Step-pool and cascade morphology, Mosquito Creek, British Columbia: a test of four analytical techniques

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Abstract: The identification and geometric definition of individual cascade and step-pool bedforms are investigated in a steep, coarse-grained, mountain stream, Mosquito Creek, by testing four analytical techniques: visual identification, zero-crossing, bedform differencing, and power spectral analysis. The test is the first use of these techniques in a headwater stream, and the analysis of two bed profiles showed that visual identification was able to (i) identify, (ii) determine the geometry of, and (iii) classify the type of individual bedforms better than the other methods. The other techniques were not able to differentiate step-pools from cascades, and the large range of grain sizes and bedform heights hampered their ability to consistently identify stepped bedforms. The step-pool (pronounced, channel-spanning steps that alternate with channel-spanning pools) and cascade (multi-tiered, partially channel-spanning structures) morphology in Mosquito Creek has formed in the last 20 years as fluvial action has restructured its previously engineered, revetment-lined, planar bed. The channel bed exhibits a morphologic regularity that power spectral analysis captured as periodic fluctuations in the bed profiles, with mean wavelengths slightly greater than those identified by the other methods. Further, the active reorganization of revetment has formed stepped structures with geometries similar (i.e., height to wavelength ratios) to stepped features found in natural mountain streams. Channel slope partially controlled bedform geometry (wavelength and height), and bedform height weakly controlled individual step spacing, but there was no relation between wavelength and grain size ($D_{90}$).

Résumé : L’identification et la définition géométrique de formes de lits de rivières individuels en cascades et en paliers d’accalmie sont étudiées dans le crique Mosquito, un ruisseau de montagne, abrupte et coulant sur un sol à grain gros-sier, en mettant à l’essai quatre techniques analytiques : l’identification visuelle, le passage par zéro, la différenciation de la forme du lit et une analyse spectrale de puissance. Ce test constitue la première utilisation de ces techniques dans un ruisseau d’amont et l’analyse de deux profils de lits a démontré que l’identification visuelle pouvait (i) identifier, (ii) déterminer la géométrie et (iii) classifier le type individuel de lit de rivière mieux que les autres méthodes. Les autres techniques ne permettaient pas de différencier entre les paliers d’accalmie et les cascades; de plus, la grande étendue des granulométries et de hauteurs de lits entraînent leur capacité d’identifier avec constance les formes de lits à paliers. Dans le crique Mosquito, la morphologie des paliers d’accalmie (des marches accentuées qui enjambent le chenal alternant avec des bassins calmes qui enjambent le chenal) et des cascades (des structures à plusieurs niveaux qui enjambent partiellement le chenal) s’est formée au cours des 20 dernières années alors que l’action de l’eau a res- tructuré son ancien lit planaire, artificiel et tapissé. Le lit du chenal montre une régularité morphologique que l’analyse spectrale de puissance a interprétée comme des fluctuations périodiques des profils du lit avec des longueurs d’onde moyennes légèrement supérieures à celles identifiées par les autres méthodes. De plus, la réorganisation active du revêtement a formé des structures en paliers dont les géométries (c.-à-d. les rapports de la hauteur sur la longueur d’onde) sont semblables aux caractéristiques des paliers trouvés dans les ruisseaux de montagne naturels. La pente du chenal a contrôlé en partie la géométrie de la forme du lit (longueur d’onde et hauteur) et la hauteur de la forme du lit a faiblement contrôlé l’espacement des gradins individuels mais il n’y avait aucune relation entre la longueur d’onde et la gra-nulométrie ($D_{90}$).

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Introduction

The purpose of this paper is to test the ability of four analytical techniques to geometrically define and identify individual bedforms in a steep mountain stream. The reliable identification of individual bedforms in headwater stream channels is critical in providing accurate geometric measures and typological information because individual bed structures...
in small channels are significant elements of the channel boundary that influence resistance to flow and channel gradient. The distinctly stair-like patterning of step-pools and cascades has led most researchers to visually identify bedforms based on flow or morphologic characteristics, or both. Yet, in an early study of stepped-bed geometry, Hayward (1980) realized that different workers surveying the same reach on Torlesse Creek failed to record coincident boundaries between bedforms that affected the identification of channel-scale elements and characterization of channel morphology. The finding of Hayward (1980) reflects the subjective nature of bedform identification, highlighting the need for an objective assessment of bedform geometries.

Two objective techniques used with success in identifying individual ripples and pools and their geometries are the zero-crossing (Richards 1976) and power spectral analysis methods (Carling and Orr 2000). Carling and Orr (2000) found that both techniques produced roughly equivalent geometric measures of bedform wavelength, suggesting their application to steeper, coarser grained streams. Because this study represents the first use of these techniques in a headwater stream, two subjective methods, bedform differencing (O’Neill and Abrahams 1984) and visual identification (Montgomery and Buffington 1997), are also employed to provide a comparative framework. Data from two longitudinal profiles present an opportunity to characterize self-organized bedform morphology in a small, steep, coarse-grained channel, Mosquito Creek, by identifying individual bedforms, classifying bedform type, and calculating bedform geometries.

**Mosquito Creek**

Mosquito Creek is located in the southwestern corner of British Columbia in the District of North Vancouver and flows south into Burrard Inlet (Fig. 1). The 8.5 km long creek starts at an elevation of 950 m, and Upper Mosquito Creek drains a 5 km² watershed and flows over a mantle of glacial sediments (e.g., till) and colluvial deposits. The hydrologic regime of Mosquito Creek is dominated by winter rains (October to March). The mean annual precipitation is 2390 mm, of which 70 mm falls as snow (data from the outlet of Capilano Lake, elevation 157 m; Fig. 1; Atmospheric Environment Service 1993). Mean annual discharge is ~0.7 m³·s⁻¹ (Water Survey of Canada 1991), and a flow of 54 m³·s⁻¹ has a 25–30 year return period. By contrast, the engineered channel is designed to pass a flow of 71 m³·s⁻¹, which has a return period of 200 years.

The 248 m long study reach, at elevation 160 m, is an engineered channel bordered by residential dwellings. The study reach is divided into two 124 m reaches (upper and lower; Fig. 1), reflecting a sharp change in slope angle, with the upper and lower reaches having gradients of 0.075 and 0.060, respectively.

In 1981 engineering works channelized the moderately sinuous channel in an attempt to stabilize and control the stream’s position within the floodplain to mitigate debris flow and flooding hazards. Side channels dissecting the floodplain were infilled with boundary materials excavated from the natural channel, which was confined to a relatively straight trapezoidal channel lined with subangular granodiorite boulder-sized revetment (Fig. 2A; median grain diameter $D_{50} = 0.5$ m, maximum grain diameter $D_{max} = 2$ m; $D$ is the intermediate ($b$ axis) grain diameter). Channel stabilization techniques also included emplacement of planar channel-spanning concrete strips ~8 m wide oriented normal to flow; one concrete strip occurs in the study reach and is considered equivalent to rock. The active channel is a small, 7 m wide cobble and boulder stream nested within the larger engineered channel, which is ~15 m wide at the bed, ~23 m wide at bankfull, and ~2.5 m deep and has ~30° banks.

**Stepped-bed morphology and grain-size distributions**

Since 1981, fluvial action has broken the planar revetment surface and formed a stepped-bed morphology (Figs. 2B–2D) incorporating mobilized revetment, debris-flow material, and clasts eroded out of till. Stepped-bed architectures in Mosquito Creek consist of steps and cascades composed of interlocked cobble- and boulder-sized grains, which alternate with finer grained pools. The bed is actively reworked with boulder-sized clasts mobilized and deposited ($D_{max} = 1.1$ m) in a catch basin 600 m downstream of the study reach (Fig. 1). The mean diameter of the five largest particles deposited in the basin is 790 mm ($b$ axis), which is $D_{50}$ of the step-grain population.

Grain-size partitioning between steps and pools is well defined in both reaches, with larger sized stones forming steps and finer grained material in pools (Fig. 3). The
Wooldridge and Hickin

Fig. 2. (A) Upstream view of channel morphology in Mosquito Creek immediately after channel confinement and emplacement of revetment in 1981. Note the trapezoidal channel cross section, planar revetment surface, debris racks, and excavator in background. Photograph by M.C. Roberts. (B, C) Step-pool morphology evident in 1999 looking (B) upstream and (C) in plan view, with flow left to right. Flow is subcritical and relatively placid in pools which alternates with tumbling flow through channel-spanning steps. (D) Cascade morphology showing continuous tumbling flow through small pools and partially developed steps with flow from upper left to lower right. Discharge is equivalent in (B), (C), and (D).

The median grain diameter ($D_{50}$) from all steps was 475 mm, with a $D_{16}$ of 250 mm and $D_{84}$ of 800 mm. The median grain diameter ($D_{50}$) from all pools was 120 mm, with a $D_{16}$ of 40 mm and $D_{84}$ of 425 mm. Comparison of mean step and pool $D_{50}$ grain sizes by one-way ANOVA demonstrated that step and pool grains come from different populations ($p < 0.05$). Similar patterns of grain-size distributions have been reported by others (Grant et al. 1990; Chartrand and Whiting 2000). Figure 3 also shows that pools are more poorly sorted than steps, with sorting coefficients (defined as the ratio of $D_{84}$ to $D_{16}$) of 10.6 for pools and 3.2 for steps. Convergence of the curves above $D_{95}$ between upper reach steps and pools shows that the largest boulders are found in both steps and pools. This is likely a result of mobile boulders rolling into pools and the presence of anchored, relatively immobile boulders in steps.

The incorporation of revetment material into steps is reflected in the irregularly shaped step-grain distribution curves and is due to a limited range of revetment sizes introduced into the channel (the minimum size was 300 mm; Fig. 3). Pool distribution curves are smooth below 300 mm, revealing the presence of more uniformly distributed naturally occurring grains forming the finer fraction in pools. The grain-size distribution curves support the notion that the persistent mobilization of the finer fraction redistributes naturally occurring grains into pools while the coarser step grains (revetment) undergo less frequent transport (Schmidt and Ergenzinger 1992; Trayler and Wohl 2000). Further, the normally loose packing of pool grains requires less shear stress to mobilize the bed than the interlocked fabric of step grains, which preserves the step architecture (Laronne and Carson 1976).

Methods

Grain-size distributions

Grain size was determined by measuring the clast $b$ axis (10 mm was the lower truncation limit; there was no upper truncation limit; Fripp and Diplas 1993). Boulders were typically only partially exposed on the surface because of their...
imbricated and interlocked nature and because they were covered by smaller and larger grains. The hidden extent of individual boulders was extrapolated to within reasonable limits but introduced conservative estimates of axis lengths.

Surface grain-size distributions were determined using a modified grid technique (1 m² grid) following Kellerhals and Bray (1971). To accurately reflect grain-size distributions, steps and pools were identified visually in the field and step-pool units were sampled, with grains identified as step or pool grains. No cascades were sampled. Each sample traversed one step-pool unit and either 50 or 100 stones were measured, with five samples collected in the upper reach \((n = 350)\) and four in the lower reach \((n = 350; \) Fig. 3). The five largest clasts at each step and most cascades were also measured \((n = 250)\) but were not pooled with or analyzed with the 700 grains measured to characterize grain-size distributions in the creek.

**Channel-bed profiles**

Two surveys of the channel-bed topography were carried out using a Duratech AL240 level. A preliminary survey in January 1999 sampled every major mesoscale bedform element (individual steps and pools) to provide an initial assessment of bedform length and organization (Richards 1976). A second survey in February 1999 measured bed elevations every 0.6 m along the 248 m long channel centreline, producing two 124 m longitudinal bed profiles (Figs. 4A, 4B) consisting of 207 points each with an error of ±5 mm per 124 m of double-run leveling. The 0.6 m fixed sampling interval was chosen for two reasons: (i) to ensure that no bedforms were excluded from the bed profiles; and (ii) to reduce the influence of individual grains (microscale bed structures) on the surveyed macroscale bed structure (the total step-pool architecture), as the sampling interval was slightly greater than the median step-forming grains \((D_{50} = 0.5 \text{ m})\). If a smaller sampling interval had been chosen, the survey would have sampled most grains more than once, potentially resulting in a profile of clast topography rather than a profile of the bed topography. Likewise, a sampling interval much greater than \(D_{50}\) would smooth the bed topography and potentially exclude bedforms.

**Visual identification**

Step-pool and cascade bedforms were identified at low discharges following the morphological classification of Montgomery and Buffington (1997). In their classification, step-pool channels are characterized by longitudinal steps formed by large clasts organized into discrete channel-spanning accumulations that separate pools containing finer material. Cascades are typically longitudinally and laterally disorganized bed material generally consisting of individual cobbles and boulders separated by small, partially channel-spanning pools (Montgomery and Buffington 1997). In the classification of Grant et al. (1990), our step-pools are their rapids and our cascades are equivalent to their cascades, whereas the step-pools of Chin (1999) include both our cascades and our step-pools. Bedform geometries calculated by visual identification, zero-crossing, and bedform differencing techniques differ slightly and are defined in Figs. 5A–5C.

Morphologically, steps (or risers in the terminology of Grant et al. 1990) were identified as discrete, imbricated, and vertically interlocked coarse-grained structures (Laronne and Carson 1976) forming topographic highs that extended across the channel (Fig. 2C). The transverse steps were separated by channel-spanning, topographically low, finer grained pools with a normally loose boundary structure that was not imbricated (Church 1978). Flow depth shallowed downstream from the step to the next step, highlighting the reverse-sloped nature of pool bottoms.

Cascades were identified as complex bedforms consisting of irregular cobbly and boulder networks giving rise to partially channel-spanning pools (Fig. 2D; Grant et al. 1990; Montgomery and Buffington 1997). Partially channel-spanning structures may represent broken steps, clasts rolled into pools agglomerating as minor cascades, or small multilevel pools forming a cascade structure. Cascades are intermediate bedforms between distinct channel-spanning steps and random incoherent grain agglomerations. As such, they display some imbricate structure but lack a fully developed interlocked grain architecture. Steps were distinguished from cascades by (i) the degree of structuring and arrangement of grains (i.e., imbrication and interlocked nature), (ii) the extent to which structures spanned the channel, and (iii) the nature of pool development (i.e., tiered or channel-spanning pools).

Hydraulically, the general character of flow through step-pools alternates between slow, subcritical flow in pools and critical to supercritical tumbling flow (Peterson and Mohanty 1960) over steps (Figs. 2B, 2C), a point utilized by Grant et al. (1990) in differentiating stepped bedforms. In conjunction with morphologic criteria, Grant et al. differentiated rapids (our steps) from cascades by comparing the percentage of stream area in supercritical flow controlled by the degree of clast protuberance, which varies with stage and discharge levels. For instance, higher discharges drown and obscure key morphologic elements, limiting the effectiveness of hydraulic parameters in identifying bedform.
Fig. 4. (A, B) Longitudinal bed profiles of the (A) upper and (B) lower reaches showing the fitted regression models. (C, D) Bed-elevation residual plots of the (C) upper and (D) lower reaches showing positive (steps) and negative (pools) departures from the regression line.

Zero-crossing analysis
Following Richards (1976), regression models were fitted to the bed profiles (Figs. 4A, 4B) to identify steps and pools as positive and negative residuals (departures from zero), respectively (Figs. 4C, 4D). In general, the residual plots display uniform scatter about the fitted lines, indicating that trends in the profiles have been largely removed. $F$ tests of different order trend surfaces revealed second-order polynomial and linear models to be significant at the 0.01 level for the upper and lower reaches, respectively (Davis 1986). Higher order trendlines were not significant at the 0.01 level and were not applied to the data. This practice was in accord with the recommendation of Chayes (1970) and ensured objectivity in selecting significant trends to apply to the zero-crossing technique.

Bedform differencing technique
O’Neill and Abrahams (1984) developed the bedform differencing technique to identify pools and riffles by differencing successive elevation measures along a bed profile. If the cumulative elevation change since the previous bedform exceeded a certain tolerance, a new bedform was identified. Tolerances of 0.25, 0.29, 0.31, 0.33, and 0.34 m were tested before the 0.31 m tolerance ($1.1 \times$ the standard deviation of the difference values) was chosen as the value that best captured bedforms unambiguously compared to bedforms identified visually (Wooldridge 1999). Selection of an appropriate tolerance required a priori knowledge of the bed morphology to differentiate microscale bed protuberances from macroscale bed architecture, highlighting the subjectivity of the technique.

Power spectral analysis
The channel-bed topography was analyzed as a stationary spatial series using power spectral analysis (Bendat and Piersol 1986) to objectively capture the wavelengths of the periodic and random topographic fluctuations. Second-order
Bedform type

Visual identification

Thirty-four bedforms (21 step-pools and 13 cascades) were visually identified in the upper reach and 21 bedforms (18 step-pools and 3 cascades) in the lower reach (Table 1). Visual identification involved assessing the three-dimensional form of alluvial structures after the fixed interval survey had delineated the bed topography, rather than subjectively defining the boundaries of a bedform. This approach was taken because bedforms in coarse-grained streams are not always distinct stair-like assemblages of discrete step-pools or cascades; instead, they vary laterally across the channel and downstream, complicating their quantification and identification.

Figure 6 highlights cross- and down-channel variation in the Mosquito Creek channel bed by comparing right bank and centreline surveyed traverses in the upper reach. Step 6 (S6) is offset between each survey, as the step is raked at an angle to the flow, posing problems for quantification of wavelength values. Steps 1 (S1) and 4 (S4) are nearly coincident between the two surveys, whereas most other steps show differing elevations and slightly offset positions. Only the centreline survey captures a partially channel-spanning cascade (C) in the lower half of the survey, and a number of isolated boulders (B) in pools were captured in the bed profiles. Topographic highs can be identified as isolated boulders from the presence of horizontal bed slopes upstream and downstream of the boulders, whereas steps and cascades show significant elevation change upstream and downstream of them. Steps are largely differentiated from cascades by their greater cross-channel continuity of topographic highs and lows between the two surveyed lines, but the figure suggests that the two-dimensional simplification of complex three-dimensional bedforms is adequate for identifying structured bedforms and drawing out statistical order.

Zero-crossing analysis

Zero-crossing analysis captured most steps but excluded two prominent steps in the lower reach due to the removal of a linear trend rather than a second-order polynomial (Chayes 1970) that would have captured one of the steps and reduced the curvature apparent in the residual plot (Fig. 4D). Table 1 shows that zero-crossing analysis identified more bedforms in the upper reach (38) than any other method because it identified nine isolated boulders situated in pools as stepped bedforms. The size of the boulders is roughly equivalent to the height of the adjacent steps, both of which are captured by zero-crossing analysis as positive residuals. Further, the method could not differentiate between cascades and steps because, like boulders, the two bedform types are positive residuals with similar magnitudes (heights) of departure from the zero-crossing. The technique more accurately captured individual bedforms in the lower reach, as it identified 19 bedforms, which is comparable to the 21 visually observed. The ability of the technique to identify bedforms is related to the longitudinal complexity in each reach (i.e., the presence or absence of isolated boulders). The fact that the isolated boulders were captured in the upper reach is important in terms of defining the degree of bed regularity and suggests that the bed is more complex than the bed in the lower reach.

Bedform differencing technique

The bedform differencing method identified 29 bedforms in the upper reach and 20 in the lower reach (Table 1) without being able to differentiate cascades from step-pools. In both reaches the technique of O’Neill and Abrahams (1984) excluded steps and included isolated boulders, identifying fewer bedforms overall than the other techniques, but its counts were still within 16% of those from the other methods. Tolerances less than 0.31 m identified more bedforms in total, but in doing so captured more isolated boulders than steps, reducing the discriminating power of the technique. Larger
tolerances identified fewer bedforms. The dependence of the method on a single tolerance to identify bedforms limited its ability to identify bedforms due to the large range of grain sizes and bedform heights in Mosquito Creek (Fig. 7).

Bedform wavelength

Visual identification

Wavelength frequency distribution plots separated by reach demonstrate that bedforms identified visually show strong grouping around their means in both reaches (3.55 m in the upper reach and 5.63 m in the lower reach; Fig. 8A). Figure 8B separates bedforms into cascades and step-pools and shows that cascades have shorter mean wavelengths (2.6 m) than steps (5.1 m). Although the cascade and step-pool wavelength values overlap, both bedform types also cluster tightly around their mean wavelengths, suggesting that bedform type can be partially discriminated by wavelength (Fig. 8B).

Zero-crossing analysis

The zero-crossing technique shows strong clustering around its upper reach mean (3.18 m), but more spread in the lower reach wavelength values about its mean of 6.07 m (Fig. 8C). Its upper reach mean is the shortest calculated because the nine isolated boulders it identified have very short wavelengths, as boulders sit in pools, thus halving the expected step-pool wavelength. These values skew the mean to a shorter value than would be obtained if the technique had captured just step-pool structures.

Bedform differencing technique

The bedform differencing technique shows a large spread of values in both reaches, with a clustering of values around the upper reach mean (4.18 m) but little around the lower reach mean (5.82 m; Fig. 8D). The large range of values in both reaches highlights the inability of the method to identify bedforms in Mosquito Creek.

Power spectral analysis

Spectral density functions of the upper and lower reaches (Figs. 9A, 9B) using an FFT indicate periodic fluctuations in the bed profiles. In the upper reach (Fig. 9A), the FFT identified

Table 1. Bedform geometric characteristics and number determined from visual identification, zero-crossing analysis, bedform differencing, and power spectral analysis.

<table>
<thead>
<tr>
<th>Analytical technique</th>
<th>No. of bedforms</th>
<th>Mean wavelength L (m)</th>
<th>Mean height H (m)</th>
<th>Bedform steepness H/L</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Upper reach</td>
<td>Lower reach</td>
<td>Upper reach</td>
<td>Lower reach</td>
</tr>
<tr>
<td>Visual identification⁴</td>
<td>34</td>
<td>21</td>
<td>3.55</td>
<td>5.63</td>
</tr>
<tr>
<td>Step-pool</td>
<td>21</td>
<td>18</td>
<td>4.25</td>
<td>5.99</td>
</tr>
<tr>
<td>Cascade</td>
<td>13</td>
<td>3</td>
<td>2.40</td>
<td>3.47</td>
</tr>
<tr>
<td>Zero-crossing analysis</td>
<td>38</td>
<td>19</td>
<td>3.18</td>
<td>6.07</td>
</tr>
<tr>
<td>Bedform differencing</td>
<td>29</td>
<td>20</td>
<td>4.18</td>
<td>5.82</td>
</tr>
<tr>
<td>Power spectral analysis</td>
<td>4.52</td>
<td>6.40</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

⁴Visually identified bedforms are also classified by bedform type as step-pools or cascades.

Fig. 6. Bed-elevation profiles compared between centreline and right-bank traverses in the upper reach. S1–S8, channel-spanning steps in both profiles; S6 and S6, the same step in both profiles; C and cascades, cascade structures; B, isolated boulders occurring in pools.

Fig. 7. Downstream trends in height (H) and grain size (D90; visual identification data).

Zero-crossing analysis

The zero-crossing technique shows strong clustering around its upper reach mean (3.18 m), but more spread in the lower reach wavelength values about its mean of 6.07 m (Fig. 8C). Its upper reach mean is the shortest calculated because the nine isolated boulders it identified have very short wavelengths, as boulders sit in pools, thus halving the expected step-pool wavelength. These values skew the mean to a shorter value than would be obtained if the technique had captured just step-pool structures.

Bedform differencing technique

The bedform differencing technique shows a large spread of values in both reaches, with a clustering of values around the upper reach mean (4.18 m) but little around the lower reach mean (5.82 m; Fig. 8D). The large range of values in both reaches highlights the inability of the method to identify bedforms in Mosquito Creek.

Power spectral analysis

Spectral density functions of the upper and lower reaches (Figs. 9A, 9B) using an FFT indicate periodic fluctuations in the bed profiles. In the upper reach (Fig. 9A), the FFT identified
a singular, prominent spectral signature with a wavelength of 4.52 m. The upper reach correlogram (Fig. 9A, inset) shows a periodic trend of positive correlations that has a similar wavelength.

In the lower reach (Fig. 9B), the FFT identified three large-magnitude, periodic spectra with wavelengths of 9.60, 6.40, and 3.84 m. Selecting a spectral signature that corresponds to a periodic physical structure in the creek is not possible from an analysis of the spectral density function alone. Instead, analysis of the autocorrelation function in the correlogram (Fig. 9B, inset) shows a poorly defined, repetitive cycle with an approximate wavelength of 6.4 m. This value is coincident with one of the spectra identified and is interpreted to represent the dominant structural wavelength in the lower reach. The multipeaked nature of the spectral density plot and obscured periodicity in the correlogram are due in part to the fact that the series is not fully stationary (see the curvature apparent in the residual plot in Fig. 4D).

Nonetheless, spectral analysis, independent of the other techniques, identified spectral peaks with wavelengths that are similar (slightly greater) to those identified by the other methods, suggesting that the channel bed is ordered enough to exhibit morphologic regularity.

**Discussion of bedform wavelength**

Although the wavelength frequency distribution plots (Figs. 8A–8D) show marked differences in the range of
individual bedform wavelengths identified by each method. Comparison of mean wavelength values indicates that the four techniques attained values within 41% of each other in the upper reach and 14% in the lower reach. The wavelength values converge in the lower reach because its morphology is more ordered (Fig. 4B) than that of the upper reach, with fewer isolated boulders and irregular topography (Fig. 4A) that hampered the ability of the techniques to define discrete steps and pools.

Scaling the wavelength (L) to the width of the channel (W), expressed as \( \frac{L}{W} \), permits Mosquito Creek wavelength data to be compared with published data. Visually identified wavelengths in the upper and lower reaches give ratios of 0.56 and 0.57 m, respectively (Table 1). The trend of greater bedform heights in the lower reach was also found by the bedform differencing technique (0.82 m in the upper reach and 0.86 m in the lower reach), except the differences are smaller and the magnitudes larger. The large values are a function of the tolerance value excluding shorter bedforms.

Visual identification also shows that step-pools have greater mean heights (0.62 and 0.67 m) than cascades (0.46 and 0.55 m) in the upper and lower reaches, respectively (Table 1). This result indicates that more grains aggregate to form steps than cascades, which increases their prominence in-channel.

Controls on bedform geometry

Individual wavelengths, within a reach, in Mosquito Creek are only weakly controlled by step height (Figs. 10A–10C), whereas Chartrand and Whiting (2000) report a very strong relationship between mean wavelength and mean height \( r^2 = 0.93 \). Plotting individual values shows that there is a high variance in the Mosquito Creek data, which may result in weaker relationships than those reported from averaged data.

Between-reach differences suggest that the abundance of shorter wavelength cascades in the steeper upper reach (0.075) reduces the mean wavelength in the reach (Grant et al. 1990; Montgomery and Buffington 1997), whereas slope declines in the lower reach (0.060) as mean wavelength values increase (Table 1). This inverse relationship between step spacing and slope is a consistent finding in step-pool studies (Whittaker 1987; Grant et al. 1990; Wohl et al. 1997; Chin 1999; Chartrand and Whiting 2000), and the range of mean wavelength values between reaches does not overlap, suggesting that slope, in part, controls bedform spacing.

Averaging wavelength and height data enable bedform steepness to be calculated as the ratio of the mean height to the mean wavelength \( \frac{H}{L} \), which allows data sets to be compared more equivalently. In Mosquito Creek, bedform steepness ranged from 0.20 to 0.15 in the upper reach and from 0.16 to 0.11 in the lower reach (Table 1). These values compare favorably with published values of 0.13 (Chartrand and Whiting 2000), 0.15–0.10 (Church 1992), and Chin’s (1999) range of ratios from 0.14 in headwater reaches to 0.06 in downstream reaches.

Scaling bedform steepness \( \frac{H}{L} \) to channel slope (s), expressed as \( \frac{H}{L}/s \) (Whittaker and Jaeggi 1982; Abrahams et al. 1995), gives a range of values from 2.0 to 2.7 in the upper reach and from 1.8 to 2.7 in the lower reach of Mosquito Creek. Values greater than 1.0 indicate that pool bottoms have reverse slopes and that local step relief \( H \) accommodates more drop than the mean channel bed gradient. The range of values agrees with published \( \frac{H}{L}/s \) ratios for streams with slopes between 0.060 and 0.075 (Abrahams et al. 1995; Wohl et al. 1997; Chin 1999; Chartrand and Whiting 2000; Zimmermann and Church 2001). The result speaks to the rapid development (less than 20 years) of a stepped profile in Mosquito Creek that mirrors natural stream geometries.
Fig. 11. Wavelength (L) as a function of grain size (D₉₀; visual identification data). Grain size is calculated from the average of the five largest stones at each step and most cascades and is approximated as equaling D₉₀.

There is no relationship between wavelength and the average of the five largest step-forming grains (Fig. 11), a finding similar to that from the work of Chin (1999) using the same measures. In contrast, Chartrand and Whiting (2000) found strong relationships between wavelength and D₉₀ (r² = 0.72) and D₄₃ (r² = 0.59). The strength of the correlations of Chartrand and Whiting decreases with increasing grain size, suggesting that the largest grains do not control step spacing, but rather that the size of the step structure is related to the wavelength. Architecturally, steps are built vertically from the stacking and interlocking of grains, meaning that it is the aggregate nature of the imbricate grains that controls the height and size of a step, not simply a few large grains.

Conclusions

Mosquito Creek bed profiles examined with four analytical techniques show that visual identification of coarse-grained bedforms provided more information about bedform geometry and type than zero-crossing, bedform differencing, or power spectral analysis. Step-pools are visually differentiated from cascades by pronounced, discrete, channel-spanning steps that alternate with channel-spanning pools, whereas cascades are multi-tiered, partially channel-spanning structures. Grain-size partitioning between steps and pools further enhances the distinction between them, with coarser grained stones forming steps and the finer fraction lining pools. Fixed interval surveying minimizes the subjectivity of the method in defining the boundaries of individual bedforms.

Longitudinal bed complexity caused the zero-crossing and bedform differencing techniques to identify isolated boulders in pools as discrete bedforms, and the large range of grain sizes and heights prohibited the bedform differencing technique from consistently identifying bedforms. The zero-crossing technique is appropriate for the objective identification of gravelly bedforms because it is divorced from the absolute magnitude of topographic highs and lows (unlike bedform differencing) and its determination of wavelength distributions is similar to visually identified distributions.

Power spectral analysis identified periodic wavelengths in both reaches, demonstrating that within 20 years fluvial action has formed a regularly patterned cascade and step-pool architecture in a previously planar-bedded engineered channel. The stepped structures correspond in their geometry (i.e., H/L ratios) to features discussed elsewhere (Chin 1999; Chartrand and Whiting 2000). Channel slope partially controlled bedform geometry (wavelength and height), and bedform height weakly controlled individual step spacing, but there was no relation between wavelength and grain size (D₉₀).

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