

Testing specific stream power thresholds of channel stability with GIS

Mark Stacey¹ and Ian Rutherford²

1 Alluvium, PO Box 204, South Melbourne, VIC, 3051. Web: www.alluvium.com.au, Email: mark.stacey@alluvium.com.au.

2 The University of Melbourne, School of Social and Environmental Enquiry, 227 Bouverie Street, Carlton, VIC, 3010. Email: idruth@unimelb.edu.au.

Abstract

Researchers have proposed several thresholds to predict the transition from unstable to stable states in incised channels. One of the most frequently applied is the 35Wm^{-2} threshold of specific stream power. However this threshold has not formally been tested in environments distinct from its origin. An approach integrating GIS and hydrologic relationships was developed to calculate specific stream power and shear stress at over 1000 sites in Fairfax County, Virginia, USA. Analysis indicated that specific stream power did not discriminate between stable and unstable sites, even when the dominant substrate material was incorporated into the analysis. Substrate type provided a greater influence statistically on channel stability than values of specific stream power, but substrate type alone did not discriminate between stable and unstable sites. Although the research methods failed to provide any practical evidence to support the notion of a stability threshold of specific stream power, dominant geomorphic theory predicts that channel stability is controlled by thresholds. The research concluded that within the geographic scope of the studied environments, no stream power thresholds appear to predict the attainment of stability in incised channels when using the adopted research methods. In absence of further refinement of such GIS methods, stream managers and researchers should continue to seek practical stability thresholds using high resolution hydraulic modelling at suitable spatial scales.

Keywords

Channel incision, stream power, threshold, GIS, Channel Evolution Model

Introduction

The clearing of catchments during the 19th century, combined with channelisation of waterways, led to widespread incision and enlargement of streams in eastern Australia, south west USA and large parts of Africa. Similarly, throughout Europe streams have been channelised during recent centuries to reduce flood hazard, also leading to channel enlargement. There is a very large literature on the causes of incision (e.g. Cooke & Reeves, 1976; Schumm & Hadley, 1957) yet it has proven remarkably difficult to manage and stabilise large incising channels, because they have such high stream-powers. It is even more difficult to rehabilitate such streams.

For this reason, in recent years the research focus has shifted to identifying conditions under which incising channels cease actively deepening and attain a state of relative stability. If this transition point can be identified then waterway managers will know if it is worth intervening in the channel in order to accelerate the recovery of the stream. Schumm *et al.* (1984) developed a Channel Evolution Model (CEM) detailing five 'stages' that incised streams pass through in their transition from natural stability (stage 1), to deepening (stage 2), widening (stage 3), infilling (stage 4) and eventual re-attainment of stability (stage 5). They then suggested that when a stream reached a certain width-depth ratio it began to stabilise.

A more quantitative estimate of this threshold 'stability point' was produced by Brookes (1983, 1987) from assessing the stability of channelised perennial, gravel-bed streams in Denmark, England and Wales. He estimated the transition point using specific stream power (SSP), which is essentially the product of streambed slope and discharge per unit width. Brookes concluded that when a stream has enlarged to the point that it has a SSP below 35Wm^{-2} , then the major phase of erosion is over. This 35Wm^{-2} threshold has been widely applied in stream rehabilitation work as it provides a neat target for waterway design and assessment. For example, the measure appears prominently in the influential stream restoration book edited by Brookes and Shields (1996). It has also been used in Australia, Japan and the USA (e.g. Erskine & White,

1996; Nakamura *et al.*, 1997; Urban & Rhoads, 2003). This paper presents one component of a larger research project that explores this threshold (Stacey, 2006). Here we present the largest independent test of whether there is a simple stream power threshold that can discriminate between stable and unstable reaches of incising streams. The other novel contribution of this research is to explore whether a stream power threshold varies with stream substrate. Based on fundamental sediment transport functions our hypothesis is that the SSP required to transport a given substrate will vary with particle size.

Methods

We estimated SSP for a much larger set of streams than has been assessed in the past, by using a Geographical Information System (GIS). Kumar and Handy (2004) assessed the geomorphic condition of streams of Fairfax County in Virginia (USA) (in the Potomac Basin). The aim of their research was to quantify critical bank height and width-depth ratio thresholds that predict the transition to stability for incising waterways within their study area. They surveyed streams in two physiographic provinces: the eastern Coastal Plain of low gradient topography and sandy soils, and the western Piedmont Upland of undulating hills and a rockier substrate (Figure 1a).

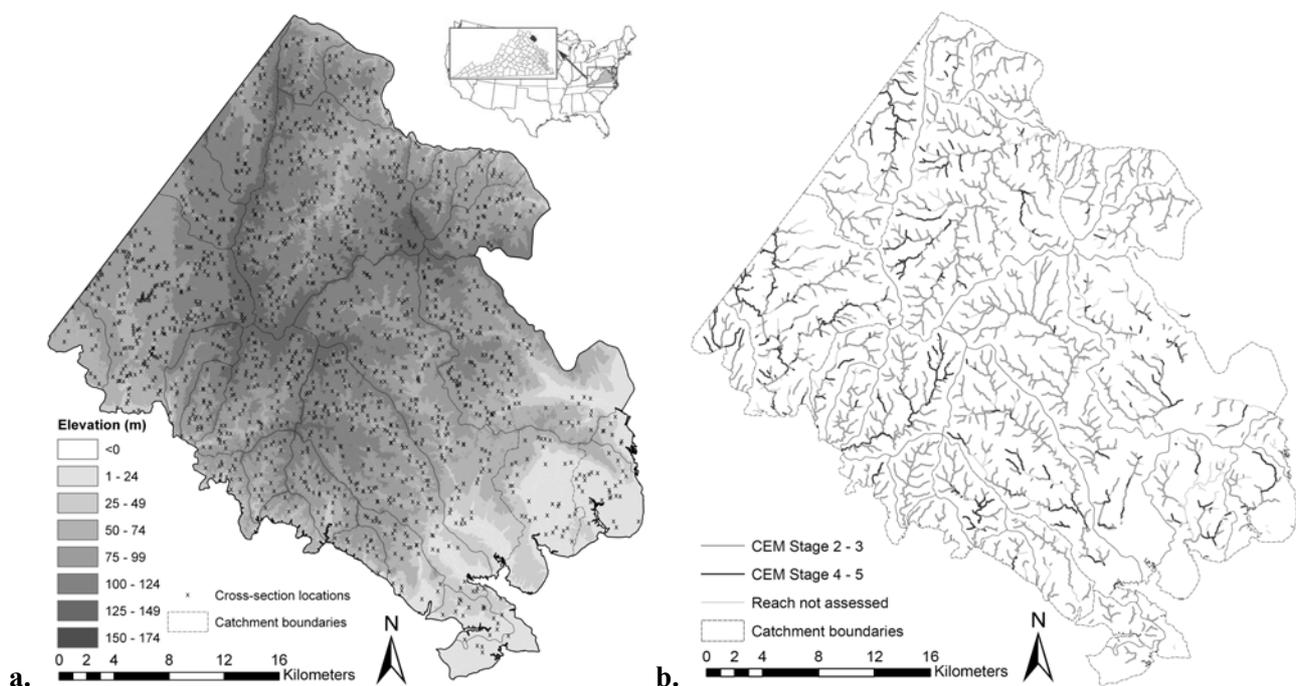


Figure 1a. Study waterways of the Fairfax Country, Virginia, USA showing location, topology and assessment cross-sections; Figure 1b. Distribution of unstable (CEM 2-3) and stable (CEM 4-5) reaches within the study area, showing both occur throughout the catchment.

Kumar and Handy (2004) studied 1279 stream reaches throughout the 1100km² study area. After measuring cross-sections, describing substrate and making other assessments, they then classified each stream reach according to the five stage CEM of Schumm *et al.* (1984). A Global Positioning System (GPS) reading at each site enabled georeferencing of the results. Further information on the field assessment methods can be found in Kumar and Handy, 2004.

Estimating specific stream power

All GIS analysis was based on a 9.14m x 9.14m resolution Digital Elevation Model (DEM) of the study area. For each reach in the DEM we estimated the SSP (ω , Wm⁻²), defined by $\omega = \gamma Q S_0 / w$, where γ denotes the mean hydraulic flow depth (m), Q the water discharge (m³s⁻¹), S_0 the longitudinal channel slope, and w the water surface width (m). Slope was estimated from the maximum elevation, minimum elevation and length of each reach.

Estimating the discharge involved flow frequency analysis, GIS catchment area analysis and discharge-area regressions. Following the work of Simon *et al.* (2004) the 1.5 year annual recurrence interval flow ($Q_{1.5}$)

was deemed the most appropriate effective discharge parameter for the study region and adopted for use. Simon et al. had identified that the median recurrence interval of effective discharge for bedload, washload and suspended load is “remarkably consistent” within the USA and consequently “using $Q_{1.5}$ as a measure of estimating the effective discharge...is reasonable” for such waterways (Simon *et al.*, 2004, p429). Flow frequency analysis of nine United States Geological Survey (USGS) gauges located within and surrounding the study area enabled the development of a strongly correlated regression between $Q_{1.5}$ (m^3s^{-1}) and catchment area (A_b , km^2): $Q_{1.5}=0.56A_b^{0.803}$ ($R^2 = 0.954$). Subsequent GIS analysis provided estimates of A_b at each cross-section, enabling $Q_{1.5}$ to be estimated from the regression equation above.

The $Q_{1.5}$ flow width was estimated by first estimating Manning’s roughness at each site using an empirical relationship between hydraulic roughness, A_b , channel geometry and longitudinal channel slope developed by Dingman and Sharma (1997). Subsequently Manning’s equation was used to estimate the width and depth of the $Q_{1.5}$ flow. With the above data, SSP was calculated at all 1279 sites.

Statistical analysis

Due to the variability inherent in the stability classification dataset, two stability categories were lumped to provide maximum clarity for the analysis. The CEM stage classifications were grouped as either stable (CEM stages 4 to 5) or unstable (CEM stages 2 to 3) – this reduced the dataset size to 1053 reaches. Data were analysed through production of summary statistics and graphs and conducting t-tests, z-tests and Pearson’s chi-square tests to detect significant differences in proportions and SSP at a 0.05 confidence level.

Results

Catchment overview

The field assessments indicated ongoing channel stability problems were evident throughout the study region. The vast majority of sites (985 of 1053) were classified as unstable and only 68 were classified as stable. Both stable and unstable sites were distributed throughout the catchments, occurring across a range of stream orders and catchment locations (Figure 1b). Catchment areas and consequent $Q_{1.5}$ estimates were typically very small (Table 1) which is probably because most of assessment sites are in the upper tributaries (Figure 1a). Over 90% of catchment areas were smaller than the minimum catchment area of gauges ($8.5km^2$) used to develop the regression equation. Longitudinal channel slopes were generally steep (Table 1), reflecting the distribution of assessment sites in the upper catchment.

Table 1. Summary statistics of desktop estimated catchment and channel form descriptors.

| Statistic | A_b (km^2) | $Q_{1.5}$ (m^3s^{-1}) | S_0 | Bankfull width (m) | Bankfull hydraulic radius (m) | Mannings n |
|-----------|------------------|---------------------------|--------|--------------------|-------------------------------|------------|
| Mean | 4.69 | 1.35 | 0.0193 | 4.72 | 0.71 | 0.084 |
| Median | 0.57 | 0.36 | 0.0172 | 3.84 | 0.65 | 0.085 |
| Std. Dev. | 14.5 | 2.96 | 0.0131 | 3.22 | 0.32 | 0.012 |
| Minimum | 0.00025 | 0.00091 | 0.0016 | 0.49 | 0.06 | 0.047 |
| Maximum | 134 | 28.6 | 0.1390 | 26.5 | 3.10 | 0.120 |

Specific stream power

Calculated SSP corresponding to the $Q_{1.5}$ flow were generally within the range of 10 to $50Wm^{-2}$ (Table 2) although several values were substantially higher or lower than this range. In this study we are testing whether a SSP of $35Wm^{-2}$ discriminates between stable and unstable stream reaches. If it does discriminate, then unstable sites (CEM stages 2-3) would have stream powers above $35Wm^{-2}$ while stable sites (CEM stages 4-5) would have stream powers below. No such threshold of stability exists (Figure 2). Furthermore, the difference between mean SSP at stable and unstable sites of all substrates is not significant (Figure 3a; $t=0.59$, $df=1051$, $p=0.554$).

Table 2. Summary statistics of SSP (ω) corresponding to $Q_{1.5}$.

| Statistic | ω : All (Wm^{-2}) | ω : CEM 2-3 (Wm^{-2}) | ω : CEM 4-5 (Wm^{-2}) |
|-----------|------------------------------|----------------------------------|----------------------------------|
| Mean | 33.6 | 33.8 | 35.6 |
| Median | 27.1 | 27.3 | 26.6 |
| Std. Dev. | 26.9 | 28.0 | 27.9 |
| Minimum | 0.14 | 0.14 | 2.70 |
| Maximum | 335 | 335 | 130 |
| Count | 1279 | 985 | 68 |

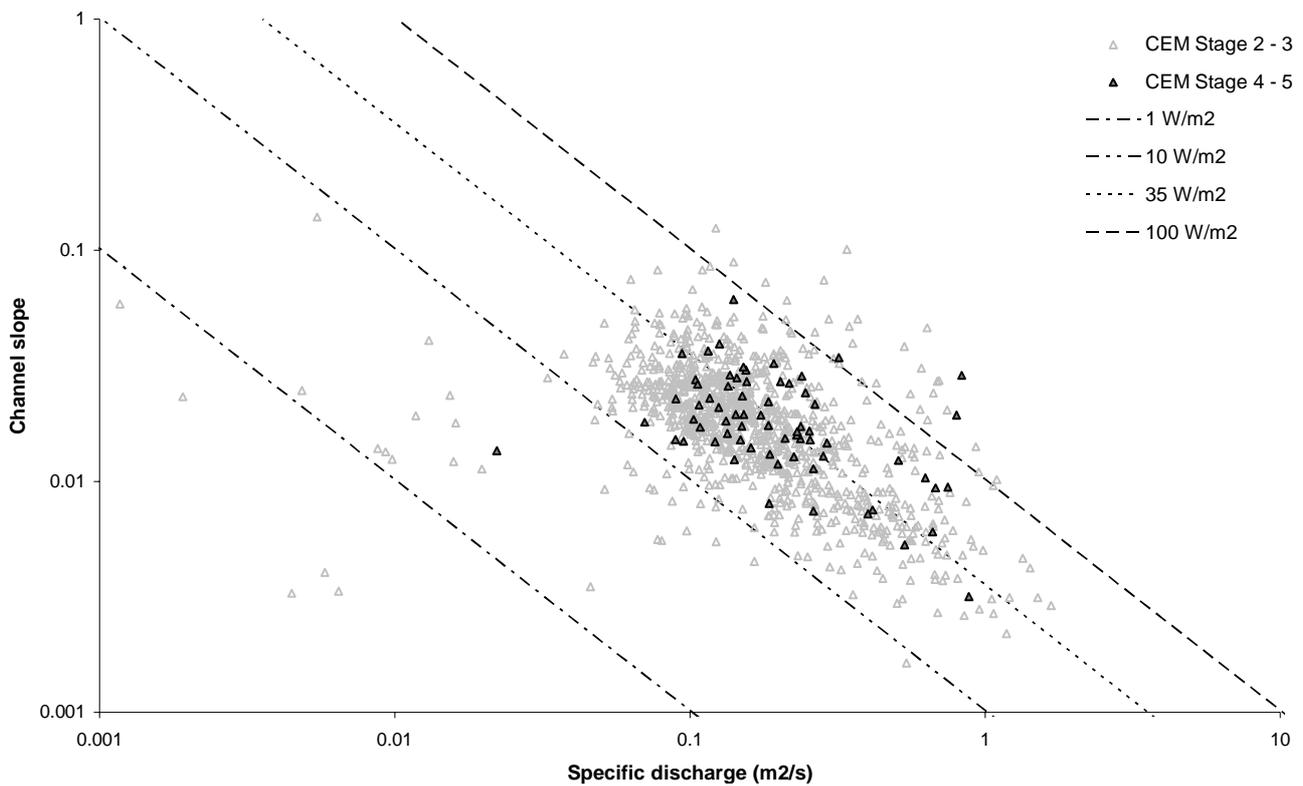


Figure 2. Channel slope against specific discharge, by stability, with lines of SSP superimposed.

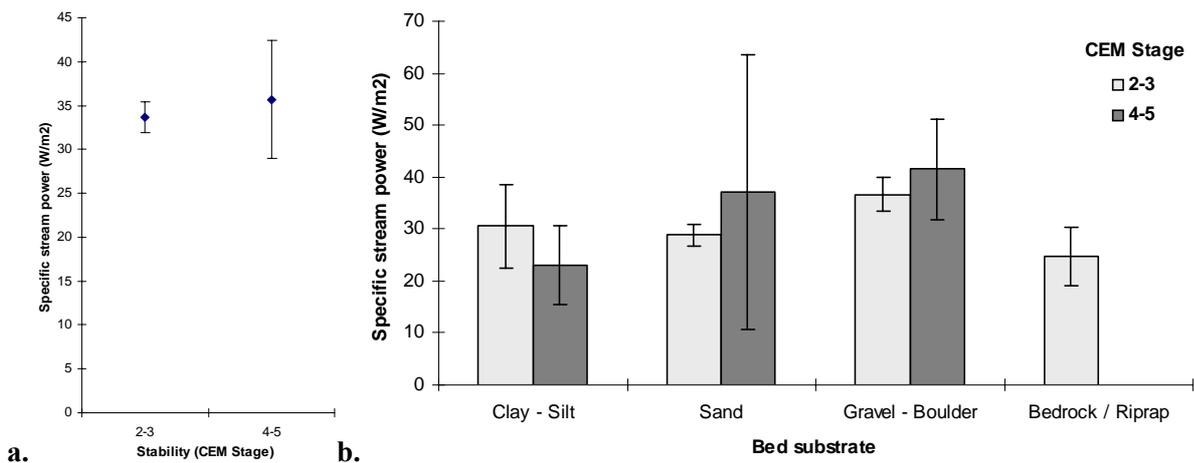


Figure 3a. Mean SSP of sites for both stability classes, with 95% confidence intervals; Figure 3b. Mean SSP of sites for both stability classes, grouped by substrate, with 95% confidence intervals.

When accounting for the influence of bed substrate it was identified that the mean SSP of stable (i.e. CEM 4-5) and unstable (i.e. CEM 2-3) sites is not statistically dissimilar for any of the four qualitative substrate material classes (Figure 3b). This suggests that there is also no threshold of SSP that discriminates between stable and unstable sites for sites of a given bed substrate.

However there are three (of a possible nine) statistically significant differences in mean SSP for sites of differing substrate material, in a given stability class. The mean SSP of unstable sand sites is significantly lower than unstable gravel-boulder sites (Figure 3b; $t=4.1$, $df=657$, $p<0.001$, one-tailed test); unstable bedrock/riprap sites have significantly lower SSP than unstable gravel-boulder sites (Figure 3b; $t=3.878$, $df=24$, $p<0.001$, one-tailed test); stable clay-silt sites have significantly lower SSP than stable gravel-boulder sites (Figure 3b; $t=3.101$, $df=48$, $p=0.002$, one-tailed test).

Substrate material

Analysis independent of SSP indicates differences exist in the proportion of stable and unstable sites for different substrate materials. The proportion of stable sites with a clay-silt substrate is significantly higher than the proportion of unstable sites with this substrate ($z=5.257$, $p<0.001$, one-tailed test). Conversely, the

proportion of stable sites with a sand substrate is significantly lower than the proportion of unstable sites with this substrate ($z=3.080$, $p=0.001$, one-tailed test). These results are confirmed by the Pearson's chi-square test indicating the the proportion of sites with a particular substrate is statistically significantly influenced by the CEM stage classification ($\chi^2=32.16$, $df=3$, $p<0.001$).

Discussion

The assessment of over 1000 sites in incised streams of Fairfax County, Virginia, USA was unable to detect a general threshold, or separate thresholds dependent on substrate type, of SSP that discriminates between stable and unstable incising channels. While sporadic statistically significant differences in SSP were identified, there were no clear trends observed throughout various methods of data analysis. Therefore, the findings of this research on the incised channels of Fairfax County, Virginia contrast Brookes' findings from his research in the perennial gravel bed streams of Denmark, England and Wales.

Substrate type provided a greater influence statistically on channel stability than values of SSP. In particular when compared to stable sites, unstable sites have a significantly higher proportion of sand substrates and a significantly lower proportion of clay-silt substrates. This trend is expected given the readily transportable nature of sand, but it does not suggest that substrate type alone discriminates between stable and unstable sites.

The adopted analytical desktop procedure was designed to enable SSP to be generated for a large number of sites using readily accessible desktop data (USGS gauge records and a DEM), thereby reducing fieldwork requirements. The benefits of this approach focus on potential savings in financial and labour resources. However the potential failings of the approach are less clear but seemingly quite influential. Failings are associated primarily with data inaccuracies hidden within the methodology. Several errors were introduced during the analytical process and these were predominantly associated with an insufficient spatial resolution of the DEM and the small catchment areas of the cross-sections.

As most of the catchment areas were smaller than the minimum gauge catchment area, extrapolation beyond the bounds of the regression relationship was required – this introduced an unavoidable and unquantifiable error. Although the 9.14m x 9.14m pixel DEM is of relatively high resolution for modern large spatial coverages, we believe that significant, unquantified inaccuracies were also introduced through the application of this GIS method. In particular an insufficient DEM resolution was attributed to producing significant over-estimates of longitudinal channel slope and frequent underestimates of catchment area. The reasons for this, which are discussed in detail in Stacey (2006), include: a bias to detect the floodplain elevation instead of streambed elevation, and alignment issues of the waterway line strings with the correct DEM pixels at fine scales.

Importantly such errors are believed to be equally influential on both stability classes and distributed approximately evenly between all sites. This indicates that there is not a systematic bias in the SSP results that would mask a true threshold response. However the SSP estimates elucidated from the desktop analysis are prone to error and may still have an inherent inability to detect a threshold of channel stability, should one actually exist.

Conclusion

Brookes' research (1983; 1987) found that a narrow range of SSP discriminates between stable and unstable incised channels following channelisation in Denmark, England and Wales. This predominantly desktop research on an extensive dataset of incised systems of Fairfax County, Virginia found no evidence to support the notion of a threshold of SSP for predicting the transition to stability in incised channels throughout this wide spatial scale. Strong interactions between stability and the dominant substrate material were observed, although substrate by itself was also unable to account for the transition to stability. The strong influence of substrate on channel stability (relative to SSP) supports a notion that cross-section stability may be dominated by localised cross-section and reach scale substrate controls, rather than catchment scale hydrological controls.

Although there was little evidence to support the notion of a stability threshold of SSP, both dominant geomorphic theory and previously developed theoretical hydraulic relationships (Stacey, 2006) predict that such channel stability thresholds should exist. The GIS method was subject to a range of non-biased inaccuracies, predominantly associated with using a DEM of insufficient resolution. The inaccuracies in the adopted GIS method highlight that data obtained from remote sensing at such spatial resolutions may not yet present a viable replacement for high quality field-measured site information. In particular the ability of this GIS method to accurately estimate SSP remains untested. In absence of further refinement of such technology and methodology, stream managers and researchers should continue to seek practical stability thresholds using field-based high resolution hydraulic modelling at suitable spatial scales.

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