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Sediment yield scale dependency in the River Eden basin, northwest England

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Abstract A preliminary assessment of the spatial scale dependency of sediment yield from the Eden basin in northwest England is made on the basis of: suspended and bed load yield estimates at scales from 1 to 1370 km^2, spot samples of suspended sediment concentration, and a dual resolution mapping exercise in which a generalized soil erosion risk map for the upper Eden (322 km^2) is complemented by a high resolution (2 m) map of erosion features and sediment transport pathways in a 5.4-ha farm field. Overall, annual specific total sediment yield decreases as basin area increases: specific bed load yield decreases rapidly but specific suspended load yield may even show a small downstream increase. The spot sampling campaign and the dual resolution mapping exercise suggest that this could reflect the impact of livestock farming in the more lowland areas. The results demonstrate the importance of sediment source and transport pathways in explaining scale dependency in sediment yield.

Key words CHASM; erosion map; scale dependency; sediment source; sediment yield

INTRODUCTION

Both inverse and direct relationships between specific sediment yield and basin area have been documented (e.g. Dedkov & Moszherin, 1992; Morris & Fan, 1997). However, the clear physically-based rules which define a general spatial scaling theory have yet to emerge. This study therefore makes a preliminary characterization of the sediment yield of the River Eden basin in northwest England (Fig. 1) and investigates the role which sediment source plays in determining the relationship between sediment yield and basin area.

The upper Eden basin (322 km^2) above Appleby is one of four mesoscale basins (order 100 km^2) which have been extensively instrumented under the CHASM (Catchment Hydrology And Sustainable Management) programme (http://www.ncl.ac.uk/chasm). Under the common experimental design, the mesoscale basin contains a pair of miniscale basins (order 10 km^2), which in turn contain microscale basins (order 1 km^2), which themselves contain hillslope patch sites (order 100–10 000 m^2). The upper Eden basin is rural and encompasses both upland (peat moorland and unimproved pasture) and lowland (pasture with some arable farming) areas, a spatial distinction which is

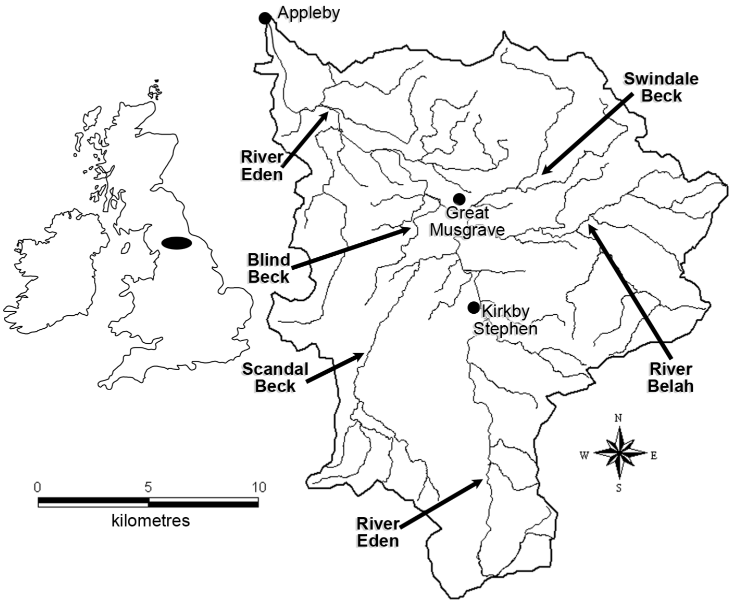

Fig. 1 Eden basin location and map.

represented by the two miniscale basins, Artlegarth Beck (upland) and Blind Beck (lowland). Elevation ranges from 125 m at Appleby, to 788 m. Annual precipitation ranges from less than 900 mm in the main valley to more than 1900 mm in the uplands. The river is gravel-bedded. Within the upper basin there are two Environment Agency gauging stations on the Eden at Kirkby Stephen (area 69 km^2) and Great Musgrave (223 km^2). Along the 6-km stretch between the two lie the confluences with the other three principal headwater tributaries: Swindale Beck (27 km^2), Scandal Beck (40 km^2) and the River Belah (53 km^2) (Fig. 1). Two further stations allow extension beyond the CHASM basin: Temple Sowerby (616 km^2) and Warwick Bridge (1370 km^2).

SEDIMENT YIELD CHARACTERIZATION

Mean annual sediment yield was estimated at nine locations on a nested basis, using the flow-duration/sediment-rating-curve method (Julien, 1998, p. 235). Flow-duration curves were obtained from the Environment Agency for the four gauging stations. Curves for the remaining five locations were then derived from an empirical relationship between flow-duration curve form and basin area (Vivier, 2002; Orange, 2004).

As a regular sediment transport monitoring programme was not in place at the time of the studies, the rating curves were constructed by indirect methods. Suspended sediment transport was represented by the standard power relationship:

$$C = aQ^b \tag{1}$$

where C is concentration and Q is discharge. Values of the constants a and b were transferred from three sites elsewhere in the UK considered to have some similarity to headwater (Gais Gill), intermediate (Kirkby Stephen), and downstream (Warwick Bridge) sites in the Eden basin in terms of area and geomorphological context. Details

Table 1 Transfer of suspended sediment rating curves to the Eden basin.

Data source: River	Area (km^2)	Reference	Quantified constants: *a*	*b*	Equivalent Eden site: Site	Area (km^2)
Cyff (Wye)	3.1	Leeks & Marks (1997)	0.025	1	Gais Gill	1.08
Ystwyth	170	Walling & Webb (1981)	0.001	1.43	Kirkby Stephen	69
Tyne	2159	Walling & Webb (1981)	3.8×10^{-6}	1.86	Warwick Bridge	1370

$C = aQ^b$; C in g l^{-1}, Q in m^3 s^{-1}.

are shown in Table 1, where the values of *a* and *b* were determined by Vivier (2002) and not from the original reference. Although this is an arbitrary approach, it is consistent with the range of exponent *b* (0.3–2) and the inverse relationship between *a* and *b* noted by Walling & Webb (1981). Values of *a* and *b* were then obtained for the other Eden sites by interpolation between the values in Table 1 on the basis of area (Vivier, 2002; Orange, 2004). The results obtained from using these rating curves should of course be considered as no more than order of magnitude guidelines.

Bed load transport was calculated as (Bathurst, 2004):

$$g_s = 22.2\times10^6\, S^{1.5}(D_{50}/D_{50S})^{-3.13}\left(q - 0.0133 g^{0.5}\, D_{84}^{1.5}\, S^{-1.24}\right) \qquad (2)$$

where g_s is bed load transport per unit width (g s^{-1} m^{-1}), q is water discharge per unit width (m^3 s^{-1} m^{-1}), S is slope (m m^{-1}), D_n is particle size of surface (armour layer) bed material for which n% of sizes are smaller (m) (obtained using the Wolman (1954) sampling technique), D_{ns} refers to the same for the subsurface material (m) and g is acceleration due to gravity (m s^{-2}). Subsurface material size distribution was not measured, owing to the difficulty of excavating the river bed. However, D_{50}/D_{50S} typically ranges between 1 and 10 and a value of 3, characteristic of the more developed gravel-bed streams, was assumed for all sites. Channel slope was taken from the UK Ordnance Survey 1:50 000 scale map in order to be representative at the larger reach scale. Bed material and slope data for the Temple Sowerby and Warwick Bridge stations were taken from Hey & Thorne (1986).

The derived annual specific sediment yields (Vivier, 2002; Orange, 2004) are given in Table 2 and plotted against basin area in Fig. 2.

SEDIMENT SOURCE

Attention was directed to investigating: the variation of sediment supply between the main headwater basins (Swindale Beck, Scandal Beck, River Belah and the Eden at Kirkby Stephen, shown in Table 2); the impact of agricultural activity on supply; and mapping supply at different scales.

Agricultural activity impact

Livestock density is generally greater in the lowland than in the upland areas. Spot measurements of suspended sediment concentration and discharge (Vogel, 2003; Orange,

Table 2 Summary of the Eden basin sediment yield estimates.

Site	Basin area (km^2)	Channel slope ($m\ m^{-1}$)	Suspended sediment yield ($t\ km^{-2}\ year^{-1}$)	Bed load yield ($t\ km^{-2}\ year^{-1}$)	Total yield ($t\ km^{-2}\ year^{-1}$)
Eden, WB	1370	0.0017	14.1	0.29	14.4
Eden, TS	616	0.0015	15.7	0.03	15.8
Eden, A	322	0.0024	25.0	0.56	25.5
Eden, GM	223	0.0023	30.2	0.54	30.7
Eden, KS	69	0.0043	50.0	15.9	65.8
Belah, BB	53	0.0102	46.8	171	217
Scandal, S	40	0.0083	40.9	90	131
Swindale, HGF	27	0.0105	33.8	177	210
Artlegarth, GG	1.08	0.0520	21.5	544	565

WB: Warwick Bridge; TS: Temple Sowerby; A: Appleby; GM: Great Musgrave; KS: Kirkby Stephen; BB: Belah Bridge; S: Soulby; HGF: Hall Garth Farm; GG: Gais Gill.

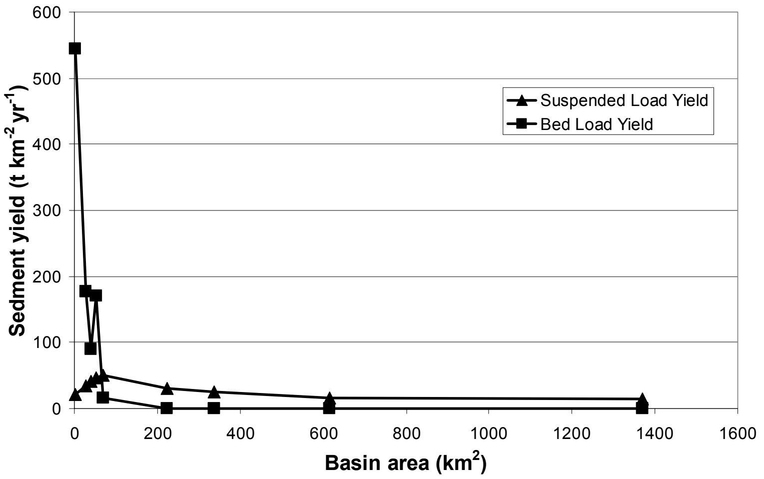

Fig. 2 Relationship between suspended and bed load sediment yields and basin area.

2004) were therefore made in the contrasting miniscale basins: the upland Artlegarth Beck at Gais Gill and the lowland Blind Beck and nearby Hill Top Farm. Data were also collected for the principal headwater basins.

Erosion mapping

Erosion mapping was carried out at two scales (Gravier, 2004). First, a soil erosion risk map was constructed using ArcGIS for the Eden basin above Appleby. Component maps for annual rainfall, soil erodibility, hillslope gradient, land cover and cattle and sheep stocking density were aggregated on a weighted basis to give a map in which risk was represented qualitatively on a scale from “very low” to “very high” (Fig. 3).

At the second scale, a high resolution (2 m) map was constructed of an approximately 5.4-ha area of Sykeside Farm, within the Blind Beck miniscale basin and also within the “high risk” zone of the soil erosion risk map. The aim was to complement

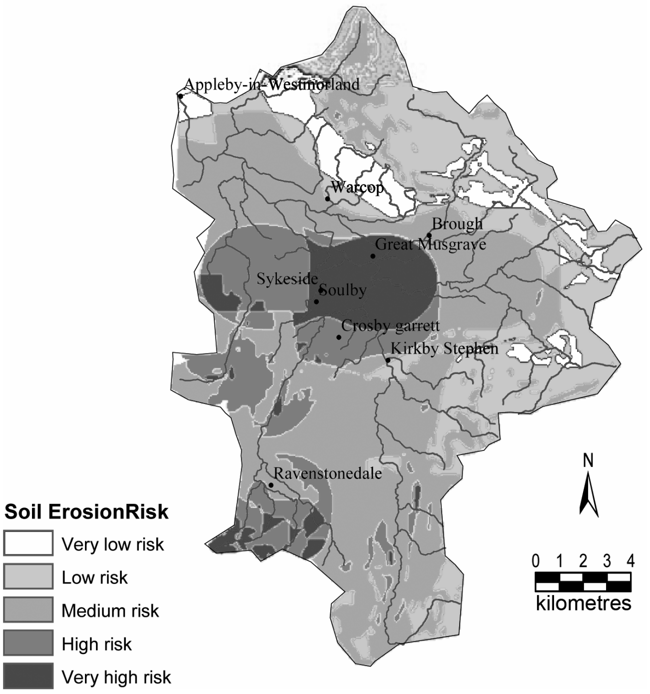

Fig. 3 Soil erosion risk map for the upper Eden basin.

the generalized risk map with information on the erosion features and pathways responsible for the supply of sediment to the channel system. A digital elevation model was built up from spatial coordinates and altitudes measured every 2 m by a differential Global Positioning System (dGPS) and converted to ArcGIS file format. Erosion features and sediment transport pathways, such as drainage ditches, sheep paths, stream banks and areas of bare soil were identified by visual survey and integrated into the map as digital photographs (Fig. 4).

ANALYSIS

Overall the annual specific sediment yield decreases as area increases but contrasting patterns are shown by the component suspended and bed load yields (Fig. 2).

Suspended load yield

The estimated specific suspended sediment yields vary within a narrow range of 10 to 50 t km^{-2} year^{-1}. These values are probably slight underestimates, at least for the smaller basins: Walling & Webb (1981) quote measured yields of up to 250 t km^{-2} year^{-1} for small north Pennine basins and the few spot samples of suspended sediment concentration also suggest that the estimated rating curves may underestimate the true suspended load. On the other hand, yields of less than 50 t km^{-2} year^{-1} have been widely measured on the east side of the Pennines at scales of 500–8000 km^{2} (Wass & Leeks, 1999). The absolute values should therefore be viewed as preliminary estimates, to be upgraded as measurements become available.

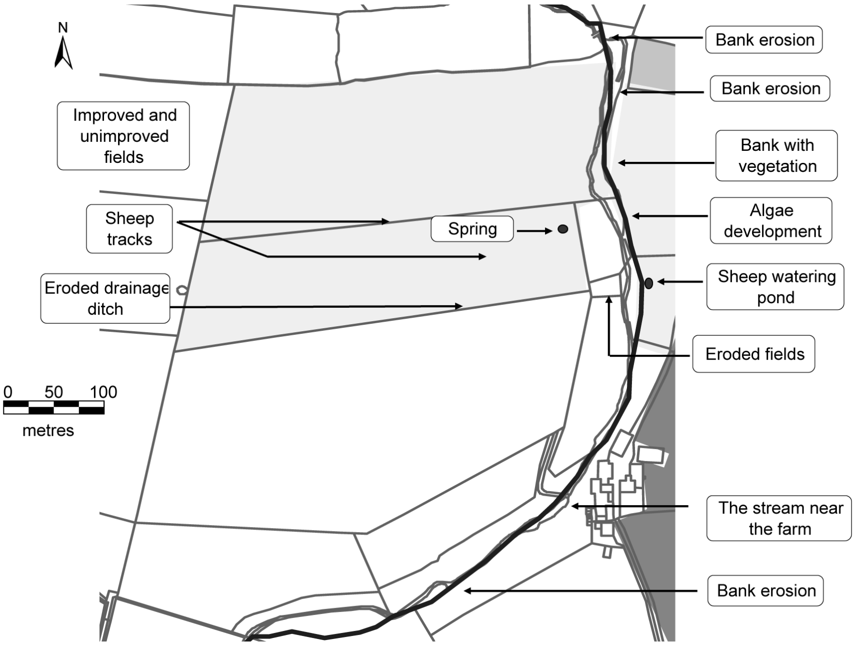

Fig. 4 Fine resolution map of sediment sources and transport pathways, Sykeside Farm.

The relative values show an increase in yield with area for the small basins, followed by an inverse relationship at the larger scales. Given that the change in relationship occurs at the data point for Kirkby Stephen (which is a hinge point in the variation of the assumed rating curves (Table 1)), it is possible that the pattern is, at least in part, a function of the choice of rating curves. On the other hand there is evidence from the field measurements that the middle reaches of the upper Eden may provide an enhanced sediment yield. In particular, comparison can be made between the total headwater inputs (representing an area of 189 km^2) and the output from Great Musgrave (area 223 km^2). Based on spot samples for four low flow occasions in summer 2004, the combined average input of the four headwater catchments (0.90 g s^{-1}) is similar to the average output from Great Musgrave (0.95 g s^{-1}), suggesting that at low flows there is a little net supply or deposition along the intervening reaches. However, for a (single) high flow event, the Great Musgrave output (1940 g s^{-1}) is three times greater than the combined headwater input (621 g s^{-1}). Caution must be exercised, given the unrepresentative nature of a single spot measurement. Nevertheless, it is possible that, compared with the headwater basins, the middle reaches may be contributing a proportionally higher sediment load during the higher transport events. Possible sources are ditches and minor streams, bank erosion and the channel bed.

The role of land use is further highlighted by the spot measurements. In 2003, measured concentrations during the low flow period at a ditch at Hill Top Farm near Great Musgrave were up to 30 mg l^{-1} (compared with less than 5 mg l^{-1} in the main rivers). Similarly, in 2004, low flow concentrations were marginally, but consistently, higher at the Blind Beck lowland miniscale basin (1.4–2.3 mg l^{-1}) than at the Gais Gill upland microscale basin (0.35–0.79 mg l^{-1}). The minor lowland water courses may therefore be contributing higher concentrations of suspended sediment than their upland counterparts, reflecting the impact of agriculture (and livestock farming in particular).

Bed load yield

The estimated bed load yields fall sharply from 544 t km^{-2} year^{-1} to rather less than 1 t km^{-2} year^{-1} as area increases from 1 to 1370 km^{2} (Table 2). The values are generally comparable with those of 18–144 t km^{-2} year^{-1} measured in upland gravel-bed rivers in Scotland and England by Richards & McCaig (1985) and Newson & Leeks (1985). However, the large variation is probably exaggerated by the assumption of a value of 3 for D_{50}/D_{50S} in equation (2). It is possible that the value should be higher for the steeper smaller rivers (reducing the sediment yield estimate) and lower for the gentler gradient larger rivers. Nevertheless, a downstream decrease in bed load yield accords with expectation. As slopes decrease and as distance from the primary sediment sources increases, the ability of the flow to collect and transport bed load decreases. Thus, from Table 2, the combined annual input from the four headwater basins is 18 500 t year^{-1}, whereas the output from Great Musgrave is 120 t year^{-1}. Even allowing for error in the bed load estimates, this suggests that much of the bed load discharge from the hills (above an elevation of about 200 m) enters storage in the lowland reaches.

Dual resolution mapping

The mapping exercise reinforces the above analysis. In the basin-scale risk map (Fig. 3), the weightings of the components are such that livestock density, land use and soil characteristics outweigh rainfall and slope. The central lowland area therefore exhibits a higher risk than most of the surrounding uplands, which is consistent with the variation of spot measurements of suspended sediment concentration. In other words, the supply of suspended sediment to the main river network is likely to be enhanced in the lowland areas, compared with the upland areas, by anthropogenic activity.

The use of regional datasets does not allow a complete representation of the potential for soil erosion, while the integration of the component maps to show overall risk does not allow for connectivity, i.e. the spatial links between sediment sources, sinks and delivery. The basin-scale risk map cannot therefore identify the exact location and nature of erosion features and sediment sources. By contrast, the fine resolution map (Fig. 4) shows very clearly sediment sources and their connection (or lack of connection) to the channel system. In this case the primary sediment sources are bank erosion in the minor streams. Transport pathways include ditches and livestock tracks.

CONCLUSIONS

Overall, specific sediment yield in the Eden basin is likely to decrease as basin area increases. In the headwater basins, bed load yield is likely to equal or even exceed suspended load yield. In the more lowland reaches, bed load provides only a few percent of the total yield, while suspended load is likely to be enhanced by anthropogenic activity. Thus bed load yield declines rapidly as area increases, but suspended load yield may even show a small increase as area expands to include the lowland farms.

Given the approximate nature of the sediment yield estimates, the above conclusion should be considered as a hypothesis to be tested further as the CHASM project data begin to become available. The results show, however, the importance of accounting for sediment source and transport pathways in explaining scale dependency in sediment yield. In this context, dual resolution mapping provides a means of comparing generalized erosion probabilities at the basin scale with specific sediment sources and transport pathways at the local scale.

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