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LOCAL VARIATIONS OF CROSS-SECTIONAL FORM IN A SMALL GRAVEL-BED STREAM

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ABSTRACT

The local behaviour of selected cross-sectional variables is analysed for four stream lengths located at different positions along the profile of Cave Stream in the Southern Alps, New Zealand. Bankfull width and mean depth are correlated with stream bed height. Riffle sections are distinguished from pool sections in having wider and shallower channels. However, bed topography has little apparent influence on cross-sectional form as a spatial series. The series for the two upstream lengths are dominated by random effects and only in the downstream lengths where the stream becomes large enough to counteract external constraints does any degree of regularity in the variation of cross-sectional form begin to develop.

INTRODUCTION

The size and shape of a river channel cross-section depends largely on the quantity and character of the water and sediment delivered to the channel reach, and on the composition of the channel boundary. Although the distinction is not necessarily clear-cut, the overall dimensions of a cross-section are determined principally by a set of formative discharges whose range varies with flow regime (Harvey, 1969; Stevens, Simons and Richardson, 1975), while cross-sectional shape is more closely related to the characteristics of the sediment in motion and in situ (Schumm, 1960). At the scale of the longitudinal profile, therefore, discharge, sediment load and boundary composition are the dominant controlling variables, and channel width and mean depth generally increase with discharge in the downstream direction (Leopold and Maddock, 1953).

Underlying these downstream changes are local variations of both a random and systematic nature. Aside from measurement error, random fluctuations can be generated by local changes in vegetation and boundary conditions and by localised channel erosion associated with the non-uniformity of stream flow. Transient behaviour in channel variables may be induced below tributary junctions where a stepped increase in discharge and introduced load occurs (Richards, 1980). River channel cross-sections thus tend to be irregular and, within a given reach where the ranges of the controlling variables are relatively uniform, their form may be expected to vary stochastically about a mean. However, systematic tendencies have been identified at the local scale, associated with changes in planimetric geometry and, in particular, bed topography (Richards, 1976b). The principal aims of this paper are to examine the local behaviour of selected channel variables, bankfull width, mean depth and width-depth ratio, and to assess the extent to which that behaviour varies between stream lengths at different positions along a profile.

STUDY AREA AND FIELD PROCEDURE

Data were collected in the basin of Cave Stream, a left bank tributary of Broken River in the Southern Alps, South Island, New Zealand, which rises at 1460 m and flows at an average gradient of 0.080 m m^{-1} to its mouth at 620 m (Figure 1). Mean annual precipitation increases from 760 mm at 720 m to 1780 mm at 1500 m in the Craigieburn Range where 30 per cent falls as snow. Short tussock grassland is the characteristic vegetation in the lower parts of the basin, with beech forest dominant in the headwater area. Sandstones, coals and, beyond the study reaches, limestones underlie the interior of the basin, whilst greywacke and argillite outcrop in the upper parts. Extensive tracts of glacio-fluvial gravels cover these rocks and form the surface layers of a well-developed terrace sequence formed during later periods of the Pleistocene (Gage, 1958). This sequence, together with remnants of more recent terraces at lower elevations, testifies to the ability of the

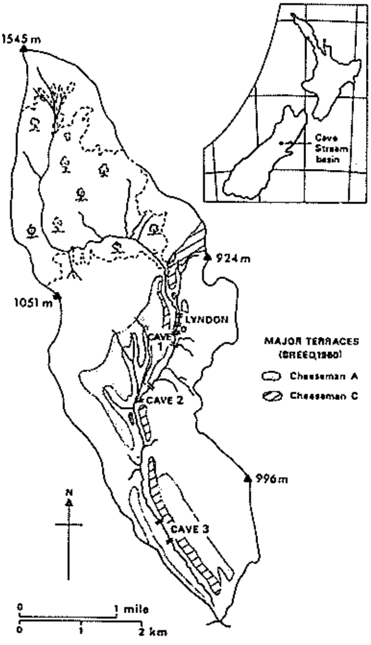

FIG. 1—Cave Stream basin, with study lengths and main terraces indicated.

stream to respond to changes in external conditions in the medium and long terms. Air photographic evidence, on the other hand, suggests that the stream has remained relatively stable, at least in plan form, over the past few decades.

Four stream lengths of broadly similar planimetric geometry were selected for study, straight reaches and gentle curves being dominant. Each length had no tributary entering between the upstream and downstream ends. Consequently the discharge range within any one stream length can be regarded as relatively constant. Three of the lengths, designated Cave 1, Cave 2 and Cave 3, were located along the main stream (Figure 1). Since the headwater area of Cave Stream is densely forested and channel adjustment is particularly susceptible to random influences in such an environment, the fourth length was located on the principal tributary, Lyndon Stream (Figure 1), rather than on the main stream itself, thereby providing some indication of the lower discharge conditions characteristic of headwater reaches. Bankfull cross-sectional geometry was surveyed at 60 (Lyndon Stream) or 50 (Cave Stream) equi-spaced points along each length, measurement intervals being 2 m for Lyndon, 4 m for Cave 1, 6 m for Cave 2 and 8 m for Cave 3. Sample spacing is important since an inconsistent sampling interval can lead to problems of interpretation (Anderson and Richards, 1979). These distances were chosen to maintain an appropriate relation between channel width, possible bedform wave-length and sample spacing in that approximately 10 riffle-pool elements, if present, would be included in each survey, assuming a riffle spacing of 6 times average width (Keller and Melhorn, 1978). A combination of methods, including those adopted by Wolman (1955) and Riley (1972), was used to identify the bankfull channel.

The stream lengths differ little in average gradient (Table 1). Subsamples of bed material taken along each length were not significantly different, but significant differences in bed material size did exist between Lyndon and the other lengths and between Cave 1 and Cave 3. Although bank material composition varied, it did not appear to change systematically and most banks were sufficiently cohesive to stand at a high angle. Assuming that $w=aQ^{\frac{1}{2}}$ is an adequate description of the change in width (w) with discharge (Q) downstream (Blench, 1957; Osterkamp and Hedman, 1977), the ratio of average bankfull widths for two stream lengths can indicate their relative discharge from

$$Q_1/Q_2=(w_1/w_2)^2 \tag{1}$$

Relative to Lyndon with a base discharge of unity, discharges for Cave 1, Cave 2 and Cave 3 are respectively 2, 6 and 14 units. Relative discharge therefore has a range exceeding that of either average slope or mean grain size (Table 1) and can be expected to be a major contributor to any inter-length variation in channel geometry.

ANALYSIS OF THE CROSS-SECTIONAL SERIES

All the width and depth series have a tendency to oscillate (Figure 2). The degree of fluctuation varies little between the two variables for any one stream length but does vary from one length to another, the

TABLE 1—Average values of channel parameters.

	Slope m/m	Mean Grain Size, mm	Discharge Ratio
Lyndon	0.022	20	1
Cave 1	0.020	40	2
Cave 2	0.017	44	6
Cave 3	0.019	54	14

main contrast being between Lyndon and Cave 1 on the one hand where there is limited dispersion about a well-defined mean and Cave 2 and Cave 3 where the associated histograms show a tendency toward bimodality (Figure 2). Kolmogorov-Smirnov tests indicated significant differences at the 99 per cent level between every pair of stream lengths for both variables. However, a ranking of the differences was not consistent. The ranked order for increasing width was Lyndon, Cave 1, Cave 2 and Cave 3, whilst that for increasing depth was Lyndon, Cave 2, Cave 1 and Cave 3. Assuming that both width and depth increase with discharge downstream, Cave 2 had smaller and Cave 1 larger mean depths than expected. The anomalous depth of Cave 2 may be attributed to the relatively large number of riffle sections along that length. Differences in parameter means between lengths were expected but those associated with the variability of the channel parameters within a single length were not. Despite the greater variability within Cave 2 and Cave 3, width and mean depth were more strongly correlated there than in the other two stream lengths, in one of which there was no significant correlation (Table 2). Whereas width and depth tend to increase together at the longitudinal scale in response to discharge, they were inversely related at this local scale.

Apart from the width series for Lyndon, all the series contained a trend component (Figure 2). Polynomials of up to third order were fitted to the data but only a linear relation proved to be significant in each case. Comparing the Cave Stream lengths, the rates of change of both width and mean depth increase progressively in magnitude from Cave 1 to Cave 3, underlining the relatively large variation within Cave 3. Width and depth have consistently opposite trends. The decrease in width possibly reflects a gradual damping in channel response below tributary junctions where discharge increase is stepped but the increase in depth is less easily explained and, in any case, is physically less important, judging from the regression coefficient values. Although the

TABLE 2—Correlations between bankfull width and mean depth.

	Raw data	Adjusted data	Decision
	Correlation coefficient		
Lyndon	—0.27	—0.26	Not significant
Cave 1	—0.54	—0.49	Significant, p=0.05
Cave 2	—0.85	—0.80	Significant, p=0.01
Cave 3	—0.77	—0.72	Significant, p=0.01

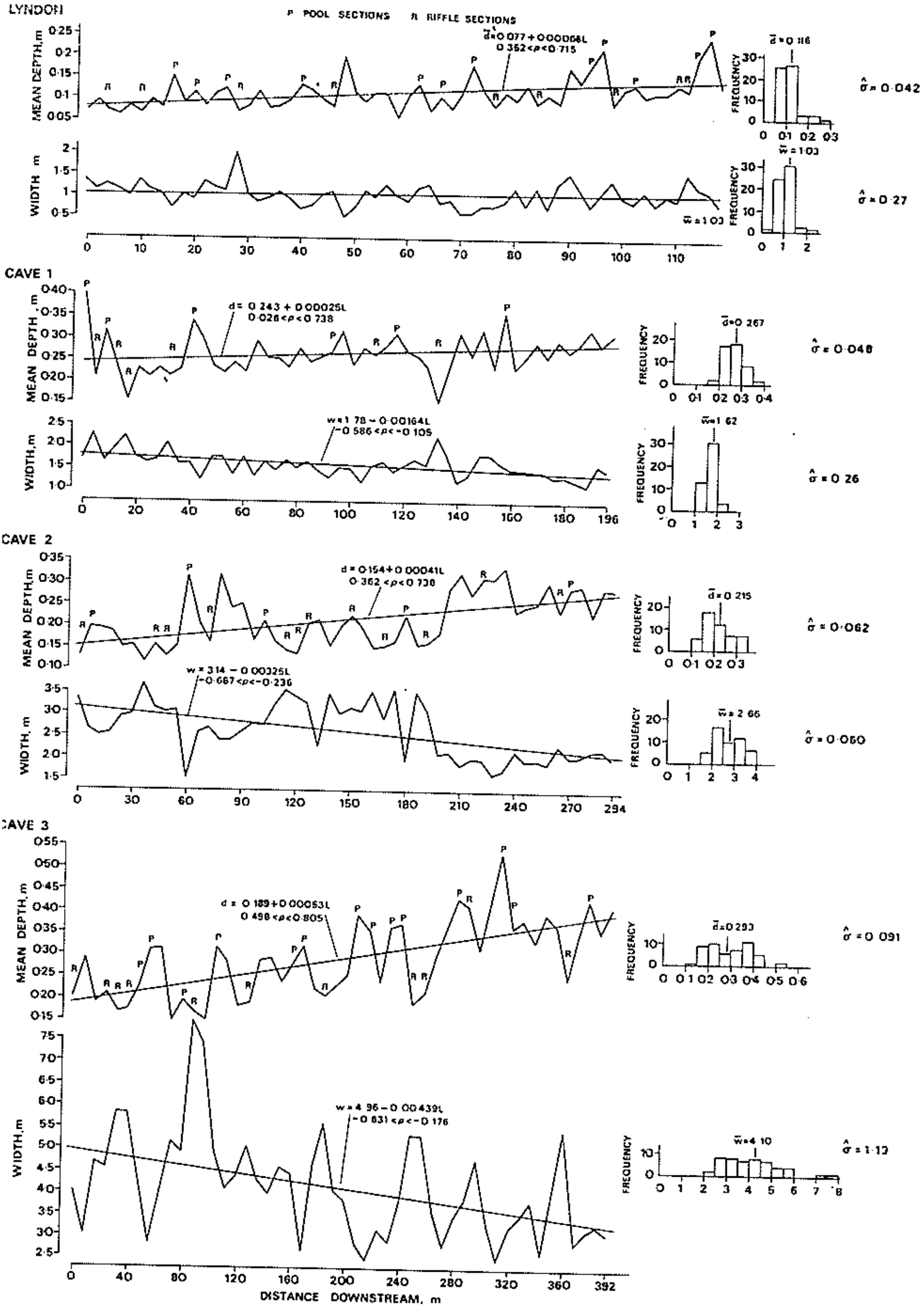

FIG. 2—Width and mean depth series and the corresponding histograms for the four study lengths. 95 per cent confidence limits for the correlation coefficients are given.

rates of change are relatively small, this behaviour has implications for empirical studies relating width and depth to other variables in a spatial context at a larger scale, in that the location of sampling points relative to tributary junctions could influence the relations. A further component in the series plots is provided by pools and riffles (Figure 2). Although riffle sections tend to be positive residuals in the width series and negative in the depth series, with pool sections being of the opposite character, the pattern is not consistent and a more detailed analysis is required to determine whether these bed forms have distinct characteristics.

The raw data were mean-corrected as appropriate and then standardized to enable analysis of data from all stream lengths identified in the field as having a pool or riffle bed, a total data set of 76 sections. Riffles had significantly wider and shallower channels than did pools, and correspondingly higher width-depth ratios (Figure 3; Table 3). Considering the stream lengths individually rather than as a whole, Mann-Whitney U tests confirmed this pattern of differences which was somewhat surprising in the cases of Lyndon and Cave 1 where the width and depth data have relatively narrow ranges (Figure 2). Although these results are not new (Richards, 1976b), they do show that a mountain stream with relatively coarse bed material has the ability to adjust its local bed and cross-sectional geometry in association. However, the degree of riffle-pool development was not the same in each study

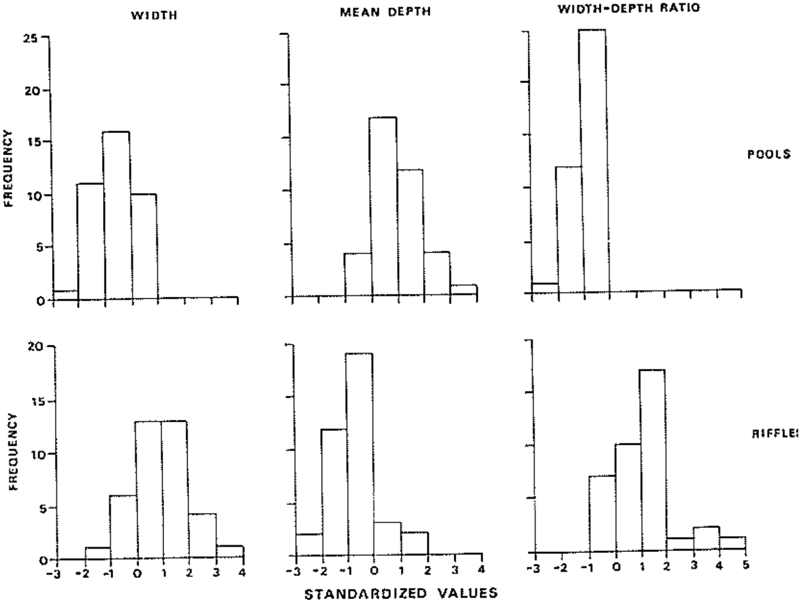

FIG. 3—Frequency histograms of standardised width, mean depth and width-depth ratio for pool and riffle sections.

TABLE 3—Statistical tests comparing pools and riffles.

	Width	Mean Depth	Width-Depth Ratio
(1) TOTAL DATA SET			
D_m	0.589	0.763	0.816
Decision	Rejected $p<0.001$	Rejected $p<0.001$	Rejected $p<0.001$
(2) LYNDON ($n_R=9$, $n_P=12$)			
U	18	2	4
Decision	Rejected $0.01>p>0.001$	Rejected $p<0.001$	Rejected $p<0.001$
(3) CAVE 1 ($n_R=6$, $n_P=6$)			
U	2	0	1
Decision	Rejected $0.01>p>0.001$	Rejected $p<0.001$	Rejected $0.01>p>0.001$
(4) CAVE 2 ($n_R=12$, $n_P=5$)			
U	4	6	3
Decision	Rejected $0.01>p>0.001$	Rejected $0.01>p>0.001$	Rejected $0.01>p>0.001$
(5) CAVE 3 ($n_R=11$, $n_P=15$)			
U	10	12	16.5
Decision	Rejected $p<0.001$	Rejected $p<0.001$	Rejected $p<0.001$

H_0: There is no signficant difference in width, mean depth or width-depth ratio between riffles and pools.

H_1: Riffles have significantly larger widths, larger width-depth ratios or smaller mean depths than do pools.

D_m=maximum difference in Kolmogorov-Smirnov two-sample tests
U=Mann-Whitney statistic
n_R=number of riffle sections
n_P=number of pool sections

length, Cave 1 having the poorest — and Cave 3 the best-developed bed. Less than half the total number of sections were defined as having a riffle or pool bed. The problem is therefore to determine the extent to which this and possibly other systematic components are responsible for oscillations in the cross-sectional series. For that purpose the spectral density function (sdf) which shows how the variance in a series is distributed with respect to frequency (f) was calculated for each series using detrended data.

The spectral density function is defined (Jenkins and Watts, 1968) as: as :

$$R(f) = 2\left\{1 + 2\sum_{k=1}^{M} \lambda_k \rho_k \cos 2\pi f k\right\} \qquad (2)$$

where ρ_k is the autocorrelation at lag k and λ_k is the Tukey window.

The choice of truncation point M is critical and represents a compromise between too high a value when estimator variance is large and the spectrum fluctuates wildly, and too low a value when resolution is poor and important features of the spectrum may be omitted (Fishman, 1969). Five values of M were tested and M=12 seemed to provide an effective compromise with limited instability in the spectra.

The 95 per cent confidence limits for the spectra, which vary with the magnitude of $\overline{R}(f)$, are (0.54 $\overline{R}(f)$, 2.66 $\overline{R}(f)$) and (0.51 $\overline{R}(f)$, 2.91 $\overline{R}(f)$) for the Lyndon and Cave Stream lengths respectively. The lower limit is the critical one in testing for significance. The spectra for Lyndon and Cave 1 cannot be regarded as significantly different from white noise, the main implication being that the variation of bankfull channel form along those lengths is dominated by random influences. Cave 2 has a reasonably consistent set of graphs in which the significant peaks occur at low frequencies or large wavelengths (Figure 4). One reason for this low frequency concentration can be discerned from the original series plots (Figure 2). If the stream length is divided into approximately three equal parts, width residuals tend to be positive in the middle part and negative in the downstream part, depth residuals being of opposite character. The upstream part is less internally consistent. Although the channel variables do fluctuate in the middle and downstream parts as suggested by the subsidiary peak in the depth and width-depth ratio spectra (Figure 4), that fluctuation is subordinate to the variation at the larger sub-length scale. Cave 2 therefore tends to be dominated by elements of large wavelength. Cave 3 provides a more variable picture. The width and width-depth ratio spectra are dominated by a single significant peak at 0.063 cycles (57 m) but the depth spectrum has no major peak which is somewhat surprising in view of the oscillatory character of the original series and the form of the width-depth ratio spectrum (Figure 4). Oscillations in depth tend to occur over a wider range of frequencies and wavelengths. Spectral analysis has revealed a broad pattern of differences: between Lyndon and Cave 1 on the one hand where random influences apparently dominate the cross-sectional series, and Cave 2 and Cave 3 on the other where respectively low frequency and intermediate frequency components become significant, suggesting some degree of regularity in the variation of cross-sectional form along those lengths. However, despite the contrasts in width and depth between riffle and pool sections, no significant oscillation occurs in the riffle-pool waveband (Figure 4). Indeed there is no reason to expect regularity of that form in the cross-sectional series of the study lengths where riffle-pool development is limited. Even in streams where consecutive riffles or pools are approximately spaced at 5 to 7 times channel width, oscillation at a constant wavelength is unlikely.

Although none of the spectra indicate oscillation at the supposed riffle-pool frequency, the possibility of correlation between cross-sectional form and bed height remains. Bed profiles were surveyed along each length using either a Zeiss theodolite or Watts quicksetting level and bed height series obtained. Again a linear trend alone proved to be significant and it was removed from the data. Cross-correlation coefficients were estimated for each pair of series according to the

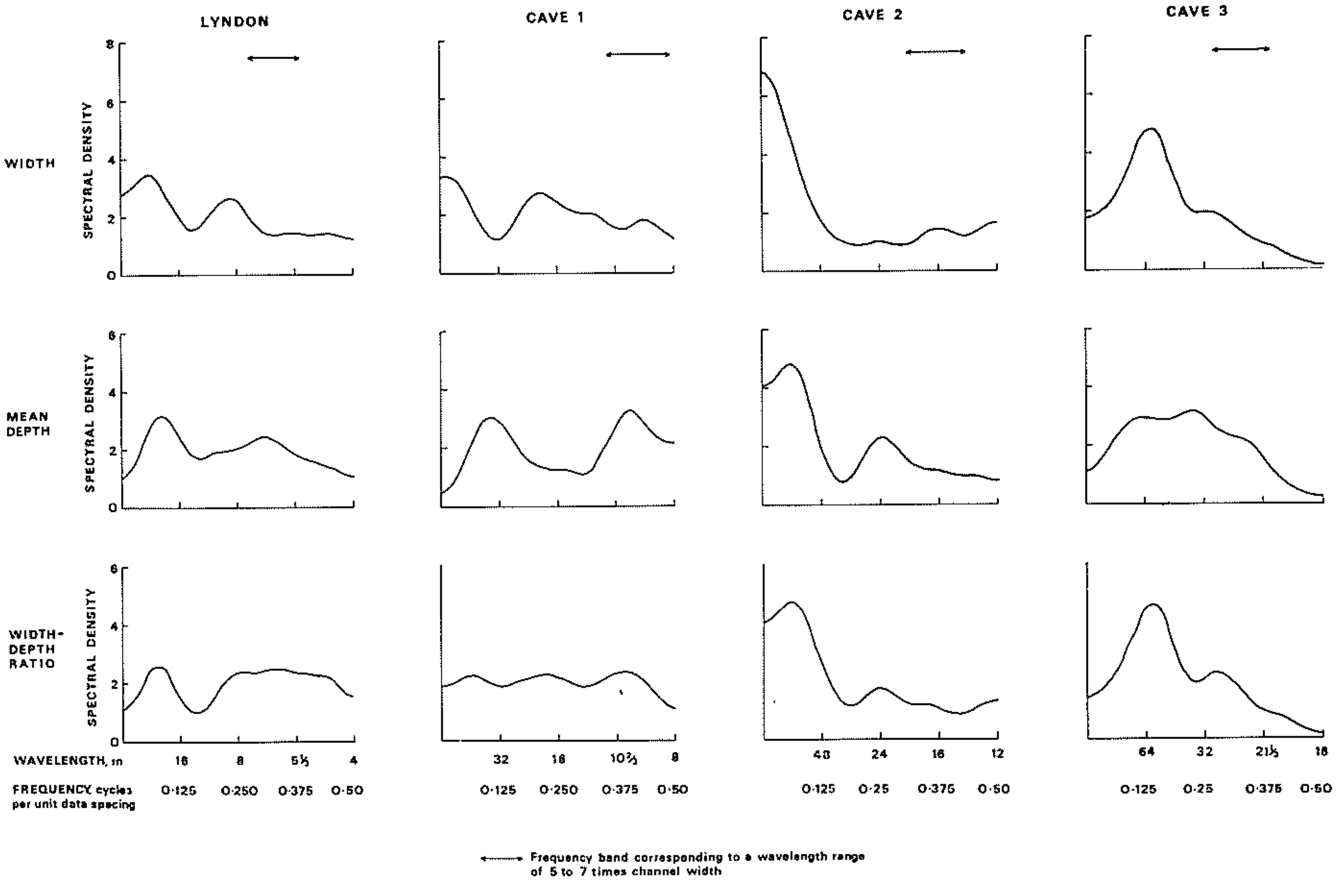

FIG. 4—Spectral density functions of the detrended width, mean depth and width-depth ratio series.

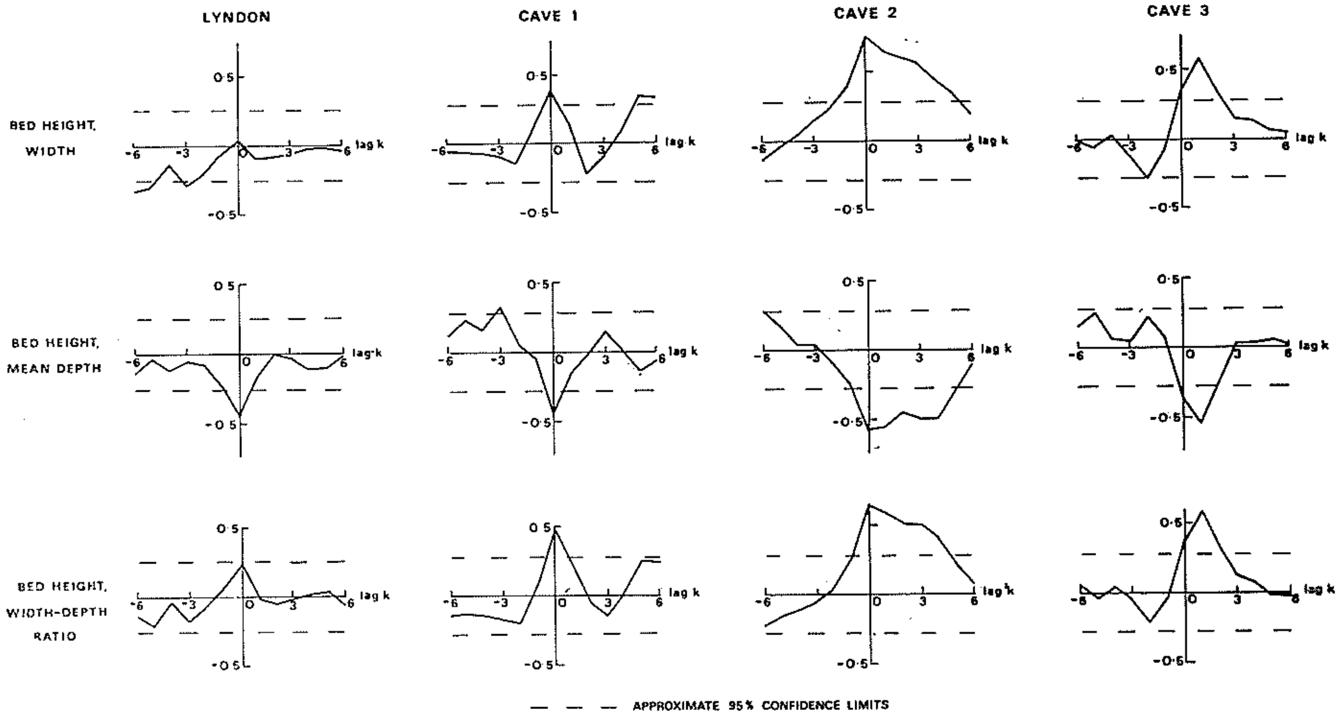

FIG. 5—Cross-correlations of residual bed height with width, mean-depth and width-depth ratio.

procedure outlined by Chatfield (1975). Figure 5 illustrates the sample cross-correlation functions relating the width, mean depth and width-depth ratio residuals to the bed height residuals at upstream (k=−1, −2, . . ., −6) and downstream (k=1, 2, . . ., 6) lags. The significant correlations are of the expected direction in that an increase in bed height, as might occur over a riffle, is associated with a greater width and smaller depth. However, the correlation functions differ in form between the stream lengths, in part paralleling the spectral results.

The correlations for Lyndon and Cave 1 are either not significant or barely so and the functions tend to be sharply peaked about a lag of 0. Any relation between cross-sectional form and bed topography is therefore localized with no influence from upstream or downstream sections. The peak correlation for Cave 3 is not only higher but also at a downstream lag of k=1. If fluctuations in cross-sectional form are a product of flow characteristics partly induced by upstream changes in bed topography, a not unreasonable assumption in view of the tendency for topographic highs to divert the flow toward the channel banks, then a lagged response is likely, particularly in the case of channel width. Insofar as Cave 3 demonstrates this type of behaviour, it is regarded as having a more structured channel form. Cave 2 appears to occupy an intermediate position between Cave 1 and Cave 3. The peak in the cross-correlation function again lies at k=0 as in the case of Cave 1, although the correlation is better, but Cave 2 also has significant coefficients at downstream lags, indicating a tendency to behave similarly to Cave 3. Changes in the strength and the form of the relationships between bed height and cross-sectional geometry seem to be progressive and reflect the different relative positions of the stream lengths along the profile.

The final stage of the analysis concerns the possible description of the observed series by parametric models of the autogressive or moving-average type (ARMA) which have been applied successfully in other geomorphological studies (Bennett, 1976; Richards, 1976a). The fitting of an ARMA (p, q) model where p and q represent respectively the order of the autoregressive (AR) and moving-average (MA) terms involves a three-stage procedure formulated by Box and Jenkins (1970), consisting of model identification, parameter estimation and diagnostic checking. The principal tools at the identification stage are the autocorrelation (ACF) and partial autocorrelation (PACF) functions which have shapes indicative of an appropriate model. In particular an AR (p) process is indicated by a tailing-off of the ACF and a cutting-off of the PACF at lag p. Two main methods were used at the final stage to test whether the residuals from the fitted model behave as white noise, the 'Portmanteau' statistic of Box and Pierce (1970) and the residual autocorrelation function (RACF). Underlying these tests was the need for parsimony of parameters.

The autocorrelation functions (Figure 6) indicate firstly, that the Lyndon and Cave 1 series are not significantly different from white noise, and secondly, that there is some degree of correlation in the Cave 2 and Cave 3 series. None of the final models fitted to the latter contain moving-average terms (Table 4), indicating that the dominant behaviour is autoregressive. Thus the value of a channel form variable at a point s is dependent on previous values of that variable but the two stream lengths differ in the extent of this upstream dependence. Cave 2 is characterised by AR(1) models and Cave 3 by AR(2) models, so that only in the case of the latter is there any tendency for pseudo-periodic behaviour. This distinction amplifies the spectral results in which low and intermediate frequency oscillations respectively dominate the Cave 2 and Cave 3 spectra (Figure 4). The corresponding RACFs indicate white noise residuals, although the second coefficient in the RACF for the width series of Cave 2 is rather high (Figure 6). Indeed an AR(2) model fitted to that series had a significant second-order coefficient but the first-order coefficient then became non-significant. Again the intermediate character of Cave 2 is emphasised. The analysis suggests that the variation of cross-sectional form along Cave 2 and Cave 3 can be regarded as a combination of a random and a systematic element, the latter being of quasi-periodic form in the case of Cave 3. Of the three variables bankfull width appeared to be the most strongly correlated. However, none of the ACFs indicate particularly strong correlations and, although all the coefficients in the models are significant at the 95 per cent level in that they exceed twice their standard error (Table 4), only two are significant at the 99 per cent level (taking three times standard error as the criterion). Systematic components therefore have a subdued influence on the cross-sectional series.

DISCUSSION AND CONCLUSION

Fluvial systems are inherently variable, a maxim which applies particularly to cross-sectional form, one of the most adjustable components of stream channel morphometry. Given that the changes in a cross-sectional variable along a short length of stream can be expressed as the sum of trend, random and systematic components, the problem is to determine their relative contributions to total variation.

All but the width series for Lyndon contained a small but significant linear trend, an increase in mean depth partly compensating for a decrease in bankfull width to maintain an approximate continuity of cross-sectional area. In the absence of marked differences in plan form between and along the study lengths, changes in bed topography offered one possible source of systematic variation underlying the trend component. Cross-correlation analysis showed that increase in bed height was associated with a greater width and smaller depth, indicating that changes in width-depth ratio can occur independently of changes in boundary composition at the local scale. Also, riffle sections had greater widths and smaller depths than did pool sections. However, less than half of the sections were defined as having a riffle or pool bed and, when the cross-sectional variables were considered in series form, none showed significant variation at the riffle-pool frequency found in other streams (Figure 4). Indeed, oscillation at such a wavelength is unlikely, particularly in this environment where bed material size and channel bed slope are relatively large. As a systematic component, therefore, bed topography has little apparent influence on cross-sectional form as

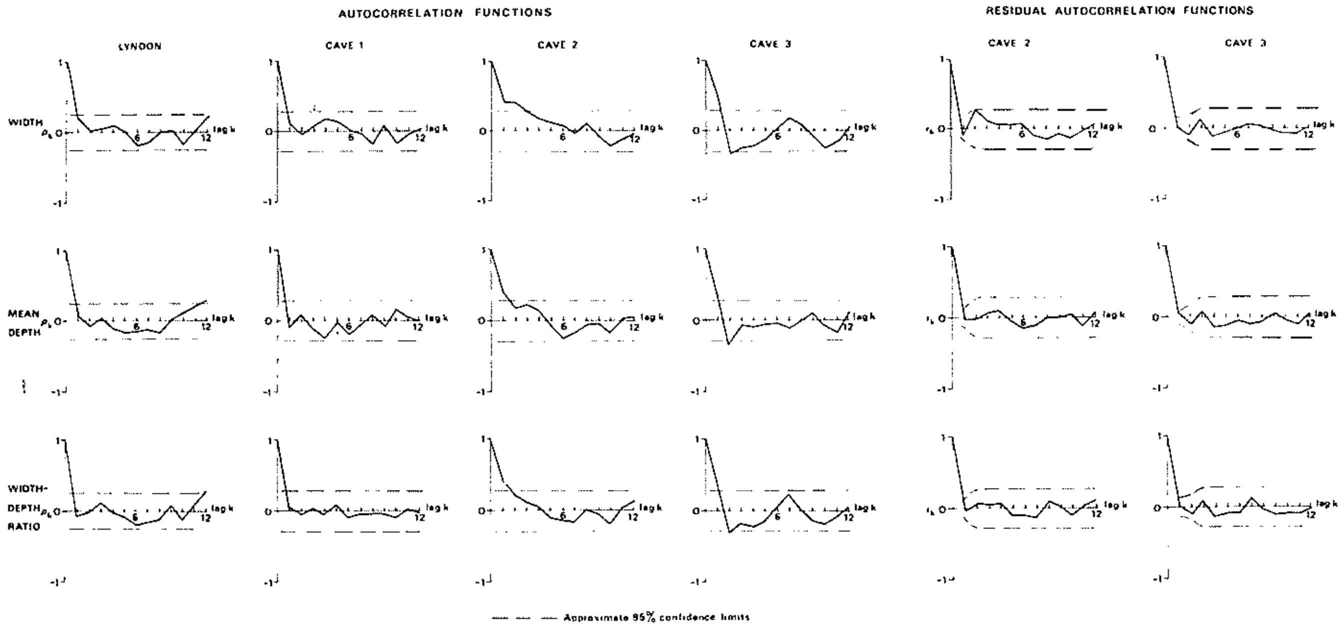

FIG. 6—Autocorrelation functions for the detrended series and residual autocorrelation functions for the fitted models.

TABLE 4 —ARMA (p,q) Models fitted to Width, Depth and Width-Depth Series.

	Width	Depth	Width-Depth Ratio
CAVE 2	$W_s = a_s + \underset{(0.13)}{0.38}W_{s-1}$	$d_s = a_s + \underset{(0.14)}{0.34}d_{s-1}$	$(W/d)_s = a_s + \underset{(0.14)}{0.38}(W/d)_{s-1}$
CAVE 3	$W_s = a_s + \underset{(0.14)}{0.52}W_{s-1} \underset{(0.13)}{-0.35}W_{s-2}$	$d_s = a_s + \underset{(0.14)}{0.29}d_{s-1} \underset{(0.13)}{-0.34}d_{s-2}$	$(W/d)_s = a_s + \underset{(0.14)}{0.44}(W/d)_{s-1} \underset{(0.13)}{-0.33}(W/d)_{s-2}$

Bracketed figures are the standard error of the coefficients.

a spatial series despite its relation to width and depth at individual sections.

The initial hypothesis that the observed series do not differ significantly from random was upheld in the cases of Lyndon and Cave 1. There, the limited variation about the mean (Figure 2) is dominated by random effects. Only the Cave 2 and Cave 3 series showed any tendency to deviate from random. The major source of variation in the former was provided by elements of long wavelength which give rise to low frequency peaks in the spectra (Figure 4). Concentration of variance at low frequencies is characteristic of first-order autoregressive behaviour (Fishman, 1969) and AR(1) models with significant coefficients were fitted to the three series (Table 4). Cave 3 was the stream length showing the strongest degree of structured behaviour in the variation of cross-sectional form. The width and width-depth ratio spectra have peaks at intermediate frequencies and all the series can be described by significant AR(2) models, suggesting an underlying tendency for pseudo-periodic oscillation. It was also the only stream length with a lagged response of cross-sectional form to bed height. Thus the width and depth of any one cross-section were related not only to upstream values of those self-same variables but also to the previous condition of the bed which can affect the pattern of flow and hence the distribution of erosion immediately downstream. The analysis suggests that systematic components become more important in Cave 2 and Cave 3. As available stream power increases downstream and the stream becomes large enough to overcome random influences, at least in part, some degree of regularity in the variation of cross-sectional form becomes apparent. However, that regularity remains somewhat subdued in this mountain stream. The sample framework and methods of analysis adopted here provide a basis for testing whether this trend is maintained beyond headwater areas and for determining the ways in which the ability of a stream to adjust its channel form changes in the downstream direction.

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