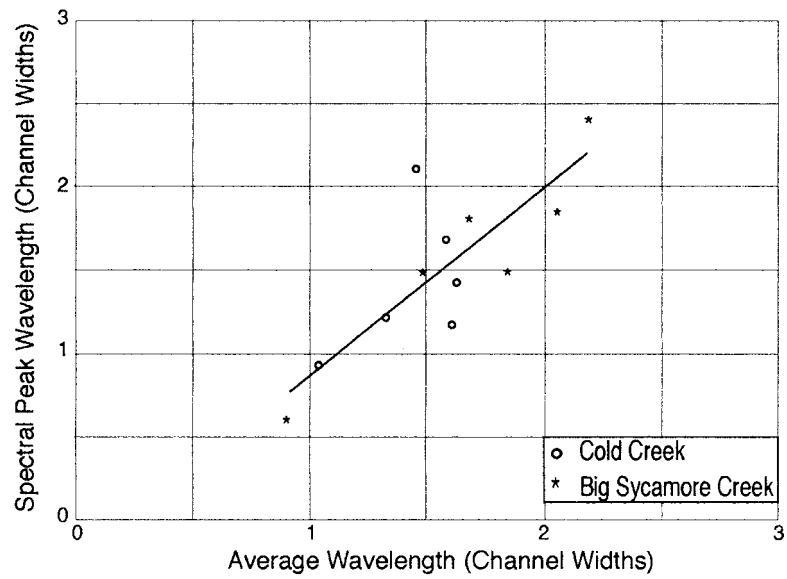


Fig. 5. Relationship between spectral and average wavelength.



Fig. 6. Step-pool sequences in Stunt Reach, Cold Creek.

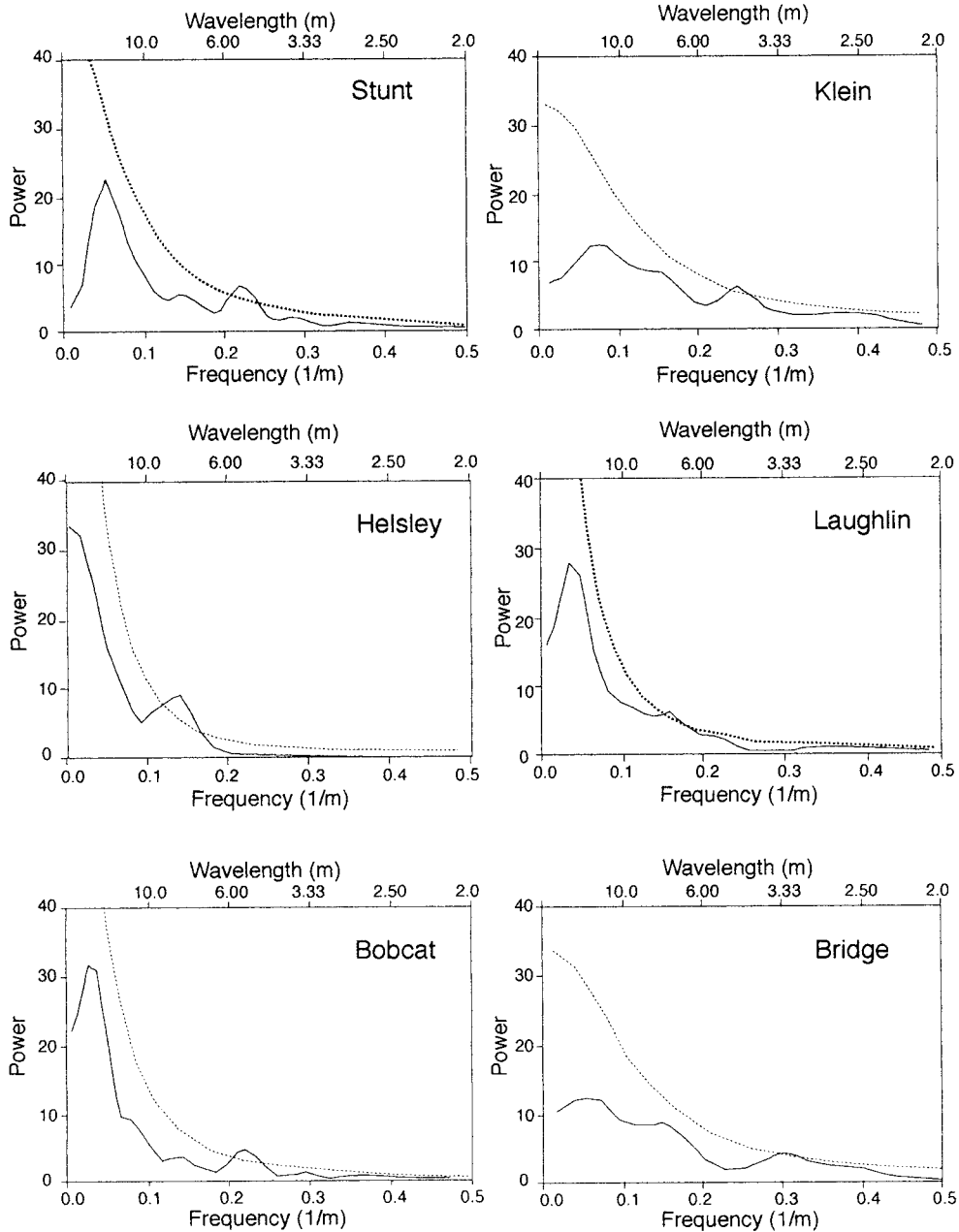


Fig. 7. Spectral density functions. Dashed line indicates 0.05 significance.

mechanism that is not obscured by external factors. Because regular wave trains of step-pools are also observed in laboratory flumes (Whittaker and Jaeggi, 1982; Ashida and others, 1984; Grant and Mizuyama, 1991), these results suggest that the periodic form may depict step-pools that were to develop under ideal natural conditions.

To explore the possible role of external factors, the discussion turns to three study reaches in the Santa Monica Mountains identified by Chin (1999a) as being affected by

tributary input, vegetation, and sideslope debris: Jude Reach in Cold Creek, and Canyon and Scott Reaches in Big Sycamore Creek (fig. 3). The channel character in Jude Reach is strongly affected by a steep, bedrock-controlled tributary about 200 m upstream (fig. 3). The tributary enters the main channel from the south, and evidently delivers a large amount of coarse materials including boulders larger than one meter. Measurements of particle size, channel width, and bed slope indicate an unusually large increase from the upstream reach (Bobcat) (table 1), revealing the effects of the tributary input. In a similar way, Canyon Reach and Scott Reach in Big Sycamore Creek are somewhat atypical in their appearance and character. Field measurements indicate relatively higher slope and particle size values than neighboring reaches (table 1). Rather than tributary input of materials, however, field inspection revealed sediment contributions from unstable sideslopes as the probable cause of the irregularity in Scott Reach, whereas large boulders and unusually dense vegetation appear to dominate the channel character in the rugged upper tributary of Canyon Reach. Table 2 shows the high variability in step-pool spacing in these reaches. The effects of external influences are also apparent in that step-pool characteristics depart from expected downstream trends (Chin, 1999a).

The spectral analytic results for the three study reaches affected by external factors (vegetation, boulders, and hillslope debris) also show significant periodicities, but the character of the spectral peaks differs from that of the well-developed reaches. Rather than single prominent peaks, these reaches are characterized by more than one significant periodicity that is not far apart from each other (table 3). In Jude Reach, the significant spectral peak wavelengths are 6.85 and 5.04 m. In Scott Reach and Canyon Reach, they are 7.07 and 5.38 m, and 6.30 and 2.10 m, respectively. The short oscillation in Canyon Reach (2.10 m) may be attributable to random elements or to the detection of channel-scale grain roughness, but all of the other significant spectral peak wavelengths in these reaches are well within the range of step wavelengths obtained by field measurements (table 2). Thus, the multiple significant peaks are associated with multiple step-pool periodicities, reflecting sequences that are less regular than those in well-developed reaches with single dominant wavelengths.

Multiple periodicities suggest untidy expressions of the internal step-pool mechanism. They suggest that, although step-pools are adjustable features under the present hydrologic regime (Wohl and others, 1997; Chin, 1998), the morphological adjustment may be imperfect in cases where channels are affected by external influences (Chin, 1999a). The fact that the multiple dominant wavelengths are close together (within ~ 1.6 m) is consistent with the hypothesis that local external factors would affect the development of steps and pools to such an extent that an otherwise regular sequence is interrupted. This interpretation is compatible with observations in laboratory flumes where regular step-pool wave trains became disturbed by large roughness elements at steep slopes (Whittaker and Jaeggi, 1982). It is also consistent with Grant and others (1990) who attributed variance in pool spacing to irregular occurrence of non-alluvial features that interferes with the tendency toward regular spacing. In a spectral analysis of meander planforms, Chang and Toebes (1970) similarly found a tendency for two or more dominant frequency peaks in the upstream reaches that they attributed to variance associated with local heterogeneities in small streams such as soil, vegetation, or debris. These results are therefore congruent in principle with the initial suggestion by Wertz (1966) that external factors may affect the ideal sequence of step-pool bedforms that would develop to produce a periodicity. However, contrary to Wertz (1966), external factors apparently obscure the development of a single dominant step-pool periodicity in streams in the Santa Monica Mountains, but they do not prevent such periodicities from being detected all together.

These results suggest that the nature and effect of external controls on step-pool channel morphology are more significant locally than the effects of general fluvial processes that tend to produce rhythmic channel forms. Similar conclusions were reported regarding the development of pool-riffle sequences (Richards, 1976; Keller and Melhorn, 1978) and the growth of free bars in steep rough channels (Furbish, 1998; Furbish and others, 1998). Thus, local external factors apparently obscure rather than destroy the effects of more general internal mechanisms, even in high-gradient channels with coarse materials.

IMPLICATIONS FOR FLUVIAL GEOMORPHOLOGY

Periodicity in step-pool sequences produces broader insights regarding rhythmic bedforms and fluvial adjustments in the larger river system. Three implications are discussed. First, periodicity of step-pools, and of the bed elevations of step-pool streams, suggests that step-pools are bedforms that reflect a fundamental mutual adjustment between flow and channel morphology. Periodicity suggests that the sequences are non-random, and implies that the regular and predictable pattern of channel bedforms arises, at least in part, because of internal processes associated with energy expenditure. One might expect, however, that although the internal signals are sufficiently strong in the reaches surveyed, they would disappear at steeper and smaller channels where the influence of large roughness elements may be disproportionately greater (Furbish and others, 1998). These findings therefore support the interpretation by Montgomery and Buffington (1997) that step-pool channels probably represent the emergence of a fluvially organized morphology in alluvial channels.

Second, the detection of a step-pool periodicity supports the notion that step-pool bedforms are analogous to meandering in the vertical, or third, dimension. The successful application of spectral analysis to identify significant wavelengths in the step-pool thalweg profile indicates that the step-pool channel bed can be described as wave forms. Thus, viewed in the vertical dimension, the step-pool streambed is a meandering form that closely approximates a sine-generated curve. The wavelength of the vertical step-pool "meander", as defined by spectral analysis and by field measurements, is approximately one to two channel widths and is several orders of magnitude shorter than those of horizontal meanders in lowland streams, reflecting the exaggerated role of step-pools in energy dissipation. In confined mountain valleys with limited freedom to adjust energy expenditure in the plane dimension, step-pools apparently represent the means to adjust boundary roughness in the vertical dimension, thereby regulating energy dissipation (Chin, 1989). A step-pool thalweg that approximates a sine-generated curve also implies a form for which flow and erosion are as uniform as possible along the channel (Langbein and Leopold, 1966; Hallet, 1990; Wohl and others, 1999). These results therefore suggest that step-pools are fundamentally similar to other rhythmic forms that exhibit sine-generated curves, including meanders, pools and riffles, rhythmic thalweg morphology in supraglacial streams (Dozier, 1976), and even channel-wall undulations in bedrock canyons (Wohl and others, 1999). Such similarity suggests that these rhythmic forms may represent diverse manifestations of a common phenomenon (Keller and Melhorn, 1978), and that common principles of energy expenditure may apply (Wohl and others, 1999).

Third, the fact that step-pools are periodic suggests that it may be possible to define the relationship between step-pools in the headwaters and the rhythmic pools and riffles downstream by developing a continuum of gravel bedforms that includes both bedforms, similar to the sequence of sand bedforms consisting of dunes and ripples. A complete treatment of this topic is beyond the scope of this paper. Nevertheless, a full interpretation of the implications of the step-pool periodicity would be incomplete without considering the theoretical justification, significance, and controls for such a continuum. The remaining paragraphs of this paper discuss

these issues, followed by an illustration using empirical data from the Santa Monica Mountains.

The continuum of gravel bedforms.—In open systems where natural rivers exchange energy and materials with their surrounding environment (Leopold and Langbein, 1962), channel forms adjust to the dominant controls of discharge and sediment load, independent variables that integrate the effects of climate, vegetation, soils, geology, and basin physiography (Knighton, 1998). Channels adjust in several ways. The adjustment relevant to step-pools is bed configuration, an adjustment in the vertical dimension through the construction of bedforms. Channel adjustments can result in a continuum of forms if the forms are controlled by interactions among a set of continuous variables. Classic examples are the channel patterns of straight, meandering, and braided, where the changing sequence has been related to power (slope and discharge) (Leopold and Wolman, 1957) and the type and quantity of sediments (Schumm and Khan, 1972; Ackers and Charlton, 1970), and the sequence of sand bedforms produced in response to increasing flow strength: ripples, dunes, plane bed, and antidunes (Simons and Richardson, 1966). Although these examples reflect components of the fluvial system that are easily adjustable over small spatial and temporal scales (spatially in terms of the downstream alluvial portion of the drainage basin, and temporally in terms of the high frequency and low magnitude of the processes) a continuum of gravel bedforms that includes step-pools should be possible if step-pools are adjustable to flow and internal hydraulics, as demonstrated by their periodic nature, and if the controlling variables are identified and considered over long timescales. Developing such a continuum of gravel bedforms would provide an important context for understanding step-pools as dependent variables in the larger fluvial system (Chin, 1998). It would also expand the spatial and temporal range governing the applicability of the adjustment and continuum concept (Knighton, 1998, p. 207) to include headwater streams and higher magnitude processes.

The idea of a continuum of gravel bedforms is not new. For example, Naden and Brayshaw (1987), Bluck (1987), Robert (1990), and Richards and Clifford (1991) recognized progressions of small to medium scale gravel bedforms that relate to particle size and slope. The idea is also inherent in many classifications of channel units and channel reach morphologies. Grant and others (1990) identified a range of channel units in mountain streams that occurs along a slope continuum: pools, riffles, rapids, cascades, and steps. Church (1992) also described a sequence of bedforms, including riffle-pools and step-pools, associated with channel type, slope, and flow characteristics. Montgomery and Buffington (1997) similarly defined alluvial channel reach morphologies in mountain streams, progressing from dune ripple to pool riffle, plane bed, step pool, and cascade channels, that varies with slope, grain size, drainage area, relative roughness, and shear stress. These classifications support the numerous observations that a continuum of gravel bedforms exists from step-pools to riffle-pools in a downstream direction (Wertz, 1966; Chin, 1989; Knighton, 1998): at one end, step-pools dominate channels with high gradients (generally > 2 percent) and coarse materials ranging from gravel to boulder (Hayward 1980; Whittaker and Jaeggi, 1982; Chin, 1999a), and at the other, riffle-pools form where slopes are less than 2 percent and sediments are within the gravel range (Keller and Melhorn, 1978; Milne, 1982; Florsheim, 1985; Keller and Melhorn, 1978).

The occurrence of step-pool and riffle-pool sequences, and variations in between them, has been explained in terms of hydraulic adjustment, process regime, and energy expenditure. Montgomery and Buffington (1997) explained that channel morphologies represent stable configurations that are adjusted to the relative magnitudes of transport capacity and sediment supply in a drainage basin. As transport capacity changes relative to sediment supply in a downstream direction, so do bedform

adjustments. Channel reach morphologies therefore vary with hydraulic variables that change systematically downstream, such as slope, grain size, and relative roughness. Church (1992) emphasized the role of relative roughness in controlling channel types, hydraulic characteristics, and thus bedforms, because relative roughness, or the ratio between grain diameter and flow depth, represents the ease with which sediments can be transported. Wohl and others (1993) found variations in pool and riffle characteristics downstream that reflect changes in energy expenditure. In lower gradient reaches downstream, a relatively greater proportion of flow energy is available to scour pools and form pool-riffle sequences, whereas steep slopes in headwater channels dictate that a greater proportion of the energy is dissipated by boundary roughness, such as step-pool systems. Bedforms therefore vary downstream along with factors that control and represent the rate and manner of energy expenditure, such as gradient, discharge, and channel resistance. The fact that similar downstream trends, from step-pool to riffle-pool bedforms, exist in bedrock channels also suggests that such changes are related to the differential expenditure of flow energy along the channel (Wohl, 1998, 2000b).

Data from Santa Monica Mountains.—Data from the Santa Monica Mountains are used to illustrate the continuum of gravel bedforms that exists from step-pools to riffle-pools downstream. The term “gravel” is used loosely here to refer to coarse-grain materials, as distinct from sand, and is not limited to sediments strictly in the 2-256 mm range. The terminology for bedforms is that of Grant and others (1990), which emphasizes the sub-unit and channel unit scales; cross references are made to the reach types of Montgomery and Buffington (1997).

Close inspection of the bedform character in Cold Creek, for which sampled study reaches cover the entire length of the main channel (fig. 3), reveals downstream trends similar to those described by Grant and others (1990), Church (1992), and Montgomery and Buffington (1997) with some modifications (fig. 8). In the upper-most reach (Preserve), individual steps are distinct and are composed of rocks that span the channel, in some cases held by a keystone boulder or bedrock outcrop. These steps have been described as boulder steps and rock steps (Hayward, 1981; Grant and others, 1990); Montgomery and Buffington (1997) classified channels containing such steps as “cascade”, meaning tumbling flow. Step-pools in the next three reaches (Stunt, Helsley, Bobcat), discussed earlier (fig. 6), are well developed, regular, and spectacular. Steps in these reaches are typically organized into channel units termed “cascades” (Grant and others, 1990), where each unit is composed of several step-pools interspersed by larger pools (details below and fig. 11). Reaches containing these cascade-pool sequences correspond to step-pool channels in the terminology of Montgomery and Buffington (1997). Next, in Jude Reach and Monte Reach, steps become less well defined and less regularly spaced. They are often channel-spanning ribs that are part of channel units resembling large riffles. Hayward (1981) described these as riffle-steps, while the term “rapids” was used by Grant and others (1990) and Church (1992). Rapids in these reaches are often interspersed by long pools and are analogous to the glides, runs, or plane bed channels described by Montgomery and Buffington (1997). The rapid-plane bed morphology then grades into riffle-pool sequences in the final surveyed reach downstream (Crater) (fig. 8). Riffle-pools were also observed farther downstream in Cold Creek as well as in Malibu Creek into which Cold Creek drains.

Figures 9 and 10 illustrate the continuum of rhythmic gravel bedforms as defined by slope, drainage area, and particle size for streams in the Santa Monica Mountains. Plotting data from both Cold Creek and Big Sycamore Creek, a sequence of bedforms from step-pools to riffle-pools is evident as drainage area (or discharge) increases and as slope decreases, with cascades and rapids occupying the intermediate range of the spectrum (fig. 9). Figure 10 further demonstrates the mutual adjustment between

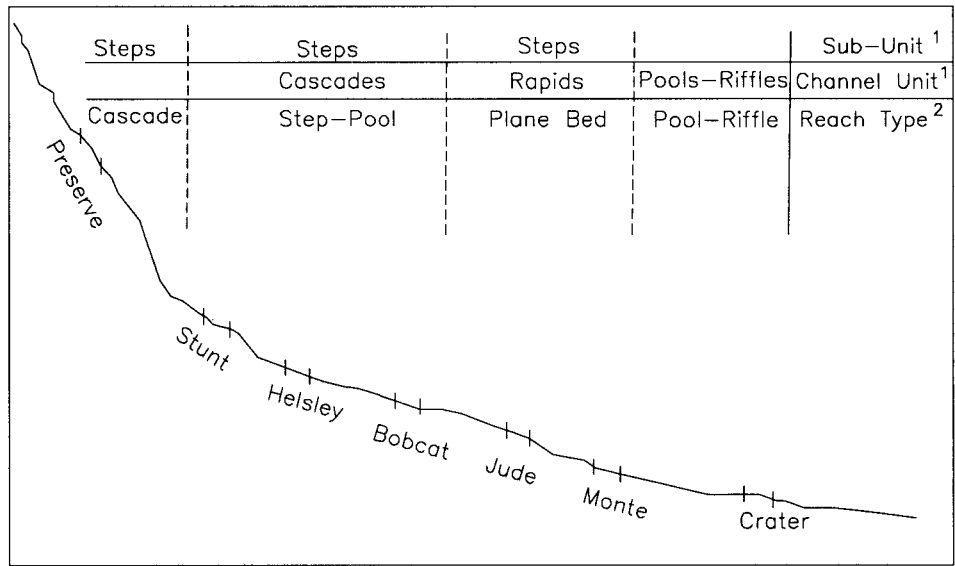


Fig. 8. Downstream variations in gravel bedforms, Cold Creek. ¹Scales and terminology of Grant and others (1990); ²Classification of Montgomery and Buffington (1997).

slope, particle size, and bedforms. The diagram shows qualitatively defined fields for the occurrence of bedform types that are associated with particular slope and particle size ranges. It indicates that, for a given bed material size in the gravel to boulder range, the adjustment to increasing slope results in the bedform sequence of riffles,

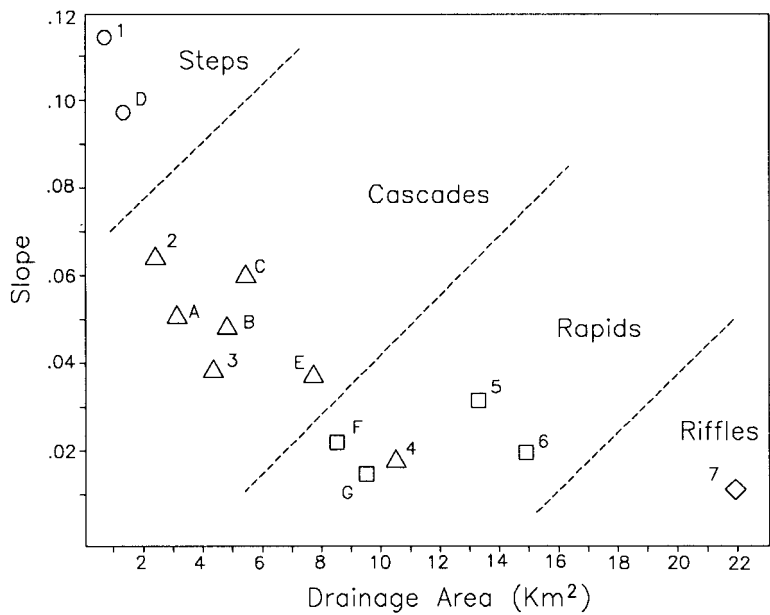


Fig. 9. Bedform sequence with increasing drainage area and decreasing slope. ○ steps; △ cascades; □ rapids; ◇ riffles. Cascades and rapids are channel units that contain steps. Numbers and letters refer to reaches specified in figure 3. Boundaries are approximate and are empirically drawn from data plotted.

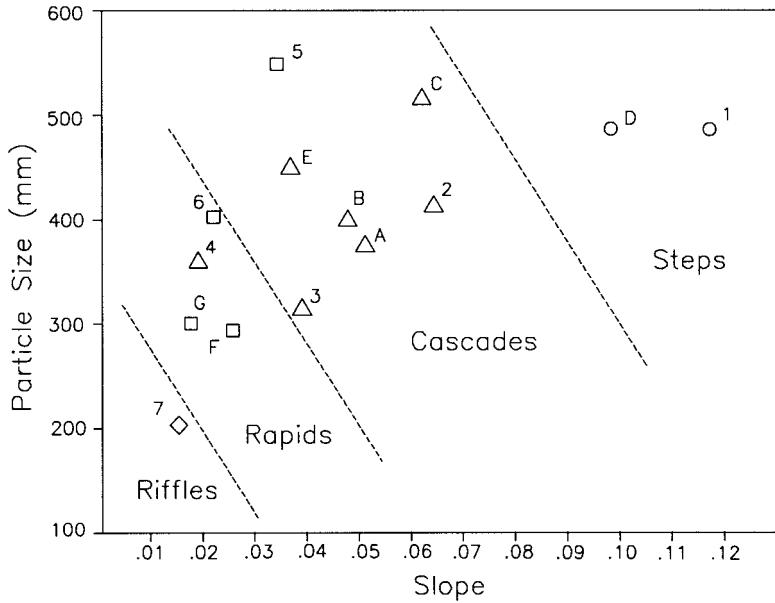


Fig. 10. Relation between slope, particle size, and bedforms. Symbols and terminology as in Figure 9. Approximate boundaries are empirically drawn.

rapids, cascades, and steps. It also shows, for example, that rapids are similar to riffles in slope but are differentiated by larger particle size. Although the boundaries defining the bedform fields are empirically drawn and are approximate, the slope ranges are compatible with those reported in the literature (Bowman, 1977; Grant and others, 1990; Church, 1992; Montgomery and Buffington, 1997; Chartrand and Whiting, 2000). Slope and particle size clearly represent major influences in controlling bedform types.

The transition from step-pools to riffle-pools.—Downstream trends revealed in figures 8, 9, and 10, together with consideration for the rhythmic characteristics of step-pool sequences, provide insights into the nature of the transition from step-pools to riffle-pools. Where steep slopes (exceeding ~ 7 percent) are coincident with large grain sizes, step-pools produce a rhythmicity at the one scale of the step-pool or sub-unit (fig. 8). Downstream, where slopes are less than ~ 2 percent and sediments are gravelly, the characteristic pool-riffles also oscillate at a single but larger scale: the scale of the channel unit or channel reach. In between are the suggested transitional forms where *both* scales of rhythmicity are evident: one at the step-pool or sub-unit, the second at the larger channel unit scale. The 2 scales of oscillations are produced because, in cascades and rapids, periodic step-pools are superimposed upon larger channel units that are themselves repetitive (fig. 11). This process is akin to the transition from ripples to dunes in sand bed rivers (Robert and Uhlman, 2001), where, in between distinct ripples and dunes, the characteristic forms are dunes with superimposed ripples (Simons and Richardson, 1966; illustrated in Richards, 1982, fig. 3.9a).

These observations suggest that both step-pool and riffle-pool tendencies are present in reaches with cascades and rapids. Where rapids may serve as end members of step-pool sequences (fig. 8), cascades may represent the beginning development of pools and riffles. The empirical data from the Santa Monica Mountains show that the undulations caused by the large pools in cascade channel units (fig. 11) are consistent

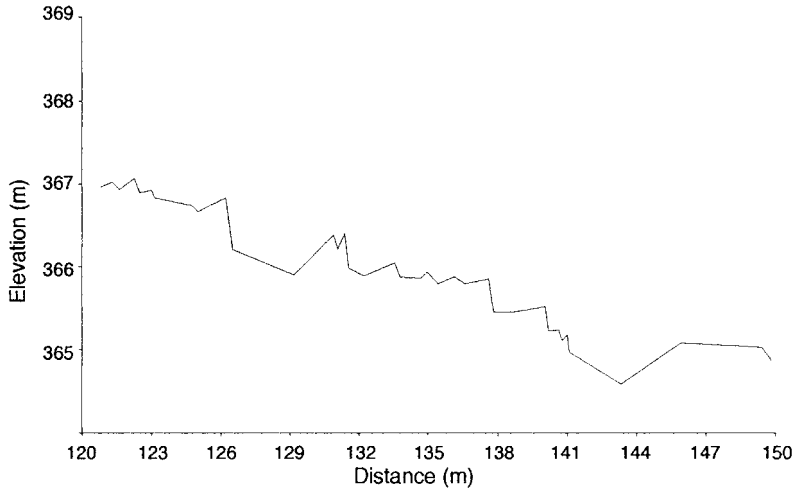


Fig. 11. Details of a cascade-pool channel unit sequence showing several step-pools interspersed by larger pools, as surveyed in Stunt Reach, Cold Creek. The sequence is similar to the schematic illustration in Grant and others (1990, fig. 2).

with pool-riffle wavelengths, on the order of 5 to 7 channel widths. The 2 scales of oscillations are also detectable by spectral analysis, where the larger channel-unit scale undulations correspond to low frequency peaks in the spectral density functions (fig. 7), even though such peaks are statistically insignificant owing to insufficient lengths in the data series. Thus, not only do channels containing cascades represent the emergence of a fluvially organized morphology, as Montgomery and Buffington (1997) suggested, but, more specifically, these data suggest that they probably represent the beginnings of the development of pool-riffle sequences, and therefore of meandering channels.

SUMMARY AND CONCLUSIONS

Successful application of spectral analysis to investigate periodicity in step-pool streams in the Santa Monica Mountains permit answers to the research questions with which this paper began. First, spectral analytic results show a distinct periodic character in the step-pool streambed. Significant step-pool periodicities vary from 0.43 channel widths to 2.40 channel widths and are confirmed by independent field measurements of step-pool wavelengths. Second, the step-pool periodicity is often evident despite the possible influence of external factors such as vegetation and boulders. Whereas well-developed step-pool sequences exhibit single prominent periodicities, those affected by external influences reveal a tendency for multiple significant peaks that reflect higher variance in step-pool spacing. Thus, although external factors would affect the periodic development of step-pool sequences to some extent, they apparently obscure rather than destroy the effects of more general internal mechanisms.

Periodicity of step-pools, and of the bed elevation of step-pool streams, suggests that step-pools are bedforms that represent a fundamental mutual adjustment between flow, channel morphology, and energy expenditure. A rhythmic streambed supports the view that step-pools are analogous to meandering in the third dimension. It also implies that, because step-pool channels are not able to adjust energy expenditure in the plane dimension, they adjust boundary roughness in the vertical dimension

instead. Rhythmicity in step-pools provides the theoretical underpinning for a continuum of gravel bedforms that displays the results of such adjustments. The continuum, as illustrated by empirical data from the Santa Monica Mountains, shows the transition from step-pools to riffle-pools and contributes to the development of a predictive model with further refinement and quantification.

In relation to fluvial geomorphology, the results of this study suggest that step-pools may represent another manifestation of a common phenomenon that produces rhythmic forms, and that common principles of energy expenditure may apply. These findings lend support to a growing body of literature that suggests that fluvial processes operating in high-gradient streams (Speight, 1967; Grant, 1997; Furbish, 1998; Furbish and others, 1998), as well as in bedrock channels (Keller and Melhorn, 1978; Wohl and others, 1999) are fundamentally similar to those in lower-gradient alluvial rivers.

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