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Techniques to quantify the variability of thalweg profiles

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Abstract This paper presents a range of techniques for quantifying the variability of thalweg profiles. Previous research has shown that the thalweg is an important morphological and ecological feature in stream systems, however, the tools to measure the morphological diversity of thalweg profiles are limited (at the reach scale using a horizontal interval of ~2 m). The methods presented are evaluated against synthetic data to determine which techniques would be most appropriate for quantifying thalweg data collected in the field. The results suggest that three techniques are the most appropriate for quantifying thalweg diversity (the wiggliness factor w, fractal dimension D, and standard deviation of depths).

Key words thalweg; physical variability; habitat; data analysis

INTRODUCTION

There is increasing interest in understanding the link between biological and physical features of streams, and diversity of physical form, if it can be described, paves the way for predicting the potential diversity of biota (Newson & Newson, 2000). Hence the physical diversity of a stream is increasingly used as an indicator or surrogate of stream health. Surface roughness and physical diversity have an important effect on measurements of species diversity, population abundance and dispersal (McCoy & Bell, 1991), and physical diversity in streams is also known to correlate well with biological diversity (e.g. Jungwirth *et al.*, 1993).

The main limitation to using physical diversity to estimate biological diversity, is that few techniques are available for rigorously quantifying the physical structure of a stream independently of flow related variables. Although flow and velocity characteristics are considered important environmental factors affecting instream biota (e.g. Degani *et al.*, 1993), this paper argues that the morphology of the stream represents the range of flows that move through the channel more accurately than can be measured. Removing flow-related variables from the process of quantifying physical diversity also considerably reduces the time and financial costs of collecting data. It also means that variability can be compared between different reaches or streams, despite differences in water depths.

To quantify physical diversity, a method is required in which data are relatively easy to collect, independent of discharge, and has relevance to both geomorphologists and ecologists. It is also important to note that many studies use methods that are applicable only to particular organisms or environments, which prohibits direct comparison and hinders any general understanding of the relationship between physical and biological diversity (McCoy & Bell, 1991). This paper presents the thalweg as a suitable feature for representing physical diversity, and evaluates a number of methods for quantifying thalweg variability. The thalweg is considered as a useful "summary" indicator of habitat diversity in a reach (i.e. non-species specific), which is based on the assumption that the greater the physical diversity, the greater the habitat diversity. The thalwegs in this paper are measured at 2-m spacings and no attempt is made to directly relate the level of physical diversity to biological data; however, other research has shown significant correlations between thalweg diversity and the number and diversity of fish species (e.g. Jungwirth *et al.*, 1993).

THE THALWEG: AN IMPORTANT GEOMORPHIC FEATURE IN STREAM SYSTEMS

The thalweg is made up of a series of topographic undulations which, in many streams, form pools and riffles. These are the characteristic macro-scale bedforms of some alluvial river channels. The thalweg, or deepest path of water along a stream, is used to measure the change in the longitudinal heterogeneity, and pool–riffle sequence of a stream. Alternating pools and riffles are recognized as a fundamental morphological characteristic, and important habitat feature of stream channels.

In Australia, many streams are alluvial clay systems that do not have the structured pool–riffle sequence of gravel-bed streams. In streams without distinct pool–riffle sequences, the presence of depressions (areas of scour) and elevated areas (areas of deposition) still provide a diversity of habitats. In this study, thalweg variability—measured as changes in bed elevation (not water level)—is used to indicate physical diversity. It acknowledged that this approach does not incorporate the micro habitat flow variables that are considered as important components of aquatic habitat (e.g. Degani *et al.*, 1993), however, the methods outlined here are more suitable for rapid assessment of instream physical diversity.

QUANTIFYING THE VARIABILITY OF A LINE

Thalweg profiles are plotted from distance and elevation measurements. Examples of thalweg profiles measured from different stream types from southeast Australia are presented in Fig. 1. The methods for quantifying profile variability can be placed into six categories: fractal theory (e.g. Sugihara & May, 1990); vector dispersion (e.g. Connell & Jones, 1991; McCormick, 1994); angle deviations from a surface (e.g. Beck, 1998; Carleton & Sammarco, 1987); parametric statistical techniques such as standard deviation and variance (e.g. Lisle, 1995); time series analysis (e.g. smoothing techniques and variograms) (e.g. Madej, 1999); and "other" techniques (e.g. "chain and tape" and the wiggliness factor) that do not fit into the above categories. There are many other techniques that measure environmental heterogeneity, however, if they do not have spatial elements in their mathematical formulae, they are not necessarily appropriate for spatial information (e.g. Shannon index; Gorman & Karr, 1978).

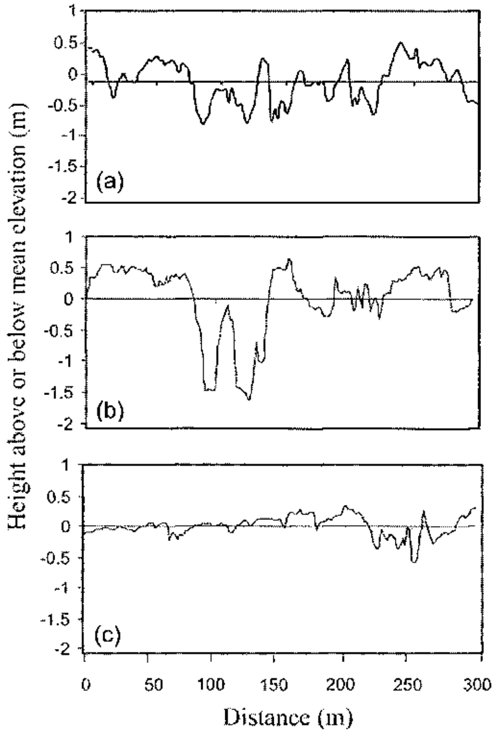

Fig. 1 Thalweg profiles collected from: (a) a gravel-bed stream (Ringarooma River, Tasmania); (b) a clay-bed stream (middle reaches of Wannon River, Victoria); and (c) a sand-bed stream (lower reaches of the Wannon River, Victoria). All profiles are 300-m long and were measured at 2-m intervals. Each profile has been de-trended for slope. Note the difference in the spacing and frequency of bedforms. Data sourced from Bartley (2001).

TECHNIQUES FOR QUANTIFYING THALWEG VARIABILITY

Loess curves "Loess curves" (*L*) are a non-parametric smoothing technique (i.e. time series approach) used to identify underlying trends in noisy data (with some adjustment for extreme observations or outliers). In this analysis a curve is fitted to the data, defined as the difference between a local linear regression and an irregular component (based on Makridakis *et al.*, 1998):

$$\hat{E}_t = Y_t - \hat{T}_t \qquad (1)$$

where $\hat{E}_t$ represents the difference between each observation Y_t and the fitted curve $\hat{T}_t$. The local linear regression is then recalculated, but this time observations with large errors receive smaller weights than for the estimate of the trend cycle curve. Then, a new irregular component is determined by subtracting the new estimate of T_t, from the data. The data are smoothed through successive iterations. For each iteration, an N value, representing the proportion of the data to be included in each local regression, is determined ($N = 0.3$ was considered the most suitable). To evaluate the variability of each profile, the mean squared error (MSE) of the residuals is calculated. The higher the MSE the more variable the profile. These calculations are carried out using the Loess function in the SYSTAT^{TM} statistical package (version 9.0).

Standard deviation of depths The standard deviation (SD) is an example of a parametric statistical technique which uses the SD of bed elevations from the highest point of the bed to evaluate thalweg variability. The greater the SD of bed elevation deviations, the greater the variability. This method was used by Lisle (1995) to assess habitat complexity independent of water depth.

Fractal dimension The fractal or the Hausdorff dimension (D) (after Sugihara & May, 1990) involves determining how the apparent length $L(\delta)$ changes as the measurement interval for the thalweg is increased. For a fractal curve, the apparent length grows linearly as the interval of measurement decreases. By plotting $L(\delta)$ against the interval of measurement, and fitting a linear regression, the fractal dimension can then be calculated by subtracting the slope of the regression from 1.0 (for $2 > D > 1$). In Fig. 2(a), the fractal dimension value for D is 1.004. The higher the value of D, the greater the variation in the bed profile.

"Chain and tape" method The chain and tape (CT) method is similar to that described in Beck (1998) and initially presented by Connell & Jones (1991); it determines the ratio of the apparent distance (L_A) to the linear distance (L_s). For thalweg data, it is calculated as the ratio of the topographic bed distance (L_A) to the length of the reach (L_s) (see Fig. 2(b)).

Vector dispersion Vector dispersion (VD) is a measure of angular variance (θ) (Fig. 2 (c)). It was calculated in Beck (1998) from a two-dimensional modification of the formula in Carleton & Sammarco (1987):

$$\mathrm{VD} = \frac{\left(n - \left[\sum_{i=1}^{n} \cos\theta_i\right]\right)}{n-1} \tag{2}$$

where n is the number of points along the transect, and θ is the angle of each thalweg point from horizontal. The greater the value of VD, the greater the variability of the thalweg profile.

Sum of squared height deviations The value of consecutive substratum height differences (Σdh^2, McCormick, 1994) is calculated as the sum of the squared differences between consecutive points along a profile. The higher the value of Σdh^2 the greater the thalweg variability.

Wiggliness factor The "degree of wiggliness" w (Ghosh & Scheidegger, 1971) was used to express the deviation of angles between points along the thalweg from the mean elevation. This method was adapted slightly to calculate the deviation of elevations between successive points:

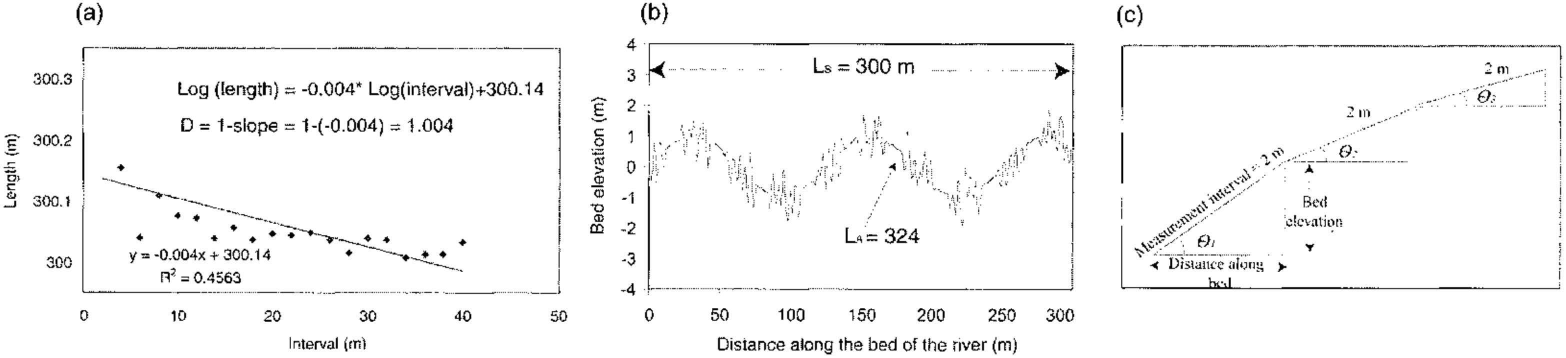

Fig. 2 (a) Application of fractals technique to thalweg data; (b) application of the chain and tape method; and (c) description of vector dispersion technique applied to the thalweg data.

$$w = \sqrt{n\sum(\Delta\Phi_i)^2} \tag{3}$$

where n is the number of angles 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.

CALIBRATION OF TECHNIQUES USING SYNTHETIC DATA

Despite the increasing application of techniques to quantify spatial variability in various areas of science, few have critically reviewed any of the available methods for fluvial geomorphic data. Therefore, it is difficult to determine which of the myriad of techniques would be the best at describing thalweg variability. It is not necessarily practical to use all of the techniques described, and in any case it is highly probable that considerable overlap exists between methods. Therefore it was important to:

- determine if these techniques adequately describe the heterogeneity of the data;
- determine if there is any overlap between the methods. This would reduce the number of techniques to a set that provides the greatest amount of information using the least number of methods.

To address these questions, it was not possible to use data collected from real thalweg profiles (e.g. Fig. 1) as it is too difficult to objectively identify profiles with high levels of physical diversity. Therefore, six synthetic data sets were created with clear differences in variability. Each of the analysis techniques were then applied to each data set and a comparison of the different methods made. A thalweg profile is considered to be highly variable when there is both high vertical variation (as this equates to high depth variability), as well as high horizontal, or angular variation (as this reflects high surface area and therefore greater habitat potential). Techniques were considered suitable when they scored high values for those profiles with both high vertical and horizontal variability. Those methods that were not suitable for quantifying the heterogeneity were removed.

The suitable techniques were subjected to a multivariate factor analysis (SPSS™ version 10.0). The principal components method within the factor analysis was used. The data had no outliers, and were normally distributed. Each variable was also evaluated for its Kaiser-Meyer-Olkin value (a measure of sampling adequacy), and only included if the value was greater than 0.01 (Howard, 1991). Each set of values was also subject to varimax rotation which more clearly identified the correlated groups.

METHODS—SYNTHETIC DATA APPROACH

The six synthetic thalweg profiles each contained a periodic variation of 150 points (of different amplitude and frequency), and three profiles also contained a random element (Fig. 3(a)). Curves with high levels of both vertical and horizontal variation were considered the most diverse. The curves are in the order of greatest expected variability (curve A) to the least variable (curve F), although (B) and (C) could be interchangeable.

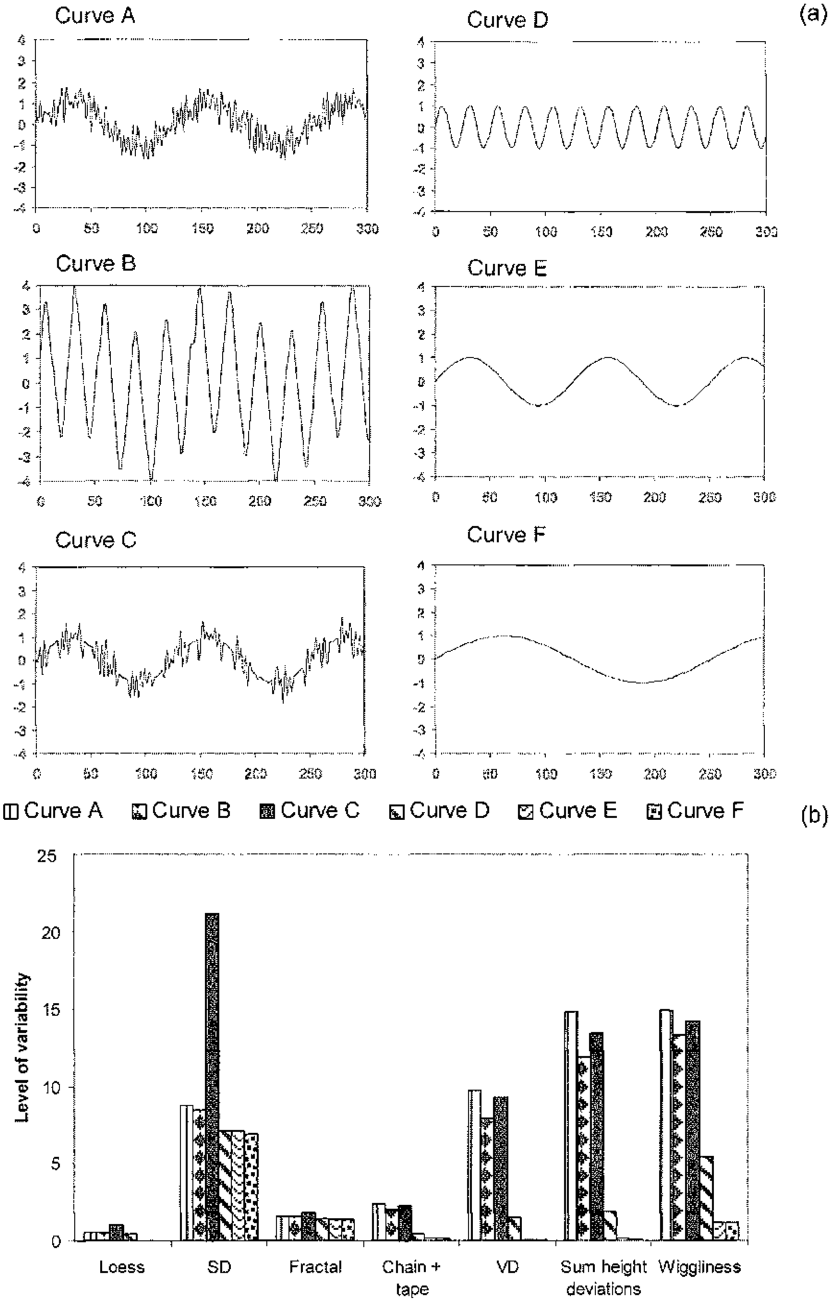

Fig. 3 (a) Synthetic thalweg curves; and (b) results of data analysis of the synthetic thalweg curves.

RESULTS OF ANALYSIS USING SYNTHETIC DATA

The results of the data analysis (Fig. 3(b)) show that all of the techniques give varying results, although the relative trend between the techniques is similar, with curves A, B and C having higher variability than curves D, E and F. The main difference between the techniques is that the L, SD and D techniques all consider curve C to have the highest level of variability, whereas the CT, VD, Σdh^2 and w put curve A ahead of curve C, then B. It is also important to note the magnitude difference between the SD result for curve C when compared to all other results. Based on these results alone, it is difficult to determine which factors are most appropriate for evaluation of thalweg variability.

The results of the factor analysis provide a clearer picture of the relationship, highlighting the similarity between the different analysis techniques. Overall, the data analysis showed that two factors (groups) accounted for 98.6% of the variance in the data, with Factor 1 accounting for 87.1% of the variance (Table 1). Figure 4 shows three distinct groups within Factor 1: Group 1—Σdh^2, CT, w and VD; Group 2—L and D; and Group 3—SD.

Group 1 calculates the degree of angulation, or height variation, of each point along the profile. Group 2 describes the arrangement of each point based on the position of previous points along the profile, and Group 3 considers the deviation of

Table 1 Results of the factor analysis (after varimax rotation).

Variable	Factor 1	Factor 2
Σdh^2	0.933	0.354
CT	0.932	0.356
w	0.925	0.369
VD	0.921	0.385
SD	0.232	0.963
L	0.563	0.792
D	0.660	0.750
% Variance	87.1	11.5
Cumulative %	87.1	98.6

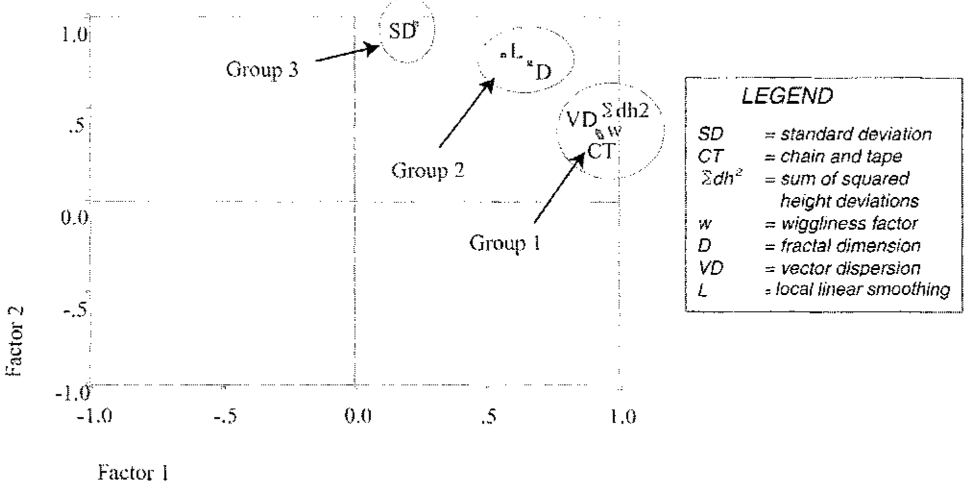

Fig. 4 Component plot of rotated factors for thalweg analysis showing the three different groups.

points away from a straight line. Each group is important, and measures a slightly different aspect of thalweg variation, which is essentially a function of the methods themselves. The results suggest that only one factor from each group is needed to adequately describe the different aspects of profile variability.

Two criteria were used to choose the most appropriate factor from each group: (a) which analysis technique is computationally the least intensive, and (b) which techniques have been critically reviewed in the literature.

For Group 1 VD and w have been considered most useful in the literature (e.g. Carleton & Sammarco, 1987), but, as w is easier to calculate it is the preferred measure. For Group 2, fractal analysis has obtained wider critical evaluation in the literature (e.g. Sugihara & May, 1990) and so is the preferred method.

CONCLUSIONS AND FURTHER RESEARCH

A number of techniques for quantifying thalweg profile variability have been evaluated using synthetic data. The results suggest that three measures together provide the best basis for describing profile variability:

- the wiggliness factor w;
- fractal dimension D; and
- standard deviation of depths of the bed profile (SD).

This study has assessed methods for quantifying stream thalweg variability as an indicator of habitat diversity. There is now the need for further research to investigate whether these indicators of habitat diversity are directly related to biological diversity. Projects need to be set up to evaluate how each of the thalweg diversity measures vary with different levels of disturbance (this needs to be done in conjunction with biological diversity measures). In addition, thalweg profiles should be collected at a variety of spatial intervals (e.g. 0.5, 1.0, 2.0, 5.0 and 10.0 m intervals) to assess how variability changes with scale along the bed. There is no single "correct" scale at which to describe populations or ecosystems and no single mechanism explains pattern at all scales, however, it is crucial that investigations continue to look for similarities between the scale at which biological and geomorphological processes operate.

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