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MEASURING THE REACH-SCALE GEOMORPHIC DIVERSITY OF STREAMS: APPLICATION TO A STREAM DISTURBED BY A SEDIMENT SLUG

REBECCA BARTLEY[a]* and IAN RUTHERFURD[b]

[a] *CSIRO Land and Water, PO Box 780, Atherton, Queensland 4883, Australia*
[b] *Department of Geography and Environmental Studies, Melbourne University, Parkville, Victoria 3010, Australia*

ABSTRACT

There is increasing evidence that greater physical diversity in a stream leads to a greater diversity of habitats, and hence species. Human impact has reduced the physical diversity within many stream systems. This paper reviews a range of techniques used to measure the physical diversity of a stream reach and specifically examines variability measures of a stream's thalweg, cross-section and sediment size at the scale of millimetres to metres. Each measure was evaluated against synthetic data with different levels of diversity. From the original thirteen, eight measures were considered appropriate for application to data measured in the field. Creightons Creek (Victoria, Australia) was selected as a test site as it contains areas that are in their original geomorphic condition, as well as sections that have been disturbed by increased bed-load in the form of a sediment slug. All eight measures showed that the area impacted by the sediment slug was less diverse in terms of its geomorphic variability than the unimpacted reaches. This suggests that massive increases in sediment load to streams will reduce the geomorphic complexity of a stream, and in turn, the diversity of habitat for biological communities. Copyright © 2005 John Wiley & Sons, Ltd.

KEY WORDS: habitat; geomorphic variability; sediment slugs

INTRODUCTION

Human impact on stream systems often leads to a simplification of their physical or geomorphological structure, or reduced 'geodiversity' (Semeniuk, 1997). Sediment slugs, which are large anthropogenically derived pulses of bed sediment, appear to reduce the morphological variability of stream systems through space and time. We examined stream structure because physical diversity and heterogeneity in streams is known to correlate well with biological diversity (e.g. Chisholm *et al.*, 1976; Downes *et al.*, 1998; Gorman and Karr, 1978) and reduced surface roughness and heterogeneity can in turn reduce species diversity, population abundance and recruitment (McCoy and Bell, 1991; Kolasa and Rollo, 1991). Thus, physical diversity is acknowledged as one indicator of stream health (Norris and Thoms, 1999) and diversity of habitat, if it can be described, paves the way for predicting the potential diversity of biota (Newson and Newson, 2000). Using measures of variability (rather than mean condition) will also allow changes of physical diversity to be compared within and between streams rather than persisting with the 'case study' approach that dominates fluvial geomorphic research.

To investigate changes in the physical or geomorphic structure of a stream requires rigorous methods for measuring morphological variability. There are, however, few techniques available to measure the geomorphic structure of a stream reach, at a scale that is compatible with aquatic habitat studies (e.g. Downes *et al.*, 1998). Many studies use methods that are applicable only to particular organisms or a specific environment, which prohibits direct comparison and hinders any general understanding of the relationship between physical and biological diversity (McCoy and Bell, 1991). The study of physical diversity in streams has also been hampered by a lack of tools for quantitatively measuring spatial heterogeneity (Cooper *et al.*, 1997).

The aim of this paper is to describe and test a set of indicators that measure how the geomorphic variability of a stream has changed following the impact of sediment slugs. However, the indicators described could also be used on

*Correspondence to: Rebecca Bartley, CSIRO Land and Water, PO Box 780, Atherton, Queensland 4883, Australia.
E-mail: Rebecca.bartley@csiro.au

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other disturbances such as changed flow regime or channel incision. This paper specifically tests measures of geomorphic diversity related to variation in thalweg diversity, cross-sectional form and sediment size. These three geomorphic variables are considered to be useful (non-biological) indicators of the physical diversity in a stream reach. They are also representative of the scales of different habitat units (after Frissell *et al.*, 1986), from millimetres (sediment size diversity), to centimetres (cross-sectional diversity) through to several metres (thalweg diversity).

We compared measures using a number of synthetic data sets that had different levels of variability. Those measures that are considered suitable are then tested on river data collected from a stream that has been impacted by a slug of sand: Creightons Creek, in Central Victoria, Australia. No attempt is made to directly relate the level of physical diversity to biological data; however, other research has shown significant correlations between physical diversity and the number and diversity of fish species (e.g. Jungwirth *et al.*, 1993).

MEASURES OF PHYSICAL DIVERSITY IN STREAMS

The level of geomorphic variability present in a stream reach is a function of processes operating at a range of scales. At the larger scale, a reach is controlled by regional geology and basin plan-form, which affect the slope of a reach, and determine whether a reach is in an erosional or depositional area. At the next scale down, geomorphic variability is controlled primarily by catchment area and hydrology, which produces variation in features such as pools and riffles. Finally, there is the small-scale variation that is influenced by factors such as woody debris and localized geological structures such as bedrock outcrops. The variability produced at each of these scales is not independent because feedbacks operate between levels. However, the variability imposed at each individual scale produces the overall variability within a given reach. It is this 'combined' physical variability that is of interest to ecologists and geomorphologists as it has implications for the level of habitat diversity present in a given stream reach. However, measures of stream physical diversity are limited, and those that do exist often focus on one particular feature or scale.

There are several methods for measuring physical habitat in streams. These include the Instream Flow Incremental Methodology (IFIM) (e.g. Bovee, 1982; Irvine *et al.*, 1987; Orth and Maughan, 1982), Physical Habitat Simulation System (PHABSIM) (e.g. Gan and McMahon, 1990; Orth and Leonard, 1990; Williams, 1996) and biotope approaches (e.g. Rowntree and Wadeson, 1996). These methods rely on measuring a flow variable which is dependent on discharge. Thus, if a habitat is going to be reliably categorized, it must be measured over a range of discharges, which is often time-consuming, expensive and dangerous. In addition, in many of these methods there is error in identifying and classifying habitat types. Roper and Scarnecchia (1995) found that differences among observer's classifications increased with the number of habitat types and decreased with the level of observer training.

This paper proposes a number of measures that quantify the physical variation in a stream reach independently of flow. Although flow and velocity characteristics are considered important environmental factors affecting instream biota (Allan, 1995), we argue that the morphology of the stream accurately reflects the range of flows that move through the channel (e.g. Emery *et al.*, 2003). Thus, the morphology of a stream can be used as a surrogate (or indicator) of the flow conditions in a reach. Removing flow-related variables from the process of quantifying physical diversity considerably reduces the time and financial costs of collecting data. Using spatial rather than temporal based measures also means that variability can be compared between different reaches or streams, despite differences in water levels. Spatial rather than temporal data also provide a range of new analysis techniques not commonly used in many aquatic habitat studies. As Newson and Newson (2000, p. 213) point out: 'The techniques of spatial analysis that are now common place in terrestrial landscape ecology should be applied to survey data sets in an attempt to refine our predictive abilities for aquatic habitat diversity'. The geomorphic measures presented in this paper provide a step towards gaining a greater understanding of the link between the physical structure of the stream and aquatic biological diversity.

METHODS

Variability dimensions

Three physical measures, representing a range of scales, were selected to characterize geomorphic variability.

(1) *The thalweg or longitudinal profile*. The thalweg is the deepest path of water within a reach and is made up of a series of topographic undulations, that in many stream systems form pools and riffles. Jungwirth *et al.* (1993) found that the number and diversity of fish species was positively correlated with the variance of the thalweg depth. Many streams do not have structured pool and riffle sequences, so we considered all longitudinal variation in the bed (not water level), at the scale of metres.

(2) *Cross-section shape*. Cross-sections are used to describe river channel form (e.g. Park, 1995; Richards, 1982), and are traditionally distance and elevation measures between left and right banks, based on a nominated discharge, usually bankfull. Cross-sections were used in this study as stream morphology is considered to be sensitive to large-scale disturbances such as sediment slugs. In addition, the small-scale (0.01–1.0 m) features within a cross-section provide important habitat for aquatic flora and fauna (e.g. edgewater habitats and macrophyte beds). Cross-sections can be used to measure lateral habitat diversity that is not necessarily picked up when measuring thalweg variability. In this paper the variability of the entire cross-section is used to estimate the morphological diversity across the stream.

(3) *Variability of sediment size*. The size, variability and characteristics of the bed sediments in a stream influence the kinds of habitats available for benthic communities (Alexander and Hansen, 1986; Wene and Wickliff, 1940; Williams and Smith, 1996). Thus, changes in the sediment load, and/or type, usually have complex long-lasting physical and biological consequences (ASCE, 1992). The relationship between benthic communities and sediment is complex, and the ASCE (1992) highlighted that 'surficial bed material is often the primary influence on community composition and density'. When the sediment characteristics of a stream are dramatically changed, there can also be a dramatic change in the rate of sediment movement, which can be detrimental for benthic communities, particularly in the short term (e.g. Culp *et al.*, 1986; Death and Winterbourn, 1995; O'Connor and Lake, 1994).

These three physical measures were chosen as they represent diversity operating at different scales, and together are considered to provide an overall estimate of reach-scale variability. For the remainder of this paper, the term 'geomorphic variability' will refer collectively to the variability of the thalweg, cross-section and sediment size in a reach. Other factors such as sediment stability and large woody debris (LWD) density are also considered important in measuring geomorphic variability; however, discussion of these factors is beyond the scope of this paper.

Measures used

The initial task in this study was to determine a range of techniques that were suitable for quantifying the variability of each of the three factors–thalweg, cross-sections and sediment size. As described above, the emphasis is on measures that are useful for assessing the effects of sediment slugs. At least thirteen different measures from a variety of disciplines were identified as suitable for quantifying the variability of thalweg and cross-section profiles (Table I, Figure 1). A further discussion of measures for thalweg profiles can be found in Bartley and Rutherfurd (2002). For all of the measures described in Table I the higher the value, the higher the variability. The variability of particles within a sediment sample can be described using three well established measures: skewness, sorting and kurtosis (Briggs, 1977), as well as substrate heterogeneity (Schwoerbel, 1961; Williams, 1980). Each of these measure is summarized in Table II. Each measure was calculated using a cumulative frequency plot of the sediment size distribution, with the y-axis representing the percentage sediment retained, or the percentage coarser.

Applying the measures to synthetic data sets

Using all of these thirteen measures will usually be redundant. Therefore, a series of synthetic data sets with clear, known differences in variability, were used to determine which measures were the most appropriate. However, it is not possible to create a synthetic curve with a specific level of 'variability' because there is no single measure for determining the 'variability' of a line. Without a quantitative basis for such an analysis, a rigorous replicated statistical approach is inappropriate. Therefore, in this paper, we examined how each of the measures evaluated variability; this is done using exploratory statistical methods. The measures were evaluated on the following criteria: (1) their ability to differentiate between different levels of variability of the synthetic curves; (2) how each measure evaluated variability compared to the other measures (i.e. certain measures may evaluate variability differently from others—there is no one correct method); and then (3) if two measures provided very similar results, the measure that was computationally easier to calculate was considered more appropriate.

Table I. Summary of the variability measures applied to the thalweg and/or cross-section profiles. The two right-hand columns describe the adjustments made to each of the techniques to bring the results from all the measures within the same order of magnitude (NA means not applied)

Technique	Description of method	Source/reference	Method of calculation	Comments	Correction to original data	
					Thalweg	Cross-sections
Loess	'Loess curves' (*L*) is a non-parametric smoothing technique used to identify underlying trends in noisy data (with some adjustment for extreme observations or outliers).	Makridakis *et al.* (1998)	The calculations were carried out using the Loess function in SYSTAT™ statistical package (Version 9.0).	*N* of 0.3 provided the most consistent results for all data sets tested (i.e. least error). To evaluate the variability of each thalweg profile, the mean squared error (MSE) of the residuals is calculated.	No correction	NA
Standard deviation of depths (*SD*)	In this method, the spatial variation of residual depths (σd_r) was assessed over different lengths of channel. To make the method independent of water depth, we used the standard deviation (*SD*) of bed elevations relative to the highest point of the bed (i.e. the highest point along the thalweg profile).	Adapted from Lisle (1995)	Excel		Multiplied by 10	NA
Trapezoidal method (*Trap*)	To determine the change in shape variability, a trapezoidal function is fitted to each cross-section (Figure 1a). The variation is then the residual sum of squares of the difference between the two curves. The standard error (SE) of the estimate is then used as a measure of the variation of the actual values from the fitted values.	Original technique	Excel and Visual Basic	The point at which the bed was separated from the banks was determined by: (a) minimizing the standard error of the trapezoid when plotted against the cross-sectional data; and (b) noting the position of the low flow (95% duration) wetted perimeter in each cross-section.	NA	Multiplied by 10
Fractal mean	The fractal dimension (*D*) is calculated using the 'fractal mean'. The 'fractal mean' calculates *D* by starting at different randomly chosen points along the cross-section, and 'walks' backwards and forwards using a boot-strapping technique.	Nams (1996)	The program VFractal (Nams 1996; http://www.nsac.ns.ca/envsci/staff/vnams/Fractal.htm) was used for this analysis.	*D* was calculated for a 95% confidence interval, using a random seed start number of 1.0, a window range of 0.25 and the number of divisions were set to 30.	$(D-1)\times 10$	$(D-1)\times 10$

Chain and tape (*CT*)	The chain and tape (*CT*) method is calculated as the ratio of the apparent distance to the linear distance (L_A/L_s), which is the length of the topographic bed distance (L_A) divided by the length of the reach or cross-section (L_s) (e.g. Figure 1b).	Similar to that described in Beck (1998) and Connell and Jones (1991)	Excel	The chain and tape method was slightly adjusted for the cross-sections to account for variations in length. In this case it was calculated simply as the wetted perimeter or length along the bed divided by the width of the channel at bankfull.	(C − 1) × 10	(C − 1) × 10
Vector dispersion (*VD*)	Vector dispersion (*VD*) is a measure of angular variance (θ). It was calculated from a two-dimensional modification of the formula in Carleton and Sammarco (1987) and given by $VD = \frac{\left(n - \left[\sum_{i=1}^{n}\left(\frac{A}{C}\right)\right]\right)}{n-1}$ where n is the number of points along the transect, and A is the distance between each point (e.g. 2 m) and C is the distance along the bed (e.g. Figure 1c).	Beck (1998) and Carleton and Sammarco (1987)	Excel	The same equation was used for both the thalweg and cross-sections. The differences in cross-section lengths are already accounted for within the equation (C value).	Multiplied by 100	Multiplied by 10
Sum of squared height differences (Σdh^2)	The value is the summation of the squared differences between consecutive points along a topographic profile.	McCormick (1994) and Beck (1998)	Excel	To account for the different cross-section lengths, each cross-section was divided by the wetted perimeter (WP).	Divided by 10	Divided by 10

(*Continues*)

Table 1. Continued

Technique	Description of method	Source/reference	Method of calculation	Comments	Correction to original data	
					Thalweg	Cross-sections
Degree of wiggliness (w)	The 'degree of wiggliness' (w) measures the deviation, from the mean elevation, of angles between points along a profile. This method was adapted slightly to calculate the deviation of height elevations (rather than angle) between successive points as follows: $$w = \sqrt{n \sum (\Delta\Phi_i)^2}$$ where n is the number of points and $\Delta\Phi$ is the vertical deviation of each point from mean elevation. The value of w is dependent on the length of the line, and so values should only be compared for profiles of equal length.	Ghosh and Scheidegger (1971)	Excel	As the cross-sections are generally of different lengths, the non-dimensional degree of wiggliness ($\bar{w}$) is more suitable and was applied to all of the cross-sections in this paper. This is simply w divided by the wetted perimeter (WP), which then describes the variability per unit length of the line (or cross-section).	Divided by 10	No correction needed

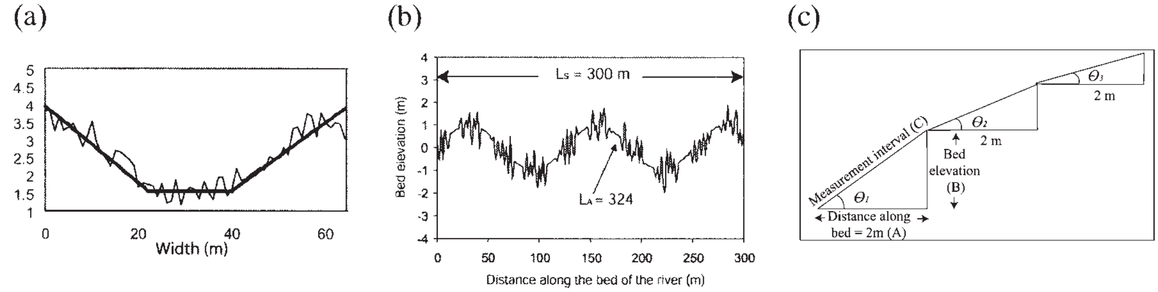

Figure 1. (a) Application of the trapezoidal method to stream cross-section profiles. (b) Example of the chain and tape method applied to hypothetical thalweg data, where L_A is the apparent distance (distance along the bed) and L_s the linear distance (straight line distance). (c) Description of vector dispersion technique applied to thalweg data (after Beck, 1998), where A is the distance between points, B is the bed elevation and C is the distance along the bed calculated using Pythagoras theorum

Thalweg measures. Six synthetic thalweg profiles of 300 points were created. The six curves cover the basic forms of variability that can be expected for natural river thalweg profiles, and provide an example of 'decreasing' heterogeneity (Figure 2). A number of specific characteristics are used to define variability for thalweg profiles. These include the variation in amplitude (reflecting high variability in the depth along a stream bed caused by features such as pools and riffles), as well as high frequency (reflecting high surface area and therefore greater available habitat). In addition to amplitude and frequency, the random (or superimposed) element created by features such as woody debris is also important. High levels of amplitude, frequency and random variation produce greater surface area and therefore habitat in a stream. These synthetic profiles were developed to reflect the extreme range of conditions found in measured thalweg profiles from both disturbed and un-disturbed streams (data not shown). In most natural streams, the thalweg will often be a combination of a number of curve types; however, for the purpose of differentiating between the different measures, the curves were given an extreme morphology (e.g. curve B has high magnitude compared to frequency). An analysis technique was considered suitable when it scored high values for those profiles with both large amplitude, frequency and random variation.

A sinusoidal curve was the basis for each profile which had varying amplitude and frequency. Curves A and C also contained a random element, created by a random number generator (Figure 2). The curves are organized from greatest variability (curve A) to the least variability (curve F). There is no 'correct' way to define the variability of a line, therefore it is not possible to have a true standard measure of variability against which other measures can be tested. However, the synthetic profiles are considered to be different enough (based on the criteria used to assess variability—amplitude, frequency and random variation) to be able to differentiate between those techniques that are suitable and those that are not.

To assess the effect of random variability in curves A and C, the following analyses were carried out. Five replicates of curves A and C were developed (curves not shown) that had the same curve structure but with different random patterns (i.e. different starting points using the random number generator). These replicate curves were then subject to the same analysis and the results were assessed using a one-sample t-test to determine if varying the random element of the curve actually had an impact on the overall results in terms of ranking the curves. The assumptions of normality and homoscedasticity were met in this analysis.

Cross-section measures. To test the various cross-sectional analysis techniques, ten synthetic cross-sectional profiles were developed to represent different levels of variability. Each was constructed using a parabolic curve, and a random profile (calculated from random number generator) (Figure 3). The level of randomness and the overall shape of the curves was chosen to represent realistic river cross-section profiles. Unlike the thalweg profiles, cross-sections usually have varying widths. To take this into consideration, the curves differed in length as well as shape variability. This provided a more rigorous test of the analysis techniques, and enabled the level of variability per unit width to be evaluated. A cross-section is considered to be highly variable when there is both

Table II. Summary of the variability measures applied to the sediment samples

Technique	Description of method	Equation	Source/reference	Comments
Phi skewness	Skewness is a measure of the asymmetry of a sediment sample, or the non-normality of the distribution Measuring skewness requires a comparison of the mean and median phi values.	$Sk = \frac{\phi84-\phi50}{\phi84-\phi16} - \frac{\phi50-\phi10}{\phi90-\phi10}$	Briggs (1977)	The distribution can be either positively or negatively skewed. Positive skewness represents a fine tail to the sample, negative skewness represents a 'coarse' tail.
Phi sorting	Sorting is a measure of the dispersion or scatter of sediment within a sample, and is simply an expression of the standard deviation of the size distribution.	$Sorting = \frac{\phi84-\phi16}{2}$	Briggs (1977)	A high degree of sorting is represented by a low value. Hence, a sample with a wide range of sample sizes will be poorly sorted and have a high sorting value, whereas a sample containing a small number of phi sizes would have a low sorting value.
Kurtosis	Kurtosis measures the 'peakedness' of the size distribution. Kurtosis incorporates aspects of both sorting and the degree of non-normality	$Kurtosis = \frac{\phi90-\phi10}{1.9(\phi75-\phi25)}$	Briggs (1977)	A poorly sorted sample will tend to have a relatively flat particle size distribution.
Substrate heterogeneity	The heterogeneity, or degree of particle size diversity, can be estimated by using the ratio of the D_{10} to D_{60} of the sediment size in millimetres. This is calculated using the cumulative percentage of sediment retained in sieves.	$\text{Heterogeneity} = D_{10}/D_{60}$	Schwoerbel (1961)	Williams (1980) applied this method to assess the relationship between species abundance and substrate heterogeneity, and suggests that values will range from approximately 1.0 for low heterogeneity, to around 6.0 for high heterogeneity, although some streams may have heterogeneities greater than 10.0.

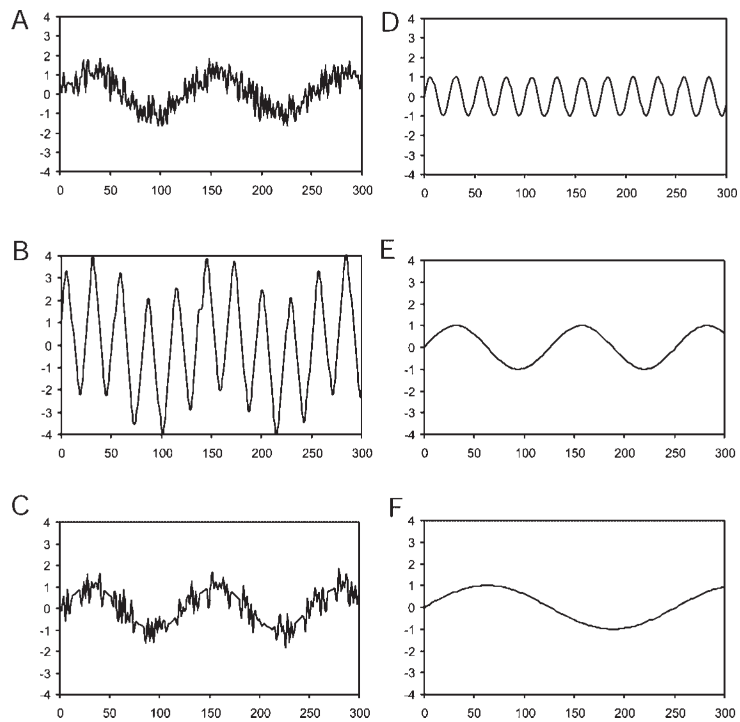

Figure 2. Synthetic thalweg curves. Curve A was developed by alternately adding and subtracting a random number from a basic sinusoidal curve (amplitude of 1.0 and a frequency of 0.1). Curve B is a sinusoidal curve with an amplitude of ± 3 and frequency of 0.1. Curve C was developed by adding a random number to the first ten values of the sine curve (amplitude of 1.0 and a frequency of 0.1), then having five values with no random number added; this pattern was continued for the remainder of the profile. Curves D, E and F were sinusoidal curves with an amplitude of 1.0 and a frequency of 0.5, 0.1 and 0.05, respectively

high vertical variation, as well as high horizontal, or angular variation. A cross-section does not necessarily have to be very deep (i.e. from bankfull) to be considered variable. It does, however, have to have a range of depths and surfaces at a variety of elevations to be considered morphologically diverse.

The curves in Figure 3 are listed in order from highest expected variance (A) through to the lowest expected variance (J). In general, the curves have a similar amplitude, as all cross-sections have a basic parabolic or trapezoidal form; however, the frequency level, and complexity of the random elements, decreased from curve A to J. The greater the combined frequency (which suggests there are a greater range of depths) and random variability, the greater the surface area, and thus potential habitat. To test how variability changes per unit width, four groups of paired curves were used. Curves A and C, B and D, G and H, and I and J are pairs of the same curve, with the first being twice the length scale of the second. Curves E and F are not matching pairs, but are slight deviations from curve D. Increasing the number of synthetic curves was initially considered to be important for evaluating how the different techniques measured variability. However, as discussed with reference to the thalweg profiles, it is difficult to use a quantitative technique to determine the exact order of the profiles in terms of high and low heterogeneity, as this would produce a circular argument within the analysis. Increasing the number of curves would not necessarily help differentiate between high and low variability. Therefore, the order shown in Figure 3 is considered to be an appropriate range according to the criteria outlined, and it is expected that the shorter of the paired curves will have greater variability than the long curves, per unit length.

Sediment size measures. By definition, at least three of the techniques (skewness, sorting and kurtosis) measure different aspects of the sediment size distribution. The fourth measure, heterogeneity, is the only technique that has not been evaluated against the other measures in the literature. To assess how each of the techniques evaluated the variability of the data, and in particular how the heterogeneity index compared with the other measures, eight synthetic sediment samples were developed (Figure 4). All the samples were 1000 g and all had size

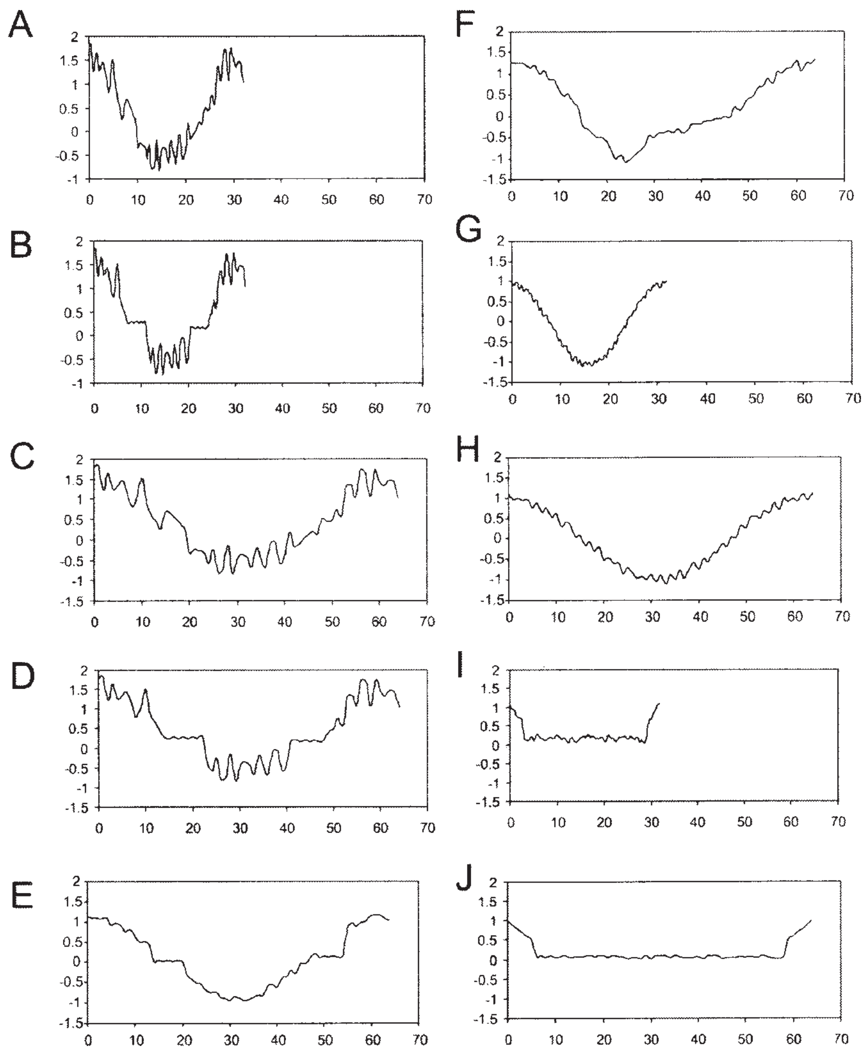

Figure 3. Synthetic cross-section profiles. Curves A–H were constructed using both a parabolic curve and random profile. Curves I and J were given a flat bottom rather than parabolic form. Curves A and C, B and D, G and H, and I and J are pairs of the same curve, with the first being twice the length scale of the second. Curves E and F are not matching pairs, but are slight deviations from curve D

distributions between 0.063 mm and 8 mm (or 4ϕ and -3ϕ). This is a typical range of sediment sizes for streams containing sediment slugs. Sample 1 represents an even distribution of sediment sizes. Samples 2 and 3 have greater proportions of coarse sediment, with sample 2 being the coarsest. Samples 4 and 5 have an increased proportion of fine sediment, with sample 4 being finer than 5; samples 2 and 4, and 3 and 5, are exact opposites of each other (i.e. reversed). Samples 6, 7 and 8 were developed using a random number generator, and thus have a random range of sizes. Each of the measures was assessed according to their ability to differentiate between samples that are dominated by a few sediment sizes (low variability), compared to samples that have a wide range of sediments (high variability).

RESULTS FROM THE SYNTHETIC DATA SETS

Thalweg results

Curve B was described as most variable by the *Loess, SD* and *Fractal* techniques, whereas the measures *CT, VD,* Σdh^2 and *w* put curve A ahead of curve B, then C (Figure 5). For the *Loess, SD* and *Fractal* techniques, curve C had

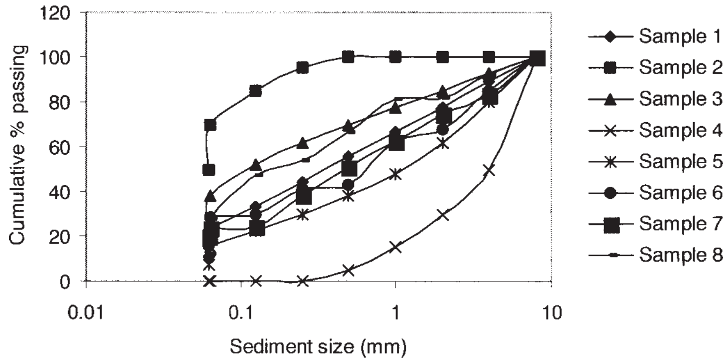

Figure 4. Cumulative plots of the eight synthetic sediment samples plotted on a log scale

a similar level of variability to curve D, whereas for the remaining techniques curve C was more similar to curves A and B. This result suggests that the *Loess, SD* and *Fractal* techniques tends to favour high amplitude with low frequency (e.g. curve B) over high frequency with medium amplitude (e.g. curves A and C). This means that different techniques may be required when trying to differentiate between large-scale (higher amplitude) and small-scale (lower amplitude) variability within a thalweg profile. This finding is also supported by the fact that the *Loess, SD* and *Fractal* measures did not differentiate between curves C and D, despite curve C having much higher frequency.

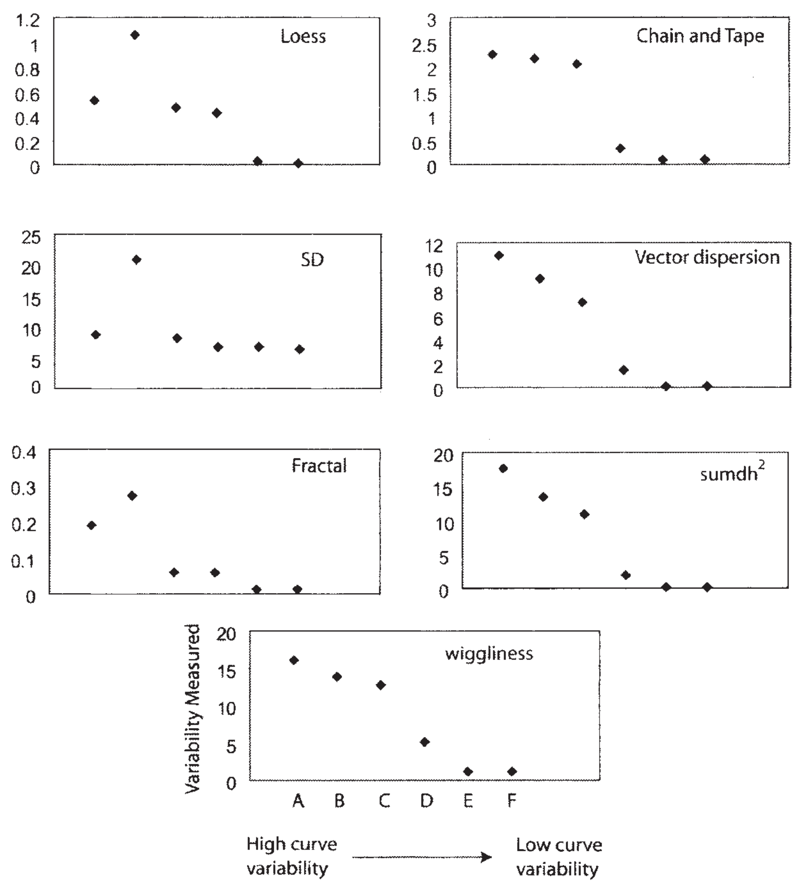

Figure 5. Results of data analysis of the synthetic thalweg curves. All plots have the same x-axis ranging from curve A on the left to curve F on the right

Table III. Results of the synthetic thalweg curves. Note that the df was 4 for all analyses of curves A and C

Curve		L	SD	D	CT	VD	sum dh^2	w
A	mean	0.557	9.218	0.19	2.283	11.355	17.744	16.254
	t	0.000	−0.375	0.000	−0.003	0.001	0.000	0.001
	p	1.000	0.727	1.000	1.000	0.999	1.000	0.999
B	—	1.056	21.200	0.27	2.230	9.280	13.445	14.233
C	mean	0.459	8.479	0.04	2.190	7.509	11.601	13.084
	t	−0.046	−0.004	0.000	0.045	0.001	0.000	0.160
	p	0.966	0.997	1.000	0.966	0.999	0.999	0.988
D	—	0.432	7.100	0.04	0.440	1.480	1.842	5.504
E	—	0.024	7.100	0.01	0.150	0.093	0.115	1.229
F	—	0.006	6.900	0.01	0.150	0.079	0.108	1.172

There were no significant differences between the results for the replicate profiles of curves A and C (Table III). There were slight variations in the results for each of the replicate curves A and C for each of the analysis techniques (data not shown); however, the difference was not significant enough to affect the final ordering of the results.

The measures reflect different aspects of variability; however, there are similarities between some measures, and it is possible to arrange the techniques into different groups. The *CT, VD,* Σdh^2 and *w* techniques (group 1) produced similar results when applied to the synthetic curves (Figure 5). This is because these methods calculate the level of angulation of each point along the line. The remaining three techniques, *Loess, SD* and *Fractal*, produced similar response curves; however, they use slightly different ways to calculate variability. The *Loess* and *Fractal* techniques (group 2) describe the arrangement of each point based on the position of previous points along the curve; and the *SD* technique (group 3) measures the deviation of points away from the mean elevation. Each group provides a slightly different estimate of variation. Both groups 1 and 2 look at how ‘wiggly’ the line is, whereas group 3 calculates the overall vertical change in the profile.

We conclude that one technique from each group is adequate to describe the variability of the thalweg profiles. Two criteria were used to choose the most appropriate technique from each group: (a) how the measure evaluated variability compared to the other measures; and (b) which analysis technique is computationally the least intensive.

Of the factors in group 1 (*CT, VD,* Σdh^2 and *w*), the wiggliness factor (*w*) was considered the most suitable technique as it evaluated the horizontal deviation of height elevations between points, but because it is dependent on the length of the line, it also takes horizontal variation into account. Hence, the wiggliness factor will be used to represent group 1. Group 2 has only two factors (*L* and *D*); as fractal analysis (*D*) is useful for evaluating variability across a range of scales, and it has been successfully applied in terrestrial habitat studies (e.g. Nams, 1996), it will be used to represent group 2. Group 3 is represented by *SD*. In summary, thalweg variability can be adequately described using the wiggliness factor (*w*), fractal dimension (*D*) and standard deviation of depths of the bed profile (*SD*).

Cross-section results

Measures *D, CT, VD,* Σdh^2 and *w* all rank the cross-section curves in the same order of variability: with curve B and D as the most variable, and curves J and I as least variable (Figure 6). The trapezoidal measure provided different results to the other measures, suggesting that curve D has the highest variability, followed by B, C then A.

In the remainder of this paper, a number of these measures will be applied to cross-sections measured on a real (rather than synthetic) stream. Based on the synthetic data, application of any of the techniques (*D, CT, VD,* Σdh^2 and *w*) would provide similar and appropriate estimates of cross-sectional variability; only the trapezoid method (*Trap*) would provide a slightly different estimate. However, it is not practical to apply all of the techniques described here, so a sub-group of techniques is chosen based on (a) how the measure evaluated variability compared to the other measures; and (b) which analysis technique is computationally the least intensive.

As *VD* and *w* both calculate the deviation of angles around each data point, only one of them would be required. The *VD* measure takes the length or width of the cross-section into account within the original calculations, and is therefore considered computationally the least intensive. On this basis, *VD* was adopted for this study.

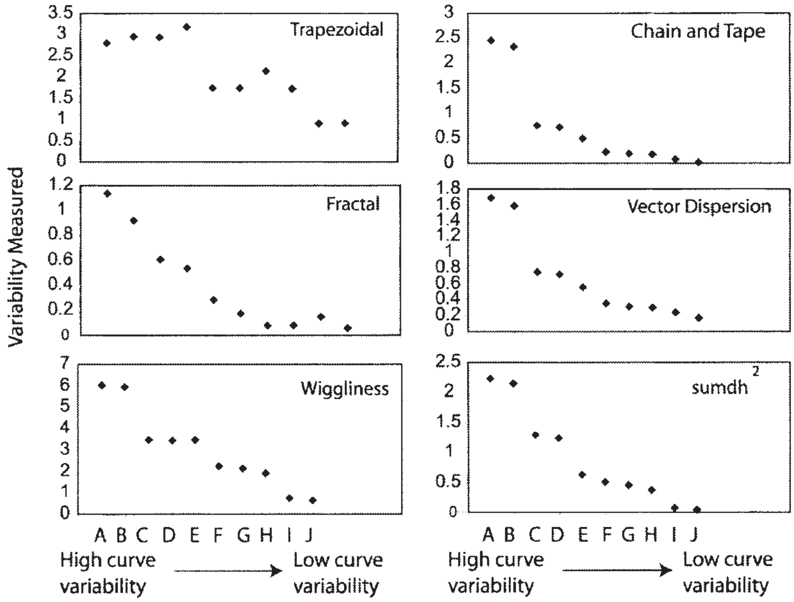

Figure 6. Results of synthetic cross-sectional analysis. All plots have the same x-axis ranging from curve A on the left to curve J on the right

Of the remaining techniques, fractal analysis was not as well suited to the parabolic-shaped cross-sections as they were to the longer linear-based thalweg profiles, hence it was not used. The final two techniques are Σdh^2 and *CT*. The Σdh^2 provides an estimation of height deviations across a profile, whereas *CT* is simply a ratio of lengths; it does not really incorporate changes in height or angle along the transect. For this reason, Σdh^2 was adopted to represent cross-sectional variability and, therefore, potential habitat variability. The trapezoidal technique (*Trap*) performed differently from all of the other techniques, therefore it was also adopted.

In summary, the initial six measures that were chosen to quantify the cross-sectional heterogeneity were reduced to three: vector dispersion (*VD*), sum of the squared height deviations (Σdh^2) and the trapezoid method (*Trap*). Each of these measures uses slightly different methods to quantify the variability of a cross-section. The *VD* method measures the deviation of angles along the line, the Σdh^2 measures the change in elevation between consecutive points, and the trapezoid method measures the deviation of a cross-section away from a trapezoid. Together, these three measures provide a comprehensive description of cross-sectional variability.

Sediment size results

Based on the results (Table IV) all of the techniques were able to differentiate between the samples with high heterogeneity (e.g. Sample 1) compared to samples that are dominated by coarse sediment (e.g. Sample 2; typical

Table IV. Results of the synthetic sediment sample analysis

Sample	Skewness	Sorting	Kurtosis	Heterogeneity
1	0.01	3.06	16.80	19.96
2	1.00	0.97	1.75	1.33
3	0.40	2.93	15.40	6.67
4	−0.91	1.02	1.96	6.05
5	−0.38	2.98	15.63	46.67
6	−0.24	3.46	21.23	28.09
7	−0.11	3.55	15.05	26.47
8	0.28	2.97	13.45	10.53

for streams impacted by a sediment slug). However, kurtosis does not provide a direct measure of the variability of the sample, only the shape of the distribution. Skewness differs from both sorting and heterogeneity as the scoring index is represented using a 'bell-curve' scale. This means that samples that have the greatest variability will have a skewness of zero as the size classes are evenly distributed. Although this provides useful information about the distribution of sediments, the measurement scale is not comparable with the other indices (see Table IV). Therefore, the remaining two techniques, sorting and heterogeneity, seem to be the most appropriate. Even though they are similar in their scaling systems (i.e. high number, high heterogeneity), they are poorly correlated (Pearson's correlation coefficient; $r = 0.39$, $p = 0.097$) and provide slightly different estimates of the variability of the data. It is important to point out that although the heterogeneity method is suitable for quantifying the heterogeneity of sediment samples, it appears to bias samples that have a high proportion of fine sediments (e.g. Sample 5 in Table IV). However, this appears to be an artefact only of the synthetic data set (i.e. there are five size fractions less than 0.5 mm represented in the synthetic data sets and only four fractions greater than or equal to 0.5 mm). In summary, the two variables that will be used to assess the variability of the sediment samples are *sorting* and *heterogeneity.*

APPLICATION OF TECHNIQUES TO REAL RIVER DATA

A total of thirteen different measures were assessed for their suitability in differentiating between geomorphic data of high and low diversity; eight measures were considered appropriate. We applied these eight measures to real river data to assess if they are able to distinguish between different levels of geomorphic disturbance, that is, the presence of a sediment slug. Creightons Creek (central Victoria, Australia) was the site selected to assess a sediment slug (aggradation of the bed by sand as a result of increased bedload), which has altered the physical structure and diversity of some, but not all, sections of the stream.

Creightons Creek is *c*. 141 km^2 and is one of a number of streams that form part of the Granite Creeks system in the Goulburn–Broken Catchment. A full description of the history, geology, landuse, mechanisms of sediment delivery and slug evolution on Creightons Creek are given elsewhere (see Bartley *et al.*, 2001; Davis and Finlayson, 2000; O'Connor and Lake, 1994). In short, gully erosion led to a massive increase in bedload that aggraded the bed in the middle reaches of the stream (the impacted area), and is progressively moving downstream into the 'unimpacted area' (Figure 7). Our prediction is that all eight geomorphic diversity measures will identify the sediment slug as being less variable than the reaches up- or downstream.

Field design

To collect the geomorphic variability data, four 100 m reaches were surveyed in the unimpacted area downstream of the sediment slug, and four reaches in the main body of the slug (Figure 7). Site selection was based on the location within the sediment slug, as well as access to the site. Sediment depth was used to differentiate between the unimpacted and impacted reaches with impacted sites having sediment depths greater than one-fifth of

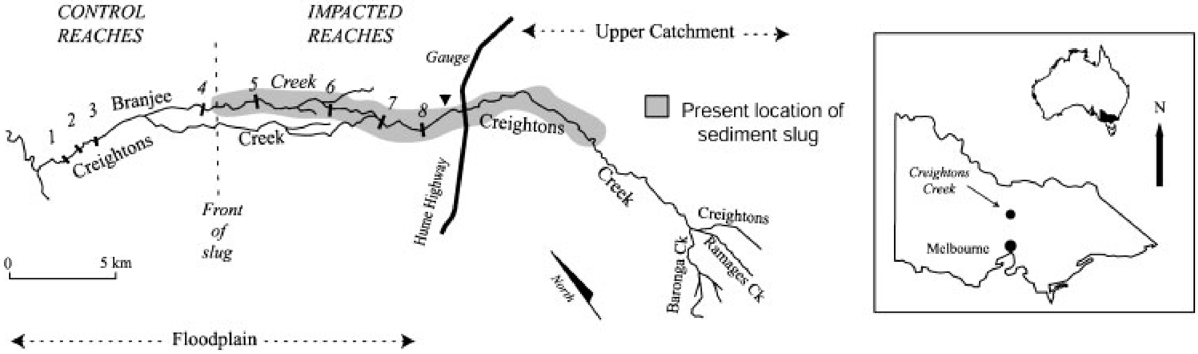

Figure 7. Location of eight reaches along Creightons Creek. Note that reaches 1 to 4 were located downstream of the main body of the slug (unimpacted) and reaches 5 to 8 were located in the floodplain section of the sediment slug (impacted)

the mean bank height (Bartley, 2001). Unimpacted sites contained ‘natural’ or background levels of sand-sized sediment, and sand depths were considerably less than one-fifth mean bank height. As all of the reaches are located on the floodplain, the geology, vegetation and hydrologic characteristics are similar enough to be comparable.

Number of samples

Assessment of the thalweg profiles from Creightons Creek, using autocorrelation analysis, (Chatfield, 1996) suggests that sampling at intervals greater than 4–6 m will not adequately represent the variability of the bed (data not shown). Therefore, to ensure that the longitudinal variability within each reach was captured, the thalweg (bed elevation, not water level) was measured at 2 m intervals. As the bed slope often changes depending on its position in the catchment, the slope (or trend) was also removed from the thalweg profiles using residuals (distance against elevation) from a least-squares regression line (after Richards, 1976, p. 75).

In each reach, ten randomly placed cross-sections were surveyed to the bankfull point. Post-hoc Power Analysis (Fairweather, 1991; Mapstone, 1995) confirmed that five cross-sections would be sufficient for characterizing the cross-sectional variability of a reach. This result was also supported by other statistical methods outlined in Eckblad (1991). Therefore, the measurement of ten cross-sections appears to adequately provide enough detail and reliability for further statistical analysis. It is expected that a larger, more variable stream would require more samples.

Bankfull was easily identified in each of the cross-sections due to the distinct change in slope between the channel and the floodplain. Bankfull was located by placing pegs at the point where bank slope became small (slope $< 5\%$) compared to the steepest part of the bank (after Western *et al.*, 1997). A measurement interval of 50 cm was chosen for the cross-sections, as this was sufficient to define the morphological diversity of the cross-section, whilst being practical considering the large number of cross-sections measured (80 cross-sections). Both the thalweg and cross-sections were measured using surveying level and staff.

Bed sediment size was homogenous in most of the study reaches, so a bulk sediment sample (1000 g) was taken from the thalweg of five of the ten cross-sections in each reach (see Bartley (2001) for more details of sampling design). Following the collection of the sediment, all samples were returned to the laboratory for size analysis which produced cumulative frequency plots of the size distribution of each sample (data not shown). The same size classes and analysis techniques were used as described in the synthetic data analysis.

Data analysis

Data from the unimpacted and impacted reaches were compared using independent sample Student *t*-tests (thalweg data) and nested ANOVA (cross-sections and sediment size data). The data met the requirements and assumptions of a nested ANOVA (i.e. subordinate level of classification, randomly chosen, normality and homoscedasticity) (Sokal and Rohlf, 1995). Tukey’s post-hoc test was carried out to determine where the significant differences lie both between, and within, groups. The nested ANOVA calculations were carried out in SPSS™ (Version 10.00), using the GLM (general linear model) function.

RESULTS USING CREIGHTONS CREEK DATA

The eight variability measures differentiated between the reaches that had been impacted by the sediment slug, and those reaches that the slug has not yet reached.

Thalweg results

The results showed that each of the three measures used to quantify thalweg variability were significantly more variable in the unimpacted reaches than in the impacted reaches (Figure 8). This indicates that the sediment slug has simplified the variability of the thalweg. There were some differences in the level of variability calculated by the different measures. For example, in reaches 1–3 the *SD* measure recorded the highest variability (followed by the fractal dimension and wiggliness factor), whereas in reach 4 the fractal value (*D*) recorded the highest value. This is because the *w* and *D* measure the arrangement of deviations along the line (angular variability), whereas *SD* is a surrogate for depth variation or vertical variability. Reach 4 produced different results because of its location

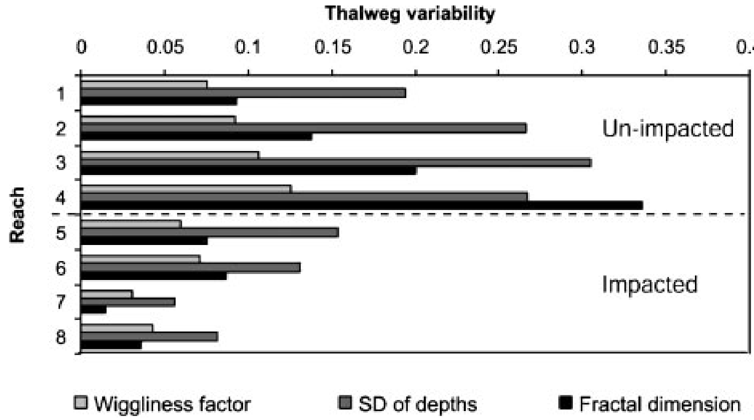

Figure 8. Results of the thalweg variability analysis on Creightons Creek. wiggliness factor ($t = 3.51$, df = 6, $p = 0.012$); standard deviation of depths ($t = 4.73$, df = 6, $p = 0.0032$); and fractal dimension ($t = 2.49$, df = 6, $p = 0.047$)

near the front end of the sediment slug (Figure 7). In reach 4, some sand has started to fill in pools; however, there has not been sufficient input of sediment to completely infill the thalweg, and quite variable bed-forms have developed, resulting in higher fractal values. This type of result suggests that small to moderate levels of geomorphic disturbance may increase diversity; however, there is a threshold point at which high levels of disturbance will reduce the diversity.

Cross-section results

The three measures used to quantify the cross-sections demonstrated that the impacted reaches were significantly less variable than those in the control reaches (Figure 9). There were, however, also significant differences measured within each of the groups using the trapezoidal method. For example, the trapezoidal technique determined that reach 2 was different from all other reaches except reach 3. This result suggests that not only is the variability different between 'sites' (impacted versus unimpacted) but also between 'reaches' within sites that have not been impacted by a sediment slug.

It is important to note that although the general trend of each of the techniques was similar, there were subtle differences that are highlighted by looking at the ordering of the results. The *trapezoidal* method considered reach 2 the most variable followed by reaches 3 then 1. The *VD* technique considered reach 3 the most variable followed

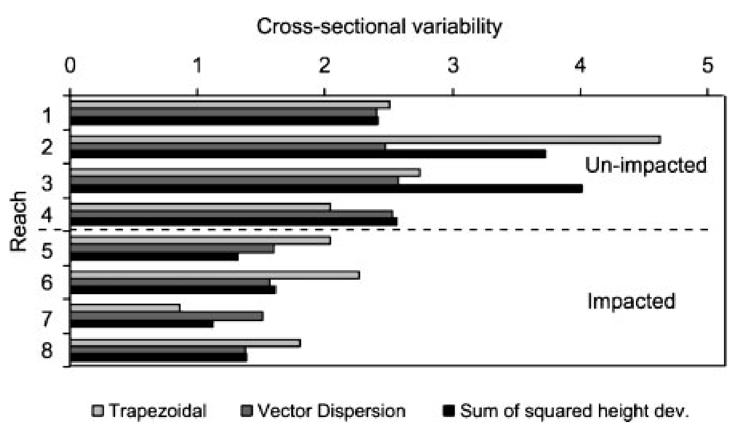

Figure 9. Results of the cross-sectional variability analysis on Creightons Creek. Only the mean values for each reach are shown. Trapezoidal ($F = 6.257$, df = 7, $p = 0.0001$); vector dispersion ($F = 6.99$, df = 7, $p = 0.0001$); sum of squared height deviation, Σdh^2 ($F = 12.688$, df = 7, $p = 0.0001$)

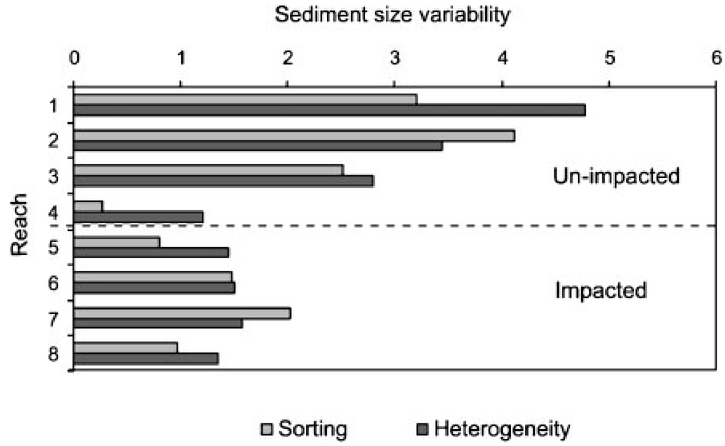

Figure 10. Results of the sediment size variability analysis on Creightons Creek. Only the mean values for each reach are shown. Sorting ($F = 2.955$, df $= 7$, $p = 0.017$); heterogeneity ($F = 4.397$, df $= 7$, $p = 0.002$)

by reaches 4 then 2 and the Σdh^2 placed reach 3 first then reaches 2 and then 4. Each of the techniques provided a slightly different assessment of the variability of the cross-sections. The trapezoidal method measured the deviation of the cross-section away from a trapezoid shape, and the *VD* and Σdh^2 techniques looked at the smaller scale angle and elevation changes. It is interesting to note that although the VD and Σdh^2 techniques produced similar results for the synthetic curve analysis (Figure 6), each technique still assessed the cross-sections slightly differently. For example, on Creightons Creek the vector dispersion (*VD*) technique gave higher variability values to reaches that were deep relative to their width; hence, the *VD* method may be biased towards incised streams (considering them to be more variable than stable reaches). The Σdh^2 technique did not seem to be biased by any particular channel form.

Sediment size results

The sediment size variability results showed that there was a significant difference between the impacted and unimpacted sites for both the sorting and heterogeneity data (Figure 10). The results exhibited a slightly different pattern from the thalweg and cross-section data because of the low values of reach 4 (compared to the other reaches within the control section). As with the cross-sectional data there were also differences between reaches within the unimpacted sites. The heterogeneity data suggested that reaches 1 and 4 are significantly different ($p < 0.05$) and the sorting values suggested that reaches 2 and 4 were significantly different ($p < 0.05$). The main reason that reach 4 was so different from the other control reaches was its position near the front of the slug. Reach 4 has predominantly sand-sized fractions present on the bed surface, and although the depth of sediment is low (<0.4 m, and less than one-fifth the mean bank height), it has resulted in an overall reduction in sediment diversity. These results suggest that the sediment size variability may be more sensitive to change than larger geomorphic features such as cross-sections or thalweg profiles.

DISCUSSION AND CONCLUSION

We proposed a set of measures that quantify the geomorphic variability of a stream by considering the spatial variability in the thalweg, cross-sections and sediment size of a reach. The methods improve on earlier measures by assuming that hydraulic variability will be reflected in the structural complexity of the bed and banks, and by avoiding subjective descriptions of 'habitat'.

Eight measures were used to quantify the geomorphic variability of reaches along Creightons Creek. These measures differentiated between areas that have been disturbed by excess sand, compared to areas that have not. All eight measures could be used in future research attempting to rigorously quantify the change in physical diversity following disturbance; however, some techniques may be more appropriate and efficient in certain situations.

The measures used to quantify the variability of the thalweg provided similar results. The only minor difference was that the *SD* measure calculates variability according to changes in elevation and the other measures (fractal dimension and wiggliness factor) calculated variability using angles along the bed. The *SD* measure would also be a more appropriate measure for evaluating variability of pool depths, and a version of this method was used in a recent study by Madej (2001) which examined longitudinal profile variability. Therefore, in summary, the fractal dimension would be suitable for looking at habitat at a range of scales (e.g. 0.5, 1.0 and 5.0 m intervals) both within and between reaches. The wiggliness factor is more appropriate for assessing small habitat variation along the thalweg profile and the SD technique is a relatively quick and easy method for assessing the variation in pool depth between reaches.

All three measures used to assess cross-sectional variability differed. When choosing a particular measure, it is important to select one that will estimate variability based on the overall configuration of the channel. The measure should not be biased by the position of the cross-section in the catchment, or the type of channel (e.g. gravel versus clay bed streams). Similar work carried out on other streams (see Bartley, 2001) suggests that the trapezoidal technique has the potential to bias results for stable streams (e.g. gravel-bed streams) that have relatively flat beds (based on measurements across the channel at an interval of 0.5 m). The trapezoidal technique may, however, be useful in identifying higher levels of sinuosity in less disturbed streams, as sinuous channels would be characterized by a deep thalweg on the outside bend, producing a non-trapezoidal shape. Overall, however, the trapezoidal method needs to be used with some caution. The vector dispersion (*VD*) technique tends to give higher variability values to reaches that were deep relative to their width; hence, the *VD* method is biased towards incised streams (considering them to be more variable than stable reaches). The sum of squared height deviations method (Σdh^2) appears to be appropriate in a range of situations. In summary, the trapezoidal technique is best suited to assessing habitat at the scale of the whole cross-section, as the bed and the banks are both considered important in this measure. The *VD* measure is best suited to assessing cross-sectional variability (or habitat) in undisturbed or unincised streams, and the Σdh^2 method is best for evaluating the smaller scale habitat changes across a river.

There were just two analysis measures that were considered suitable for quantifying sediment size variability: sorting and heterogeneity. These measures gave very similar results for each of the study reaches and in future studies either of these estimates could be used.

It is also important to note that not only are there differences between measures, but the methods themselves (thalweg, cross-section, sediment size) also have different sensitivities and therefore different potential to measure levels of geomorphic change. In many stream systems impacted by a sediment slug, the sediment size variability will be the first geomorphic variable to respond to disturbance; it is the most sensitive of the three measures. As the bed of the stream begins to fill up, the thalweg would be next to respond. Initially the thalweg profiles may become more complex as small amounts of sand provide diverse bed-forms; however, once the sediment level is high enough to drown out the dominant habitat features such as pools and riffles, the thalweg variability will be reduced. The third and final geomorphic feature to respond will be the cross-sections. In some cases, where the increase in sediment is not large, there may not be any significant change in the cross-sectional diversity. If there is a detectable change in cross-sectional diversity, then it is likely that the sediment slug is of considerable magnitude.

In summary, not only will the different measures (e.g. fractals, vector dispersion, sorting etc.) give different results for a given data set, it may be suitable to use the different measures (e.g. thalweg, cross-section, sediment size) at different phases of a disturbance to quantify geomorphic change. This result has a number of implications for the different habitat units within a stream. For example, those species that are dependent on specific elements of the grain size distribution will be the first to be disturbed. Next, those habitats related to the longitudinal profile of the stream such as pool and riffles will be altered. Finally, if the amount of sediment is large enough, the littoral or edge-habitats will be affected. The order described is specific to streams disturbed by sediment slugs and it is possible that this order would be different for different types of disturbance (e.g. incised streams or regulated rivers).

Contribution of this work in relation to previous research

Previous studies that have attempted to quantify the diversity of channel shape have generally focused on a single variable such as the thalweg (e.g. Madej, 1999, 2001) or sediment size (e.g. Williams, 1980). This study has extended previous research by using three different geomorphic features that represent different aspects of the geomorphic structure of the channel. Together these variables (thalweg, cross-sections and sediment size) present a well-rounded description of the physical structure of the stream. There are, however, other variables that would need to be taken into consideration depending on the research question of interest. For example, large woody debris (LWD) is considered to have a considerable impact on the physical structure of the stream, providing unique hydraulic habitats (Keller *et al.*, 1995; O'Connor, 1991). This study has not explicitly measured the effect of LWD; however, it is assumed that physical changes imposed on the stream by LWD will be indirectly measured by either the thalweg or cross-sectional variability. It is important to record the location and amount of LWD as it has been shown that even highly disturbed streams that contain considerable LWD may have variable substrates (Shields and Smith, 1992).

Measuring geomorphic variability at different scales

The scale at which the data are measured is also important for future studies. There is no single 'correct' scale at which to describe populations or ecosystems and no single mechanism explains pattern at all scales (Levin, 1992). Depending on the size of the stream, and the nature of the disturbance, the data may need to be collected at different intervals to that used in this study. For example, studies looking at the link between physical stream diversity and macroinvertebrate diversity would need to measure variability at much smaller scales (e.g. 10^{-3} to 10^{-4} m; e.g. Downes *et al.*, 1995).

Application to other types of disturbance and future research needs

The measures presented in this study have the potential to be applied to other disturbance types to assess changes to the physical structure and diversity of a stream (e.g. incised streams or downstream of dams). There is also the potential to use these measures to quantify the level of geomorphic recovery in disturbed systems (e.g. Bartley and Rutherfurd, 2001). However, further research in this area will require an integrated effort between geomorphologists and ecologists to determine whether these indicators are directly related to biological diversity. Projects need to be set up to evaluate how each of the measures varies with different levels of disturbance at a variety of scales. Current research being conducted on the biological diversity (macroinvertebrate and fish abundance) on Creightons Creek plans to use some of these indicators to evaluate the relationship between physical and ecological diversity.

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