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Predicting slope–channel connectivity: a national-scale approach

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Abstract Concern for problems associated with increased fine sediment loads in British rivers has focussed attention on the source of the sediment. Available evidence suggests that much of the sediment is derived from erosion of agricultural land and this has in turn directed attention to both rates of soil loss from agricultural land and the connectivity between the catchment surface and the channel network. In order to provide a basis for identifying problem areas and to underpin the development of effective sediment control strategies, the need to provide a national-scale assessment of slope–channel connectivity has been identified. The basis for developing a preliminary national-scale assessment of slope–channel connectivity, based on readily available national data sets and a 1 km × 1 km grid is described.

Key words connectivity; connectivity index; connectivity ratio; sediment delivery; slope-channel connectivity

INTRODUCTION

Recent years have seen a growing awareness of problems linked to a perceived increase in the transport and storage of fine sediment in British rivers. These problems include the siltation of salmonid spawning gravels (e.g. Sear, 1993; Theurer *et al.*, 1998; Walling *et al.*, 2003), the degradation of aquatic habitats and river water quality, and the transfer and storage of sediment-associated nutrients and contaminants in river systems (e.g. Owens *et al.*, 2001). In examining these problems and the potential for their control, attention has been directed to the source of the sediment (Russell *et al.*, 2001; Walling *et al.*, 2003). Available evidence suggests that much of the sediment is derived from erosion of agricultural land and that many of the problems should be seen as reflecting the off-site impact of increasing rates of soil loss from agricultural land.

A considerable body of knowledge exists regarding rates of soil loss within England and Wales (cf. Morgan, 1985; Evans, 1990; Harrod, 1998; McHugh *et al.*, 2002) and this provides a useful basis for identifying areas at risk from accelerated soil loss and for assessing national patterns of sediment mobilization by soil erosion. However, it is well known that estimates of rates of on-site soil loss do not provide a direct indication of the suspended sediment yields from local catchments (Walling, 1983). Much of the sediment mobilized by soil erosion may be deposited prior to reaching a watercourse or stream and the specific sediment yield (t km^{-2} $year^{-1}$) of a catchment may be substantially less than the equivalent local rates of soil loss. Any attempt to identify catchments or areas at risk from increased inputs of fine sediment to the stream system should therefore take account of both the erosion risk and the potential for transfer of the mobilized sediment to the stream network. Where local rates of soil loss are high, but only a small proportion of the mobilized sediment reaches the stream network, the overall risk in terms of increased inputs of fine sediment to the stream system could be relatively low. Equally, areas where the local rates of soil loss are relatively low could still represent a risk, in terms of sediment inputs to the local stream systems, if a substantial proportion of the mobilized sediment reaches the stream system. Information on the efficiency of slope–channel transfer is therefore needed to "convert" estimates of soil loss to estimates of sediment input to the stream system and to identify areas where the local streams and rivers are most at risk from potential increases in rates of soil loss from agricultural land and which should therefore be targeted for implementation of erosion and sediment control measures.

The relationship between on-site rates of soil loss and the sediment yield at a catchment outlet is frequently expressed in terms of the sediment delivery ratio, which represents the ratio of the sediment output from a catchment to the gross erosion within the catchment (Walling, 1983). The sediment delivery ratio will, however, be influenced by both the slope-channel connectivity and deposition and storage of sediment within the channel and flood plain system. In addition, the gross erosion will include mobilization of sediment by erosion from both the slopes of a catchment and from the channel network. In order to characterize the efficiency of slope–channel transfer, the authors have coined the term *connectivity ratio*, to provide a measure which is directly analogous to the sediment delivery ratio, but which refers only to slope–channel transfers.

A NATIONAL SCALE ASSESSMENT OF SLOPE–CHANNEL CONNECTIVITY

The basis

As part of a wider national study of sediment delivery to watercourses (McHugh *et al.*, 2002), a preliminary attempt has been made to identify the broad countrywide pattern of slope–channel connectivity and to produce a raster-based map of England and Wales depicting values for the connectivity ratio on a 1 km × 1 km grid. In view of the preliminary nature of the study, emphasis was placed on using readily available national spatial data sets for potential controlling variables, in order to derive estimates of the connectivity ratio for individual grid cells.

Controlling factors

Existing understanding of the controls on sediment transfer from the slopes of a catchment to the adjacent watercourses, and thus the connectivity ratio, can be seen as highlighting three primary controls, namely, the transport capacity of surface runoff, the spatial distribution and density of the receiving watercourses, and the characteristics of the mobilized sediment. As a first approximation, these three primary controls can, in turn, be represented by six key influencing factors, which need to be incorporated into any algorithm for estimating the connectivity ratio. The six factors are:

(a) a runoff potential factor;
(b) a slope steepness factor;
(c) a slope shape factor;
(d) a drainage pattern factor;
(e) a land-use factor;
(f) a sediment characteristics factor.

The runoff potential factor provides a measure of the amount of surface runoff available to transport sediment and the land-use factor will primarily reflect the surface roughness.

Spatial data sets

The following five data sets were available for use as base data layers within a GIS, in order to derive estimates of the six factors:

(a) A 50 m spatial resolution DEM (Ordnance Survey).
(b) A 25 m resolution land cover data-set for 1990, with land-use classified into 25 categories (CEH, Monks Wood).
(c) Hydrological effective rainfall (HER) data at a spatial resolution of 1 km (derived from the ADAS Magpie database).
(d) A 1:50 000 river network coverage (CEH, Wallingford).
(e) 1-km grid soil data based on the 1: 250 000 map for England and Wales (NSRI), including information on texture and HOST classification from which storm runoff potential (the standard percentage runoff, SPR) can be derived.

The cell-based modelling functions from the GRID module of Arc/Info GIS were used to generate secondary data layers and to scale data to the required spatial resolution (1-km grid cells).

Factor derivation

The parameterization of the controlling factors was necessarily constrained by the availability of relevant national data sets, and was based on existing theoretical functions, empirical relationships and expert judgement. Further details of the derivation of the individual factors are provided below.

The runoff potential factor Surface runoff is the ultimate driver of sediment transfer. Its magnitude will depend primarily on rainfall characteristics, surface condition and soil properties. Two existing spatial data sets were combined to represent the potential for surface runoff generation, namely, the hydrologically effective rainfall (*HER*) and the HOST soil classification (Boorman *et al.*, 1995). As part of the HOST classification there is an empirically-derived base flow index (BFI) data set from which the standard percentage runoff (*SPR*) can be estimated using established relationships (Boorman *et al.*, 1995). The runoff potential factor for each cell was estimated as:

$$\text{Runoff potential factor} = (HER \times SPR / 100)^{1.4} \quad (1)$$

The exponent 1.4 conforms to the generally accepted relationship between sediment transport by runoff and runoff amount.

The slope steepness factor The slope steepness factor is represented as $S^{1.4}$, where S is the sine of the slope angle. The exponent 1.4 is based on the widely accepted relationship between overland flow transport capacity and slope gradient (e.g. Prosser & Rustomji, 2000). To take account of the variability of slope steepness within a 1-km grid cell, derivation of the slope steepness factor was based on a 50-m sub-grid. Values of slope angle for the individual

50-m grid cells were calculated from the DEM using the "slope" function available within the GRID module of Arc/Info GIS. The slope angle for the overall 1-km grid cell was derived using the focal functions within the GRID module.

The slope shape factor It is generally accepted that a surface with a convex profile is more efficient in terms of sediment transfer, because transport capacity increases downslope. In contrast, concave surfaces are more commonly associated with deposition. To derive this factor, a 50-m grid was superimposed onto the DEM and the slope profile shape within each 50-m grid cell was characterized as either dominantly convex or dominantly concave. The proportion of convex elements (cells) within a 1-km grid cell was used to represent the effect of slope shape on sediment transfer and to derive the slope shape factor. Again, several functions available within the GRID module were used for this purpose.

The drainage pattern factor The drainage pattern will influence both the spatial distribution and density of the watercourses within a local area and will therefore influence the slope–channel transfer distance. Although drainage density (km km^{-2}) is widely used to represent the drainage pattern, it only takes account of the total length of the drainage network within a cell and not its spatial configuration. In this study an improved index is proposed, based on the integration of the higher resolution sub-grid (50 m) and the river network coverage (1:50 000). The average (median) distance from all 50 m land cells within a 1-km grid cell to the nearest river channel (*D*) is used to represent the effects of drainage pattern on sediment transfer. An exponential decay relationship is used to derive the drainage pattern factor:

$$\text{Drainage pattern factor} = e^{-1 \times k \times D} \qquad (2)$$

where k is a scaling constant depending on the units used.

The sediment characteristics factor Sediment transfer is a size-selective process. Fine particles are likely to be more easily transported and are therefore less prone to deposition. The grain size composition of an eroding soil can therefore be expected to exert a significant control on the efficiency of slope–channel transfer. Since most sediment is mobilized by rill and interill erosion processes, the texture of the surface soil is clearly most important. The d_{50} or median grain size is frequently used in sediment transport equations for overland flow, to characterize the grain size distribution of the sediment (Meyer & Monke, 1965; Everaert, 1991). In the absence of detailed information on the texture of surface soils at a national scale, an estimate of the d_{50} of the surface horizons of the soil within each 1-km grid cell was derived from the available data on the percentage sand and silt content. For use in estimating the connectivity ratio, the sediment characteristics factor was expressed as $d_{50}^{-0.5}$. The exponent –0.5 conforms to existing work on the relationship between overland flow transport capacity and particle size (Meyer & Monke, 1965; Everaert, 1991).

The land-use factor Land-use has many effects on environmental systems, but its influence on surface roughness is likely to be most important in influencing the efficiency of slope–channel transfer. Surface roughness can be characterized by Manning's roughness parameter (n) and the parameter $n^{-0.6}$ has been used as the land-use factor. The exponent –0.6 is based on reported relationships with overland flow transport capacity (e.g. Moore & Burch, 1986). Land-use information has been derived from the CEH land cover data set, based on the dominant land-use in the 1-km grid cells, and Manning's n values have been allocated to individual categories, based on existing practice documented for several physically-based soil erosion and water quality models.

Estimating the connectivity ratio

In order to estimate the connectivity ratio for each individual 1-km grid cell, it is necessary to integrate the values obtained for the six controlling factors. In the absence of a detailed physically-based understanding of the influence of the various factors on sediment transfer and their relative importance, and acknowledging the high degree of spatial and temporal lumping involved, a conceptual formulation using a structure analogous to that employed by the Revised Universal Soil Loss Equation (Renard *et al.*, 1991) has been employed. In this approach, a connectivity index (*CI*) is initially derived. This index is seen to be a function of the sediment transport capacity modified by the effects of slope shape and drainage pattern, with the effects of slope shape and drainage pattern being treated as multiplicative:

$$CI = f\,(TC \times f_{sp} \times f_{dp}) \tag{3}$$

where TC is the sediment transport capacity, f_{sp} is the slope shape factor and f_{dp} is the drainage pattern factor. In the absence of an empirical calibration of equation (3), a simple logarithmic function has been assumed:

$$CI = \log\,(TC \times f_{sp} \times f_{dp}) \tag{4}$$

where the logarithmic transformation has been used to avoid possible distortion associated with the non-normal distribution of the spatial data sets. To take account of the different magnitudes of the values obtained for the slope shape and drainage pattern factors, these factors were scaled to values between 0 and 1, using a simple linear stretch routine.

The sediment transport capacity parameter *TC* incorporates the influence of surface runoff magnitude, slope gradient, surface roughness and sediment size. These variables can be represented by the runoff potential factor, the slope gradient factor, the land-use factor and the sediment characteristics factor, respectively. The *TC* factor can therefore be calculated as:

$$TC = q^{1.4}\, S^{1.4}\, n^{-0.6}\, d_{50}^{-0.5} \tag{5}$$

Equation 4 was used to derive estimates of *CI* for each 1-km grid cell and these values were scaled to the range 0–1, using a simple linear stretch routine.

In order to derive values for the connectivity ratio, which represents the proportion of the soil mobilized by erosion from the land surface within a grid cell that will reach the stream channels within or adjacent to that grid cell, it is necessary to scale or calibrate the values obtained for the connectivity index (0–1). In the absence of a clear empirical basis for calibrating the values of the connectivity index, these values were scaled to the range 0.2–0.7, based on existing knowledge of the sediment budgets of small agricultural catchments (e.g. Walling *et al.*, 2002). The spatial distribution of the resulting connectivity ratio values for England and Wales is shown in Fig. 1.

PERSPECTIVE

The spatial distribution of the connectivity ratio shown in Fig. 1 conforms to existing understanding of the expected pattern. The broad distinction between higher values in the west and lower values in the east reflects both the increased runoff in western areas and the more impervious nature of the underlying rocks in these areas, which are in turn reflected by

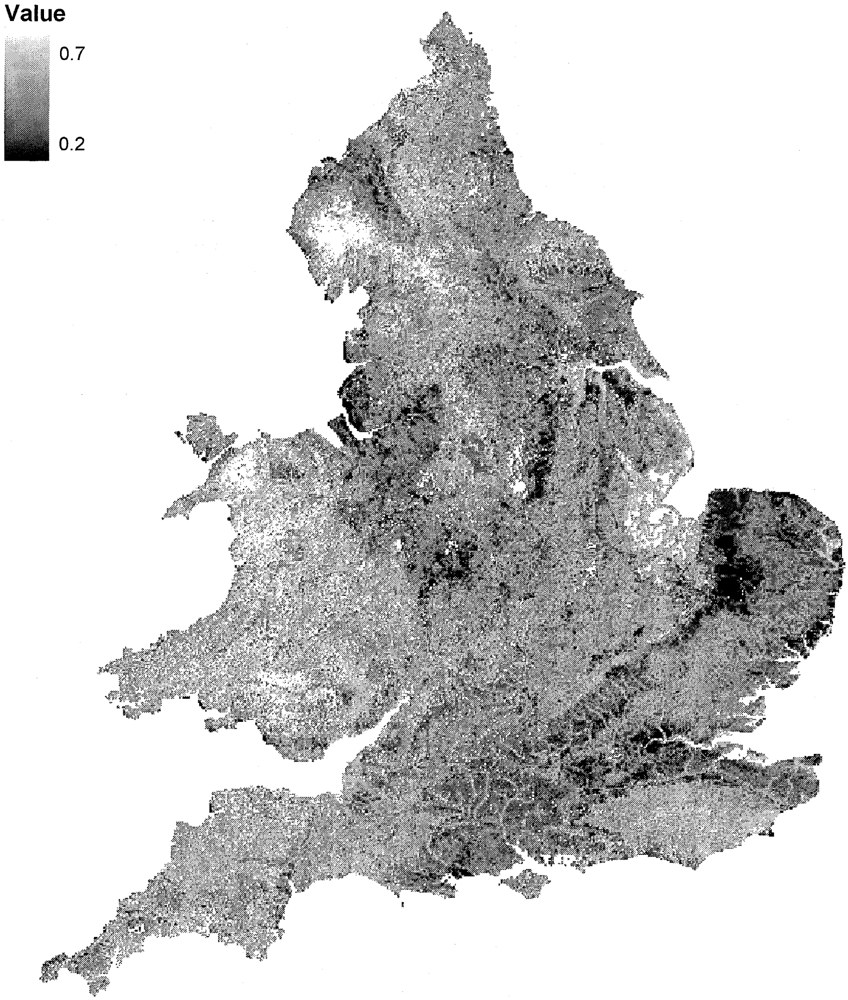

Fig. 1 The spatial distribution of the connectivity ratio.

higher drainage densities and increased amounts of surface runoff. The reduced drainage densities and reduced incidence of surface runoff associated with areas underlain by chalk and limestone are clearly reflected in the low values of connectivity ratio associated with areas underlain by chalk and limestone.

The results presented in Fig. 1 must, nevertheless, be seen as preliminary. Further work is clearly required to refine the approach outlined. The basis of the GIS-based procedure used to derive values of the connectivity ratio for individual grid cells is summarized in Fig. 2, and this should be seen as providing a framework which requires further improvement and refinement. This should include incorporation of additional controlling factors, refinement of the parameterization of existing factors, and more rigorous calibration of the relationship between the connectivity index and the connectivity ratio. In terms of incorporation of additional factors, there is a clear need to take account of the more adventitious effects on

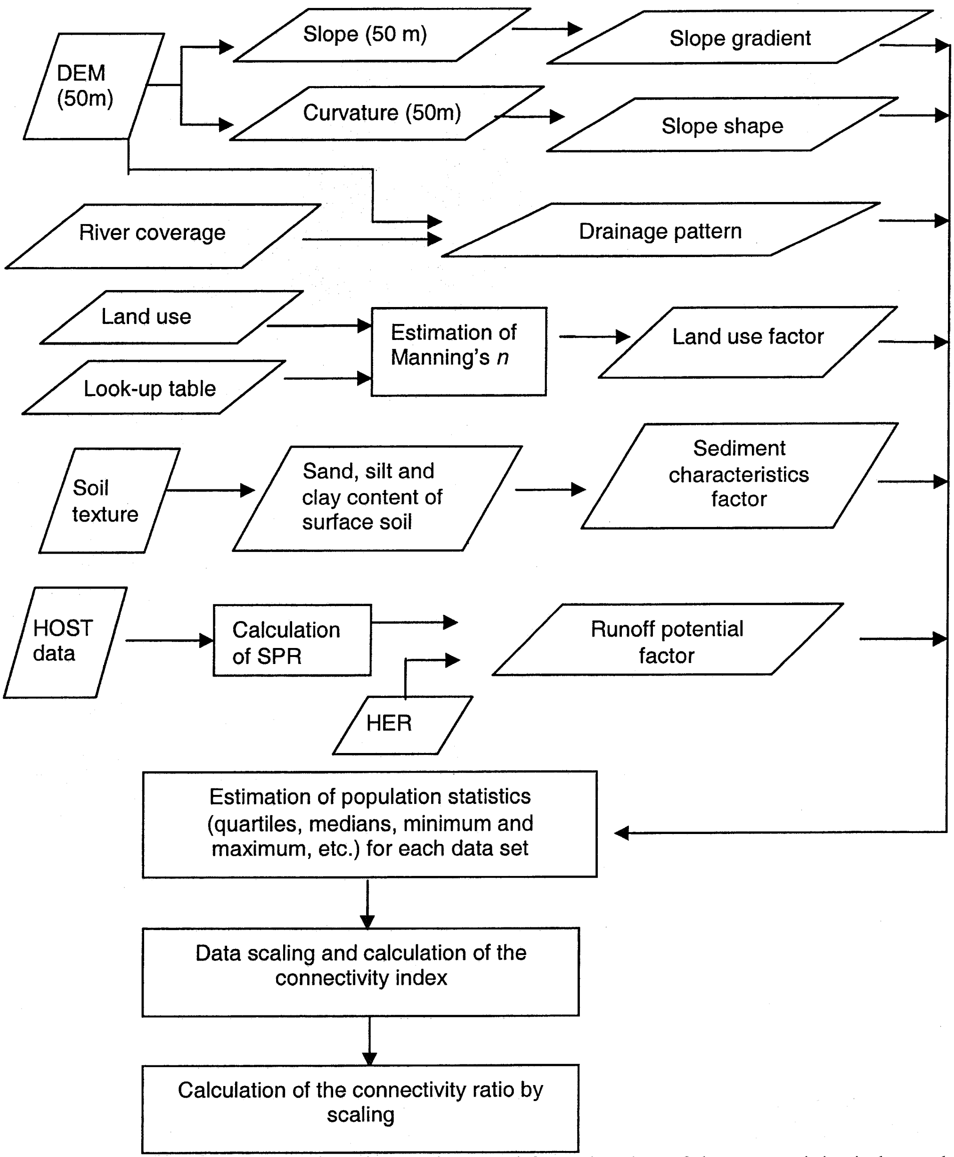

Fig. 2 Flow chart of the GIS-based procedure used for estimation of the connectivity index and ratio.

connectivity associated with features such as field boundaries and associated gateways, as well as the important role of tracks and roads in routing water and sediment towards stream channels.

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