A study of spatial scaling in suspended sediment yield along a rural river system – the River Eden, Cumbria, UK

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Abstract Specific suspended sediment yield was calculated for sub-catchments at a range of scales within the Eden catchment, northwest England. Suspended sediment load was calculated using the flow duration/sediment rating curve method. Specific sediment yield did not show a significant relationship with catchment area, but was found to be spatially variable, particularly between smaller catchments. In order to explain the observed pattern, spatial analysis of catchment characteristics thought to influence sediment yield was carried out. Some variables were derived from GIS data; others were surveyed in the field. No individual variables had a significant relationship with specific sediment yield, suggesting that the factors affecting sediment yield are complex. However, no variables had a significant relationship with catchment area either, indicating the complex nature of the catchment morphology. It is suggested that the catchment area–sediment yield relationship provides a poor basis for understanding spatial variability in sediment yield because of the variability in the underlying processes both within and between catchments. An alternative method of conceptualising spatial variability in sediment yield is now being developed.

Key words specific sediment yield; River Eden; spatial variability; scale; land use

INTRODUCTION

Nonlinearity between process response and spatial scale is a characteristic common to many geomorphological and hydrological systems (Bloeschl, 2001; Slaymaker, 2006). Hence, knowledge of how spatial scale affects system behaviour is of fundamental importance to the overall understanding of these systems. Sediment systems are an example of a system strongly affected by spatial scale. The relationship between specific sediment yield (SSY) and catchment area (A) can be used to characterise the scale dependence of sediment delivery within catchments or between catchments in a region.

In the idealised catchment described by Schumm (1977), specific sediment yield is hypothesised to decrease with increasing catchment area. This is because for the smallest catchments hillslopes are steep and directly coupled to channels, allowing for efficient sediment transport and delivery, while at larger scales the development of flood plains and the overall decrease in valley gradient provides more opportunity for deposition. Other models and studies have suggested that the relationship between area and SSY might be positive where the catchment is undisturbed and most sediment originates from channel bank erosion and not from hillslope sources (e.g. Church & Slaymaker, 1989; Dedkov, 2004; Lu *et al.*, 2005; Birkinshaw & Bathurst, 2006) or that the relationship may be initially positive and then negative (de Vente & Poesen, 2005). The wide range in the SSY–A relationships documented in the literature indicates that the relationship is not a simple one and that many factors influence how sediment delivery processes vary with changes in scale.

The aim of this field-based study is to quantify the spatial pattern of a catchment's sediment yield and then to identify the processes behind this, with particular attention to understanding the effects of scale on sediment yield. The study site is the upper Eden catchment in northwest England (Fig. 1), which has been instrumented as part of the UK national CHASM (Catchment Hydrology And Sustainable Management) project (http://www.ncl.ac.uk/chasm). The Eden is a gravel bed river. The catchment is predominantly rural but there is a spatial contrast in land use from the peat moorland uplands to the improved pasture of the lowlands. Elevation ranges from 125 to 715 m a.m.s.l. Annual precipitation ranges from less than 650 mm in the valley to over 2000 mm in the uplands. The monitoring infrastructure comprises 10 sites, of which six lie in a nested system. Four sites outside the nested system were monitored in order to represent the range of characteristics across the catchment (Fig. 1, Table 1).

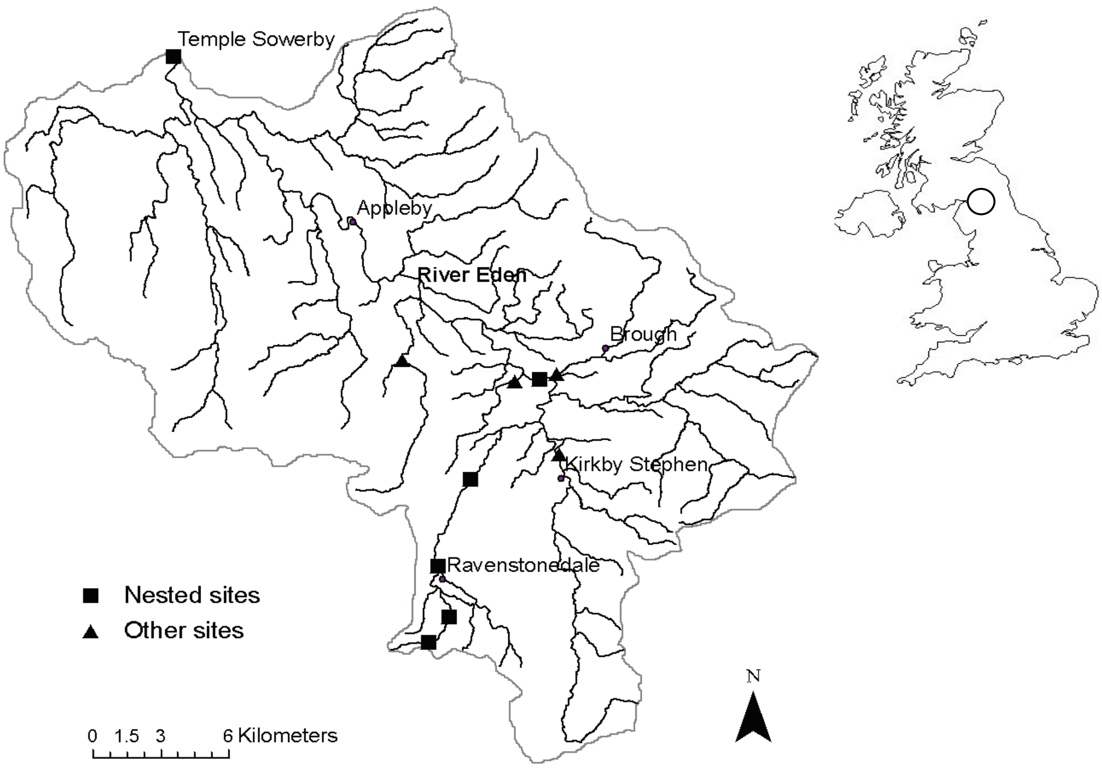

Fig. 1 Eden basin location and map showing monitoring sites.

Table 1 Sites in the Eden catchment used for flow monitoring and suspended sediment sampling. Italics indicate sites within the nested catchment system; EA stands for Environment Agency.

Site	Catchment area (km^2)	Number of years of flow data	Site manager
Gais Gill	*1.2*	*4*	*CHASM*
Artlegarth Beck	*2.6*	*4*	*CHASM*
Scandal Beck at Ravenstonedale	*25*	*4*	*CHASM*
Scandal Beck at Smardale	*36*	*4*	*CHASM*
Eden at Great Musgrave	*233*	*8*	*EA*
Eden at Temple Sowerby	*616*	*30*	*EA*
Blind Beck	8.8	4	CHASM
Swindale Beck	16.3	1	CHASM
Helm Beck	17.9	4	CHASM
Eden at Kirkby Stephen	69	27	EA

APPROACH

Quantification of sediment yields

Discharge is monitored continuously at each site. Water samples provided measurements of suspended sediment concentration (SSC) and this was related to discharge to form a sediment rating curve for each site. Annual suspended sediment yields were then calculated using the flow-duration/sediment-rating-curve method (Julien, 1998). Although longer-term flow records exist at Environment Agency (EA) sites, flow has been recorded at CHASM sites since at least 2002, so, for consistency, flow durations were based on the last four years of flow data. Future work is planned which will use the longer-term flow duration curves to estimate flow duration curves for sites with short records.

The quantification of suspended sediment yields was subject to several sources of error. The difficulty of obtaining a good relationship between SSC and discharge is commonly found in other studies in the literature and is because suspended sediment concentrations may be affected by temporal variability in sediment availability (e.g. Jannson, 1996). Values of R^2 for the SSC-discharge relationships presented here are typically 0.5. Another problem was the difficulty of obtaining sufficient measurements of SSC at high flows, so that in some cases curves had to be extrapolated to provide estimates of SSC for the highest flows. Additionally, the use of flow records of four years and sediment samples from one year mean that the sediment yields calculated may not be fully representative of the long-term yields. The results represent work in progress and should therefore be viewed as preliminary.

Quantification of catchment characteristics

In order to provide process-based explanations for the spatial variability in sediment yield, spatial variability in the characteristics relevant to sediment supply and delivery was analysed. GIS data for land use, elevation, geology, and soils were used to divide the catchment into three broad landscape zones: Upland, Intermediate and Central Lowland. Within each of these zones channels were classified, based on GIS analysis of stream power, channel gradient and channel confinement. From each of the channel classes a number of 500-m reaches were selected to be surveyed in the field. At least three spot-checks were carried out for every reach. At each one attributes surveyed included channel dimensions, bed and bank material, bank profile, vegetation cover and erosion severity, flood plain width and land use within 15 m of the channel. In addition, the whole reach was assessed for the overall percentage of eroding banks and the percentage of the channel which was directly coupled to the hillslopes (areas where hillslope and channel processes directly interact, such as where streams cause basal erosion of hillslope scars). The number of each type of point input of sediment in each reach was recorded. These included incidences of bank erosion acceleration, such as livestock poaching or vehicle access to the channel, and other inputs such as overland flow pathways, landslides and gullies.

The surveys were time-consuming and therefore limited in spatial extent. Further work is planned, which will examine the potential for the use of air photographs to quantify sediment inputs and pathways, allowing greater coverage of the catchment.

RESULTS

Sediment yield–catchment area relationship

The plot of specific suspended sediment yield against catchment area (Fig. 2) does not show a clear trend. Both the highest and lowest specific sediment yields are found in small catchments, while a more central value appears to be obtained as scale increases. This indicates that sediment supply and delivery processes do not operate consistently at a given scale and reflects the high complexity of these processes. It also suggests that variables which are unrelated to scale are at least partly responsible for spatial variability in SSY. Data uncertainty may, however, also affect the pattern observed.

Within the nested system the catchment morphology changes from a steep, moorland headwater to a lowland meandering flood-plain channel. This change in catchment characteristics is likely to be accompanied by a change in dominant process and should be reflected by changing SSY with distance down the system. The plot shows that SSY is highest in the smallest catchment, and then decreases to its lowest level. It then increases again before a second slight decrease. Any influence of changing catchment morphology and land-use characteristics therefore has a complex effect on the pattern of the SSY–A relationship.

Catchments outside the nested system show varying sediment yields, reflecting the variable catchment characteristics and, hence, sediment delivery processes and rates within them.

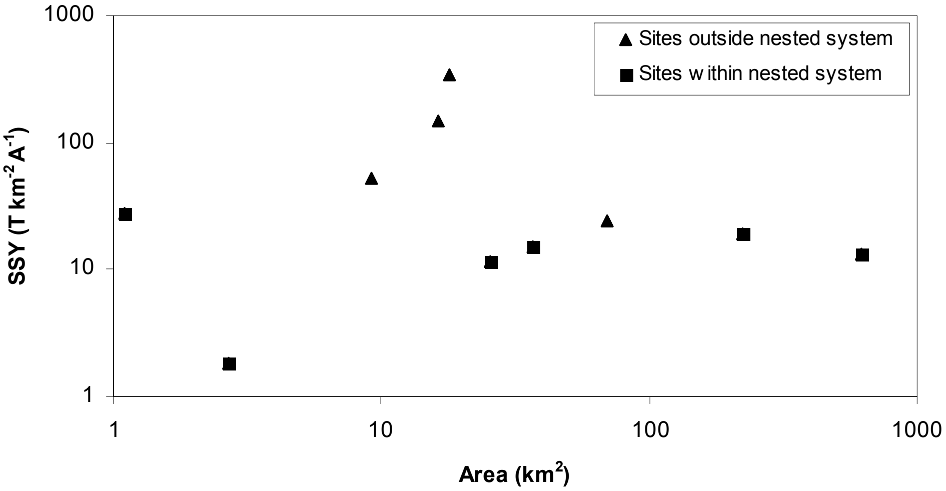

Fig. 2 Variability of specific suspended sediment yield with catchment area.

Spatial variability in catchment characteristics

If we examine the SSY–A relationship from a process-based perspective it becomes clear that catchment area is a black-box parameter and is used as a substitute for a number of variables that affect sediment delivery and which are also related to catchment scale (Verstraeten & Poesen, 2001). The main factors controlling the spatial variability in SSY must be established, and whether or not they have a direct relationship with catchment area. It should then be possible to elucidate whether catchment area exerts any influence over SSY or whether other environmental factors are more important and override scale effects.

The sediment yield of a catchment is dependent on the sediment availability, the level of connectivity (allowing sediment to be transported from hillslope to river) and the in-stream sediment transport rate (de Vente & Poesen, 2005; Vanacker *et al.,* 2007) (Fig. 3). Each of the three stages is affected by a complex range of variables which relate to the catchment characteristics. In Fig. 3 it is hypothesised that some variables affecting sediment yield are related to scale, some are completely unrelated to scale and some appear in both sections because, although they vary with scale, they may also be affected by other factors. The complex way in which many of these variables are inter-related makes it difficult to eliminate the main factors influencing sediment yield and the overall effect of scale (Verstraeten & Poesen, 2001).

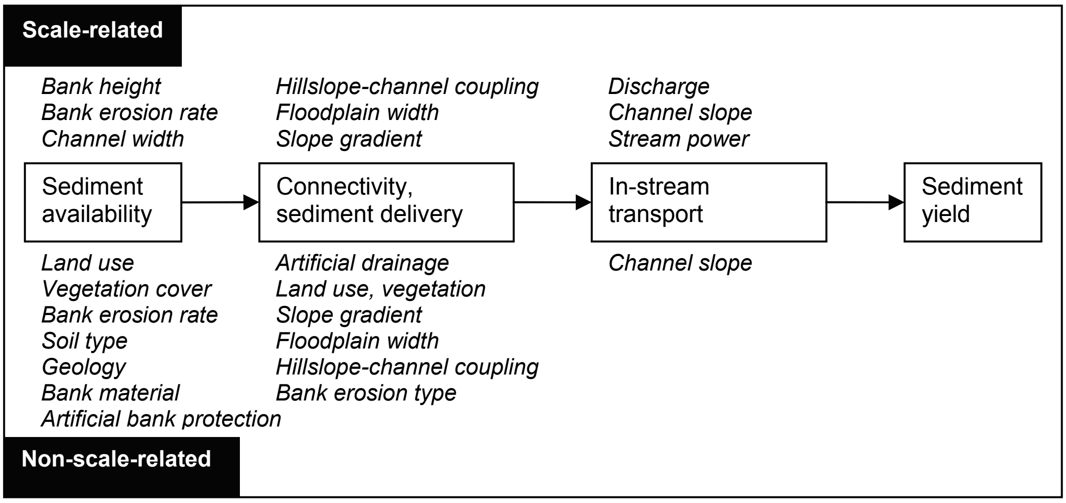

Fig. 3 Flow diagram showing how scale- and non-scale-related factors are hypothesised to link together to cause a given specific sediment yield.

The variables measured as part of the GIS analysis and field survey relate to the variables in Fig. 3. Specific sediment yield was found to have a poor relationship with each of these variables, some of which are illustrated in Fig. 4. The percentage of eroding banks in a sub-catchment showed no relationship with sediment yield (Fig. 4(a)), suggesting that bank erosion alone is not responsible for variability in sediment input. However, discrimination between different bank materials may reveal a relationship, as eroding banks with a higher proportion of fine material are more likely to contribute to the suspended sediment load.

A weak positive relationship (R^2 = 0.2) was found between suspended SSY and the percentage of land in the catchment which was managed grassland (Fig. 4(b)), suggesting that land-use practices might affect sediment supply and transport rates. Pasture in the Eden catchment generally has higher stocking densities than moorland, which is the other major land use. The field survey showed that areas of pasture had a significantly higher density of channel bank poaching by livestock, an important sediment source in grazed areas (Heathwaite *et al.*, 1990; Gruszowski *et al.*, 2003). Qualitative assessment of grazed areas also showed that there were often larger proportions of bare soil near the channel than in moorland areas owing to livestock trampling, around gateways, for example. Another reason for higher suspended sediment in areas of pasture may be that pasture is more common in lowland areas (Fig. 5). Flood plains tend to be present in these areas and channel banks contain a larger proportion of fine material, so are more erodible.

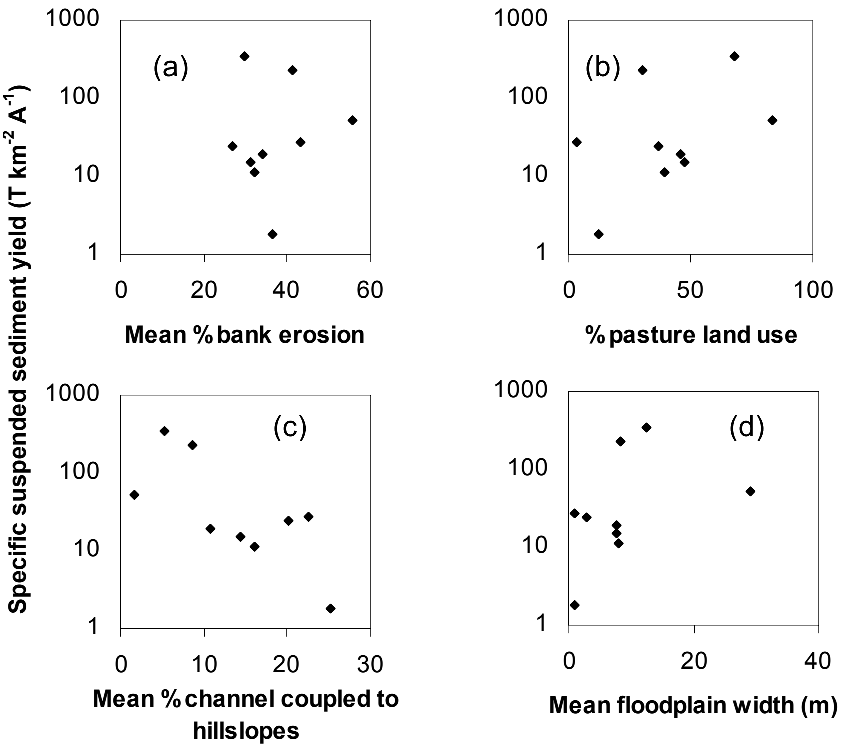

Fig. 4 Scatter plots showing the relationship between specific suspended sediment yield of a sub-catchment and (a) percentage of channel banks which are eroding; (b) percentage of the catchment used for pasture; (c) percentage of the channel which is coupled to the hillslopes; and (d) mean flood-plain width, for the Eden catchment. In each case the relevant variable is determined for the entire catchment or river length above the sediment sampling point.

A weak negative relationship was found between suspended SSY and the percentage of hillslope–channel coupling (Fig. 4(c)) (R^2 = 0.3). This is opposite to what was hypothesised, as higher levels of coupling should allow more efficient sediment delivery. Similarly, wider flood plains appear to correspond to higher sediment yields (Fig. 4(d)), whereas the hypothesis was that they would act as a buffer to sediment delivery. This suggests that other sediment delivery mechanisms must be more important. High levels of hillslope–channel coupling and narrow flood plains were mainly found in steep upland channels where other processes leading to fine sediment input, such as livestock poaching, are low. The degree of hillslope–channel coupling may relate better to bedload sediment yields, as inputs of bedload are limited to sources very close to the channel and steeper channels have a higher capacity to transport bedload. This will be investigated further in future work.

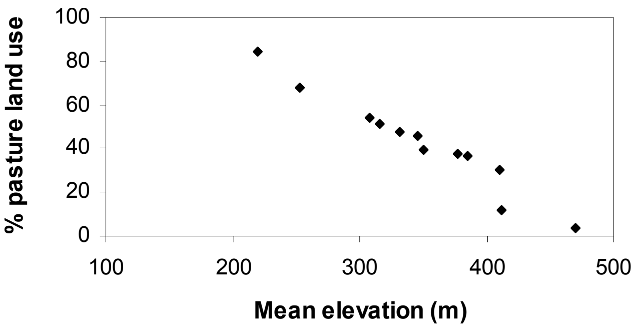

Fig. 5 Relationship between mean elevation of a sub-catchment and the percentage of pasture in it, for the Eden catchment.

In Fig. 3 some catchment characteristic variables to be investigated are hypothesised as: (i) affecting sediment yield and (ii) being related to catchment area. Using the data gathered in the field survey and GIS analysis, the relationships between some of these variables and catchment area were examined. None of the variables showed a strong relationship with catchment area and some showed no relationship at all.

If the catchment morphology followed the model of Schumm (1977), channel slope should decrease with increasing catchment area, while flood-plain width should increase with catchment area. Figure 6(a) shows that there is an overall trend for decreasing channel slope with increasing area, but that scatter is high and there are also occurrences of low slopes at low catchment areas. Figure 6(b) shows that both wide and narrow flood plains can be found in both small and large catchment areas.

One reason for this is the occurrence of small sub-catchments outside the headwater zone, where they are less likely to be steep with narrow valleys. Therefore, the assumption that all small catchments contain steep channels with high hillslope–channel coupling is an oversimplification. Some catchments are so small, with very small streams, that significant erosion or incision has not taken place and the channels occur in shallow valleys with a gentle bed slope. These are often found in the upland moorland plateau areas. Spatial variability in the boundary conditions for channel formation, such as the geology and the occurrence of glacial deposits, also affects local channel and valley morphology. Features such as steep-sided gorges found part way along several tributaries, including Scandal Beck, interrupt any general trend of increasingly gentle valley sides with distance downstream.

Therefore, even if these catchment morphological variables were affecting sediment supply and delivery rates, one would not expect them to be manifest as a relationship between SSY and catchment area. The overall catchment morphology probably affects sediment yields in a more complex way than was hypothesised.

Other catchment characteristics, which affect sediment yield, are not related to catchment area, or are related to catchment area through a mutual relationship with another variable. In the Eden the most prominent of these is land use, which shows a weak positive relationship with SSY, as discussed above (Fig. 4(b)). Land use is determined by human activity and depends on factors such as slope and soil type which affect potential for cultivation: there is a trend for increasing proportions of managed grassland at lower elevations where conditions for agriculture are more favourable (Fig. 5). Land use does, therefore, exhibit spatial patterns, which may affect the spatial patterns of SSY, but not due to any physical basis, only because it tends to follow the patterns of catchment morphological variables.

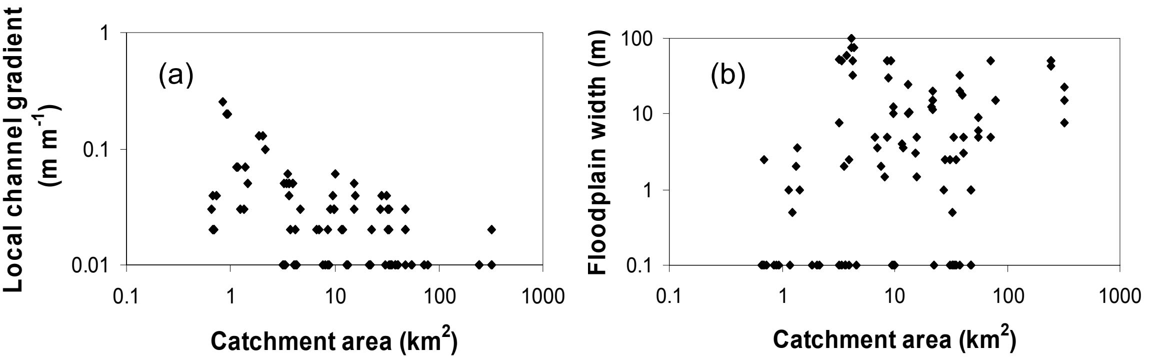

Fig. 6 Relationship between catchment area and: (a) local reach mean gradient, (b) local flood-plain width, for the Eden catchment.

CONCEPTUALISING SPATIAL VARIABILITY IN SPECIFIC SEDIMENT YIELD

Spatial variability in SSY, based on suspended sediment, in the Eden catchment is affected by a wide range of factors, many of which are interrelated. Most vary spatially in a complex way, not necessarily in relation to a morphological and measurable characteristic of the catchment. This makes it difficult to extend generalisations about the spatial variability of SSY in the Eden to other catchments, which may be subject to a different spatial pattern of boundary conditions.

The results cast doubts over the physical meaning of a simple relationship between SSY and catchment area in the Eden catchment. Having so far found no significant relationship between any catchment characteristic and catchment area, there appears to be little support for the hypothesis that SSY should vary with A. The wide range of different relationships between SSY and A in the existing literature supports this contention: no universal relationship can be obtained because the main factors affecting the spatial variability in SSY are often different in different catchments. These conclusions indicate that a different way of conceptualising SSY in a catchment is needed, in order to provide a more universal framework for understanding how SSY varies spatially.

The results suggest that the SSY of a given sub-catchment can be viewed as a function of the sub-catchment's position in relation to the overall spatial structure of the catchment. Results from the survey indicate that most of the catchment does not contribute to the sediment yield, owing to the low level of connectivity between hillslopes and channels and the high density of vegetation cover. Most of the sediment yield is from discrete sources such as areas of livestock poaching, river cliff scars or landslide gullies. The sediment yield of a catchment should, therefore, depend on the number of these type of features contained within it and how much sediment they produce.

The size of the catchment, relative to the size and distribution of the features, will be important in determining the sediment yield. A sediment-producing feature of a given size will contribute a higher proportion of the absolute sediment load of a smaller catchment than a larger one. However, it is also less likely that the feature will fall within the smaller catchment. This should result in the greatest variability in sediment yield being found in smaller catchments. The sediment yield of larger catchments reflects the integration of sediment yields from the smaller catchments contained within them, and is therefore a form of mean value. This is to some extent what is seen in the Eden catchment (Fig. 2), though sampling of a greater number of sub-catchments of different sizes would help confirm this trend.

CONCLUSIONS

Within the Eden catchment the lack of simple relationships between SSY based on suspended sediment, catchment area and other factors hypothesised as affecting SSY suggests that there are numerous factors contributing in a complex way to the observed SSY. In an idealised catchment, sediment yield is related to catchment area because of the changing relationship between the hillslopes and the channel (Schumm, 1977). However, in the Eden, catchment morphology does not follow a consistent pattern and other variables which affect sediment delivery, such as rock type, soils, vegetation and land use, are not constant throughout the catchment. The resulting sediment yield is therefore a product of the way in which these factors interact and vary spatially. The results should be seen in the context of the UK's relatively low sediment yields on a world scale; a lower level of yields may tend to mask or alter spatial dependencies.

In catchments such as the Eden, where most sediment is produced from discrete sources, spatial variability in SSY can be conceptualised as relating to the size, density and distribution of these features. This results in the highest variability in SSY in smaller catchments, tending towards a mean value in larger catchments where small-scale variability in sediment production and transfer rates is integrated into the overall yield.

Further work on the project will build on these initial results. Planned work includes: (i) improvements to the accuracy of sediment yield estimates; (ii) the addition of further sites, including a larger area; (iii) estimation of total SSY, including bedload sediment yield; and (iv) development of a simple conceptual model that is able to represent spatial variability in sediment yield within the catchment and which can be applied more widely.

Acknowledgements The authors gratefully acknowledge assistance in field data collection from Mark Wilkinson and Mary Ockenden, and the provision of flow data from the Environment Agency (EA). Carolyn Mills is supported by a Natural Environment Research Council (NERC) studentship. The CHASM project was funded by the Wellcome Trust and administered by NERC through the Joint Infrastructure Fund.

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