Tracing Sources of Suspended Sediment in River Basins: A Case Study of the River Culm, Devon, UK

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Abstract. Information on the source of the suspended sediment transported by a river is becoming an increasingly important requirement in sediment investigations. Such information is difficult to assemble by means of traditional monitoring strategies, but the ‘fingerprinting’ technique offers considerable potential. The use of composite ‘fingerprints’ in combination with a multivariate mixing model can provide a basis for determining the relative importance of both individual areas of a catchment and specific source types. The results of applying this approach to the 276-km² basin of the River Culm in Devon, UK are presented. A suite of nine fingerprint properties was employed as a composite fingerprint, and this permitted the relative contributions of seven source types to be established. These source types represented material derived from the surface of cultivated and pasture areas on each of the three main rock types and material eroded from channel banks. By collecting samples of suspended sediment at different times during individual floods, it was possible to document changes in the relative contributions of the various sources during each flood in response to runoff source and travel times. Although the multivariate fingerprint approach has a number of limitations, it also has considerable potential as a means of tracing sources of suspended sediment within a large drainage basin.

Introduction

Traditionally, programmes for monitoring suspended sediment in river basins have focused on quantifying the concentrations and loads of suspended sediment (Long 1989). However, a growing awareness of the role of suspended sediment in non-point pollution from land-use activities and in the transport of nutrients and contaminants (Allan 1986; Ongley et al. 1992), the need to develop sediment control strategies, and demands for improved understanding of catchment sediment budgets have generated an increasing need for information regarding the source of the suspended sediment transported by rivers. In some situations it is important to determine the spatial location of the main sediment sources within a drainage basin, whereas in others the need is for information concerning the nature and relative importance of the source types involved. Thus, it may be important to know which parts of a basin are the main sediment sources, whether, for example, the sediment has originated primarily from sheet and rill erosion or from channel and gully erosion, and whether the dominant source is cultivated land or other land-use types.

Such information concerning the source of the suspended sediment transported by a river is difficult to assemble by traditional measurement techniques. The relative importance of different sub-basins could be assessed by measuring the sediment loads at a number of upstream tributary junctions, but such monitoring is likely to be costly and time-consuming. Equally, traditional methods of determining the relative importance of different source types, which could involve the use of erosion pins, monumented channel sections, surface runoff traps and small erosion plots (Imeson 1974), frequently face many operational difficulties as well as spatial and temporal sampling problems and are therefore difficult to apply to anything other than a small drainage basin (Peart and Walling 1988). The ‘fingerprinting’ technique offers an alternative approach to documenting both the spatial location and the nature of the major sediment sources operating within a drainage basin; it avoids many of these problems and therefore appears to offer considerable potential (Oldfield et al. 1979; Grimshaw and Lewin 1980; Peart and Walling 1986, 1988; Stanton et al. 1992; Walling and Woodward 1992; Cattcheon 1993; Walling et al. 1993).

In essence, the fingerprinting technique makes use of chemical and physical properties of the suspended sediment to trace its source. It involves, firstly, selection of a physical or chemical property that clearly differentiates potential source materials and, secondly, comparison of measurements of the same property obtained from suspended sediment with the equivalent values for the potential sources to establish the likely source of the sediment. In the case of a simple distinction between
surficial and channel sources, the property could be one that differentiates topsoil from the underlying parent material and bedrock. Similarly, if a drainage basin is underlain by several different rock types, selection of sediment properties capable of distinguishing those rock types could provide a basis for establishing the relative importance of the areas underlain by the different rock types as sediment sources. The essential simplicity of the fingerprinting technique is, however, complicated by a number of potential problems. These include enrichment or depletion of the suspended sediment relative to the source material and transformation of sediment properties within the fluvial system (Peart 1990). In addition, it is important to select a property that is able to distinguish sources in an unequivocal manner (Walling and Woodward 1992) and to make use of a computational procedure that is capable of dealing with situations in which the suspended sediment represents a mixture from several sources.

Clay mineralogy (Garrad and Hey 1989), sediment colour (Grimshaw and Lewin 1980), sediment chemistry (Wall and Wilding 1976; Peart and Walling 1986), mineral magnetic parameters (Oldfield et al. 1979; Stott 1986; Foster et al. 1990; Oldfield and Clark 1990; Caithcheon, 1993) and radionuclide concentrations (Peart and Walling 1986; Wasson et al. 1987; Burch et al. 1988; Walling and Woodward 1992; Wallbrink and Murray 1993) have all been successfully used as fingerprint tracers, but it is increasingly apparent that the quest for a single diagnostic property capable of distinguishing all potential sources is likely to prove elusive and unrealistic. Peart and Walling (1988) have strongly advocated the use of a selection of fingerprint properties to increase the reliability of the results obtained and to permit a substantial number of potential sources to be discriminated by their fingerprints. Thus, for example, when a single tracer points strongly to the importance of a particular source, but the possibility of the sediment being a mixture of two other contrasting sources cannot be ruled out, the additional evidence provided by further fingerprint properties can provide a definitive result. Equally, when there is a need to distinguish sediment sources in terms of both location and source type, this is likely to prove possible only if several fingerprint properties can be used. Thus, a property that is sensitive to contrasts in the underlying geology between particular parts of a drainage basin could be used to apportion sediment according to its spatial source, whereas a property that is capable of distinguishing material from topsoil and subsoil sources, and from cultivated and uncultivated topsoil, irrespective of the underlying geology, could provide the basis for assessing the relative importance of different source types.

The use of several fingerprint properties has already featured in a number of studies (Peart and Walling 1986; Yu and Oldfield 1989, 1993; Oldfield and Clark 1990; Walling and Woodward 1992; Walling et al. 1993), but with the exception of the studies by Yu and Oldfield (1989, 1993) and Walling et al. (1993) the approach to synthesizing the information provided by a range of properties has generally been essentially qualitative. A quantitative approach is, however, likely to be necessary to provide reliable results, and Walling et al. (1993) used a simple multivariate mixing model to assess the relative importance of surface erosion from cultivated and pasture areas and channel erosion as sediment sources in two small Devon catchments, each underlain by essentially uniform geology. Similarly, Yu and Oldfield (1989, 1993) used a multivariate mixing model coupled with an optimized linear programming technique to establish the dominant sources of sediments in the Rhode River estuary within Chesapeake Bay, USA, and in a reservoir in south-eastern Spain.

To the authors’ knowledge, there has as yet been no attempt to exploit the full potential of the multiple fingerprint approach to establishing the relative importance of different sediment sources, defined in terms of both location and source type, within a sizeable drainage basin. This paper reports the results of a study undertaken within the 276-km² basin of the River Culm in Devon, UK, with the aim of demonstrating this potential.

Materials and Methods

Study Basin

The River Culm is an east-bank tributary of the River Exe and joins the main river at Stoke Canon, 5 km north of Exeter. Its catchment area of 276 km² is underlain by a variety of rock types, which are in turn reflected in a diversity of topographic forms (Fig. 1). The main headwaters of the river rise on the East Devon Plateau, which is underlain by Cretaceous Upper Greensand, is capped by Eocene clay-with-flints and lies at an altitude of 200–250 m above sea level (asl). The edge of the plateau is marked by a steep Greensand escarpment that has been dissected by the headwater tributaries, which have cut steep-sided valleys into the underlying Triassic Mercian Mudstones. Further downstream, the river flows through an area of gently undulating topography at an altitude of 100–150 m asl developed on Triassic Pebble Beds and Otter Sandstones. In its middle and lower reaches, the river traverses a lowland area (20–100 m asl) that has a subdued relief and is underlain by Permian mudstones, breccias and sandstones. Small outcrops of Carboniferous Culm Measures (sandstones and shales) and Westleigh Limestone marked by areas of more upstanding relief are also to be found in the western and north-western parts of the catchment (Fig. 1).

The close dependence of relief and topographic form on the underlying geology is paralleled by the hydrometeorological conditions and by the soil types and land-use patterns within the catchment. Mean annual precipitation ranges from about 1000 mm on the East Devon Plateau to about 800 mm near the outlet of the basin, and the equivalent values of mean annual evapotranspiration and runoff are, respectively, about 450 mm and 550 mm for the plateau and about 300 mm and 300 mm for the catchment outlet. Soils are predominantly brown earths on the well drained areas underlain by Upper Greensand, Permian and Triassic strata, whereas gley soils
predominate on the more poorly drained areas of the East Devon Plateau and the lowland areas underlain by impermeable marls. Land use on the East Devon Plateau is primarily pasture, with some areas of forage crops and unenclosed moorland. Mixed farming predominates on the steeper areas underlain by Triassic rocks, and arable cultivation assumes greater importance on the lowland areas coinciding with the outcrops of Triassic Pebble Beds and Otter Sandstones and Permian strata.

The mean annual yield of suspended sediment of the catchment is estimated to be about 24 t km$^{-2}$ year$^{-1}$. However, the studies reported by Lambert and Walling (1987) indicate that as much as 25% of the total suspended sediment load entering the 12-km

Fig. 1. Study catchment, showing its (A) topography and (B) geology.
reach of the river above the basin outlet, with its well developed floodplain and meander system, may be deposited during overbank flood events. No detailed catchment-wide investigations of erosion rates have been undertaken within the basin, but Ashbridge (1990) reports an average rate of bank retreat of 24 cm year\(^{-1}\) for 57 sites of active bank erosion in the lower reaches of the river. On the basis of reconnaissance measurements of rates of river-bank recession in representative areas of the basin, the same author also estimated that bank erosion contributed about 19% of the total yield of suspended sediment from the basin. The pattern of soil loss rates within the basin could be expected to reflect the interaction of several controlling factors, each with contrasting spatial distributions, including precipitation amounts, relief and land use. Thus, highest precipitation and runoff amounts are found in the headwater areas on the East Devon Plateau, the areas of steepest relief occur on the margins of the plateau and in the middle reaches of the basin, whereas areas with the highest proportion of available cultivation are to be found in the lowland areas towards the outlet of the basin.

Because of (a) the considerable diversity of physiographic conditions and land use within the drainage basin of the River Culm, (b) a degree of uncertainty regarding the likely spatial pattern of soil erosion rates, and (c) evidence that bank erosion represents a significant sediment source, this basin was judged to be a suitable catchment in which to test the viability of a multiple fingerprint approach to deciphering sources of suspended sediment. Attention was directed both to the location of the sources and to the source type.

**Sample Collection**

Collection of material necessary to characterize the potential sources of suspended sediment in the study basin was based on representative sampling of topsoil (0–2 cm depth) from uncultivated (pasture) and cultivated (arable) sites and of eroding banks along both main channel and tributary streams in areas underlain by the three dominant rock types (i.e. Cretaceous/Eocene, Triassic and Permian; Fig. 1). This combination of nine potential source materials was aimed at providing a basis for discriminating sediment originating from different parts of the catchment and for distinguishing sediment sources associated with surface erosion of both cultivated fields and pasture areas and with erosion of channel banks. The surface soils of woodland areas were not included in the sampling programme because these were judged to be unlikely to represent a significant sediment source within the study basin. In view of the large areal extent of each of the nine source material types defined above, and in an attempt to ensure the representativeness of the source samples, each sample comprised 10 or more subsamples collected within the vicinity of each sampling location. In total, 100 bulked source samples were collected. These were screened through a 63-µm sieve to facilitate direct comparison with fluvial suspended sediment. Bulk water samples were collected during storm events from a monitoring station 1 km upstream from the outlet of the basin. Suspended sediment was subsequently recovered from these samples by continuous-flow centrifugation and freeze-dried. These samples consisted almost exclusively of <63-µm particles because the clay + silt content of the samples typically accounted for >95% of sample mass. In all, 27 samples of suspended sediment, representing both a range of storm runoff events and a range of sampling times during each event, were collected. Because the bulk water samples were collected within the space of a few minutes, the samples of suspended sediment subsequently recovered by continuous-flow centrifugation represent essentially instantaneous samples of the suspended sediment load at the time of sampling.

**Fingerprinting of Sediment Sources**

In order to use multiple fingerprint properties to provide an objective assessment of the relative contributions of different parts of a catchment or of different potential source types to the suspended sediment load of a river, three main requirements need to be addressed: (a) selection of an appropriate combination of fingerprint properties that reflect different environmental controls and that are likely to be capable of discriminating the potential sediment sources, (b) statistical testing of the selected combination of fingerprint properties to confirm that individual sediment sources are clearly distinguished by their composite fingerprints, and (c) application of an objective algorithm that is able to compare the composite fingerprint of a sample of suspended sediment with those of potential sources and provide an estimate of the likely relative contributions of those sources to the suspended sediment load. Each of these requirements is considered in turn.

**Selection of appropriate fingerprint properties.** To be effective as a tracer of sediment sources, a fingerprint property should be capable of discriminating between potential sources. It should also behave conservatively during erosion and fluvial transport, so that comparisons between sediment and source material are meaningful. When a suite of properties is to be selected with a view to providing a composite fingerprint, it is also important that these should reflect different controls and behaviours in order to maximize the degree of discrimination afforded by the composite fingerprint. On the basis of previous experience with fingerprinting the sources of suspended sediment in local rivers (Walling and Kane 1984; Peart and Walling 1986, 1988; Walling and Woodward 1992; Walling et al. 1995), and after a number of trials aimed at identifying appropriate fingerprints for the study catchment, nine properties were selected. These included the concentrations of three radionuclides, four mass-specific mineral magnetic parameters, and organic carbon and nitrogen concentrations.

The three radionuclides used as fingerprint tracers included \(^{137}\)Cs, unsupported \(^{210}\)Pb and \(^{226}\)Ra. The value of the fallout radionuclides \(^{137}\)Cs and \(^{210}\)Pb as fingerprint properties has been discussed by Walling and Woodward (1992). In brief, \(^{137}\)Cs and unsupported \(^{210}\)Pb are concentrated in the upper 10 cm of the soil profile in undisturbed soils, whereas in cultivated soils they are mixed within the ploughed layer and surface concentrations are accordingly much lower. The concentrations of these two radionuclides can thus be used to distinguish sediment eroded from the surface of cultivated and uncultivated areas. Subsoil horizons (below about 25 cm) and exposed river banks (apart from the upper 10 cm) contain minimal concentrations of unsupported \(^{210}\)Pb and \(^{137}\)Cs and can therefore be readily distinguished from surface sources. The distribution of these fallout radionuclides within a drainage basin can be viewed as essentially independent of the underlying geology and soil type, and this further increases their value as fingerprint tracers. As \(^{226}\)Ra is a radionuclide produced by decay in situ decay of the uranium series, \(^{226}\)Ra concentrations are, in contrast, more directly related to rock type.

The mineral magnetic properties of soils respond to a variety of environmental controls including both the underlying geology and soil type as well as profile distribution and the presence or absence of cultivation (Dearing et al. 1985). They thus afford considerable potential as fingerprint properties, and the successful use of a wide range of mineral magnetic properties to fingerprint sources of suspended sediment has been reported by several authors, including Oldfield et al. (1979), Foster et al. (1990) and Oldfield and Clark (1990). In the present study, magnetic susceptibility (\(\chi\)), anhysteretic remanent magnetization (ARM), saturation isothermal remanent magnetization (SIRM) and isothermal remanent magnetization (IRM) were used as fingerprint tracers. Detailed definitions of the magnetic properties involved can be found in Maher (1986) and Thompson and Oldfield (1986). Organic carbon and nitrogen concentrations were also selected as fingerprint tracers because several workers have demonstrated...
that they are useful indicators of sediment provenance (Walling and Kane 1984; Santiago et al. 1992). Contrasts between the organic content of arable soils and that of grassland soils have been widely reported, and channel-bank sediments are commonly characterized by relatively small amounts of organic material.

In combination, the above selection of nine fingerprint properties was judged to afford an effective basis for characterizing the major sources of suspended sediment within the study basin, in terms of both location and source type. Because of their control by a range of different environmental factors, their use in composite fingerprints provides a valuable means of discriminating potential sources. As an example of their contrasting behaviours, Fig. 2 presents typical vertical distributions of unsupported $^{210}$Pb and SIRM in soils developed on Permian strata in the study area.

![Fig. 2. Typical distributions of unsupported $^{210}$Pb and SIRM in soil profiles from (A) undisturbed pasture sites and (B) cultivated sites in the study area underlain by Permian bedrock.](image)

The fingerprint properties used in this investigation were measured by a variety of techniques. Unsupported $^{210}$Pb, $^{137}$Cs and $^{226}$Ra were measured by gamma spectrometry (HpGe detectors), and organic carbon and nitrogen concentrations were determined with a Carlo Erba Elemental Analyzer. In the case of the mineral magnetic parameters, magnetic susceptibility was measured at 0.47 kHz by means of a standard Bartington system, and ARM, SIRM and IRM were determined with a Molspin fluxgate magnetometer. To minimize the effects of contrasts in particle size composition between source materials and suspended sediment on the values of the fingerprint properties, all measurements of the properties of source materials were undertaken on the <63-μm fraction. In the case of the radionuclide activities, the values obtained for the source materials were adjusted to be directly comparable with those for suspended sediment by taking account of contrasts in grain size composition and information concerning the preferential association of the radionuclides with specific size fractions (Walling and Woodward 1992). The carbon and nitrogen values were also corrected for enrichment (Walling 1990). Following Yu and Oldfield (1989), raw measurements of the magnetic parameters were used because the grain-size-related behaviour of the magnetic parameters is complex (Maher 1986) and no simple correction procedure is available.

### Testing of source discrimination

In order to demonstrate the effectiveness of the suite of fingerprint properties used to define the composite fingerprint used in this investigation, it was necessary to test the degree to which they were able to differentiate between a number of potential sources within the drainage basin and to confirm that each potential source exhibited a fingerprint that was significantly different from that of the other sources. This was achieved by means of the procedure described by Walling et al. (1993), which involves use of the method of average linkage between groups for cluster analysis (Hair et al. 1987). In this technique, the distance between points (source samples) measures their degree of similarity. Each fingerprint property is initially scaled so that its values range from 0 to 1. Next, the distance between every pair of samples is calculated as

$$D_{ab} = \left( \sum_{i=1}^{T} (V_{ai} - V_{bi})^2 \right)^{0.5},$$

where $D_{ab}$ is the distance between samples $a$ and $b$, $t$ is the fingerprint property, ranging from 1 to $T$ (the number of fingerprints), $V_{ai}$ is the value of fingerprint $t$ for sample $a$, and $V_{bi}$ is the value of fingerprint $t$ for sample $b$. Thus, the minimum distance between two samples is zero and the maximum is the square root of the number of tracers. The method of average linkage between groups is used to cluster the samples because it makes use of all the available information rather than being based on the nearest or furthest neighbour. The two closest samples are first placed in a single cluster, and this process continues with samples being joined to other samples, samples joining existing clusters, and eventually clusters merging. The distance between two clusters is calculated as the average distance between all the combinations of pairings of samples. The method continues with the number of clusters created decreasing by one at each step until the desired number of clusters remains.

This procedure was used to classify the 100 bulked samples of source material on the basis of the nine fingerprint properties and thus to confirm that the categories of potential source material identified previously on an a priori basis represented a meaningful subdivision of the potential source materials within the study catchment. In this case, the cluster analysis confirmed the existence of seven primary groupings that effectively corresponded to those used for sample collection. These groupings represent the three major rock types (i.e. Cretaceous/Eocene, Triassic and Permian), further distinguished according to land use (i.e. pasture and cultivated), with channel banks providing an additional group that was not subdivided on the basis of rock type. In all, eight samples were excluded from this classification, and these were distributed fairly uniformly between the categories (Table 1). Further subdivision of the raw data failed to identify a common grouping for these eight samples, so they were treated as unrepresentative outliers and were not included in the subsequent analysis. Analysis of variance was used to test that the source categories identified by the cluster analysis were significantly different statistically in terms of the values associated with the individual fingerprint properties. The values of the fingerprint properties for the individual bulk samples associated with each source type showed only limited variation, with coefficients of variation being typically 10–15%. The resultant $F$-ratios listed in Table 1 are highly significant and indicate that the differences between source types are significant at the >99% level.

Each source type was finally characterized by the mean value for each of the nine fingerprint properties, and Table 1 lists the rank order of the property values by source. The variations in the
property rank orders for individual sources shown in Table 1 clearly demonstrate the value of using a range of fingerprint properties to discriminate potential sediment sources. Thus, for example, material representative of pasture areas underlain by Triassic strata exhibited the highest unsupported 2\(^{10}\)Pb activity of any source, but it also had among the lowest values of magnetic susceptibility and ARM. Variations in the rank ordering of different fingerprint properties for a given source grouping improve the discrimination afforded by the composite fingerprints of the individual sources. Identical ranking of individual properties for a particular source category should not, however, be seen as indicating that the properties involved represent only a single independent source of information. This is the case only when they are highly correlated.

![Table 1. Classification of the samples of source material into seven source types on the basis of the nine fingerprint properties](image)

<table>
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<tbody>
<tr>
<td>2(^{10})Pb</td>
<td>2</td>
<td>1</td>
<td>3</td>
<td>4</td>
<td>5</td>
<td>6</td>
<td>7</td>
</tr>
<tr>
<td>137Cs</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>5</td>
<td>6</td>
<td>7</td>
</tr>
<tr>
<td>2(^{26})Ra</td>
<td>1</td>
<td>3</td>
<td>4</td>
<td>5</td>
<td>6</td>
<td>7</td>
<td>2</td>
</tr>
<tr>
<td>X</td>
<td>6</td>
<td>5</td>
<td>3</td>
<td>2</td>
<td>4</td>
<td>1</td>
<td>7</td>
</tr>
<tr>
<td>ARM</td>
<td>6</td>
<td>5</td>
<td>3</td>
<td>2</td>
<td>4</td>
<td>1</td>
<td>7</td>
</tr>
<tr>
<td>SIRM</td>
<td>6</td>
<td>5</td>
<td>3</td>
<td>2</td>
<td>4</td>
<td>1</td>
<td>7</td>
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<td>3</td>
<td>6</td>
<td>1</td>
<td>2</td>
<td>4</td>
<td>7</td>
</tr>
<tr>
<td>Carbon</td>
<td>2</td>
<td>1</td>
<td>3</td>
<td>4</td>
<td>5</td>
<td>6</td>
<td>7</td>
</tr>
<tr>
<td>Nitrogen</td>
<td>2</td>
<td>1</td>
<td>3</td>
<td>4</td>
<td>5</td>
<td>6</td>
<td>7</td>
</tr>
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</table>

Estimation of source contributions. To make full use of the information provided by the composite fingerprints defined in Table 1 to estimate the relative contributions of individual source types, a multivariate mixing model must be employed. Yu and Oldfield (1989) report the use of an optimized linear programming technique for this purpose. A simpler procedure, avoiding the need to establish empirical equations for use in the mixing model, has been described by Walling et al. (1993) and was used in the present investigation. The algorithm used by this procedure to estimate the relative contributions of individual types of sediment source to the suspended sediment load of the stream seeks to satisfy the following set of linear constraints,

\[ \sum_{i=1}^{S} P_s = 1 \]  \hspace{1cm} (2)

while minimizing the error term,

\[ E = \sum_{i=1}^{T} \left[ \frac{\left( B_t - \left( \sum_{s=1}^{S} V_{st} P_s \right) \right)}{B_t} \right] , \]  \hspace{1cm} (4)

where \( P_s \) is the fraction of material derived from source type \( s \), \( V_{st} \) is the average value of fingerprint property \( t \) for source type \( s \), \( S \) is the number of source types, \( B_t \) is the suspended-sediment sample value for fingerprint property \( t \), and \( T \) is the number of fingerprint properties considered. Initially, the source contributions \( P_s \) are set equal and the error term \( E \) is calculated. New errors are calculated for a series of changes in the values of \( P_s \), and the change that minimizes the error term is selected. This step is repeated until no further improvement in the error term is possible, at which point the magnitude of the change is halved. This sequence continues until the potential change falls below a specified level of significance, i.e. no further reduction in the error term is possible. In this study, the objective function or error term defined in Eqn 4, which is based on minimizing the sum of the relative errors, was used in preference to one based on minimizing the sum of squares of the deviations because the latter gives increased weight to the larger deviations. It was judged more appropriate to give similar weight to each of the fingerprint properties. A similar approach was taken by Yu and Oldfield (1993).

Results

The mixing model was applied to the data on fingerprint properties, as assembled for each of the samples of suspended sediment collected from the River Culm, to estimate the relative contributions of the individual sediment sources. The individual fingerprint properties provided consistent results, and values of the error term \( E \) in Eqn 4 were typically in the range 0.5–1.0, representing an average error of ±5–10% in the predicted value for each sediment property. The coefficient of efficiency (Aitken 1973) was used to test the degree of correspondence between the measured suite of values of fingerprint properties and the values predicted by the optimized mixing model for individual samples. Values of the coefficient of efficiency were in the range 0.85–0.99 and were commonly >0.93, again confirming the goodness of fit associated with the mixing model and the consistency of the evidence provided by the individual fingerprint properties. The relative contributions from
Sources of Suspended Sediment in River Basins

Table 2. Mean contributions from the individual source types to the suspended sediment load of the River Culm

<table>
<thead>
<tr>
<th>Source type</th>
<th>Mean contribution (%)</th>
<th>Estimated mean yield of suspended sediment(^A) (t km(^{-2}) year(^{-1}))</th>
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</thead>
<tbody>
<tr>
<td>Cretaceous/Eocene</td>
<td></td>
<td></td>
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<tr>
<td>Pasture</td>
<td>9.2</td>
<td></td>
</tr>
<tr>
<td>Cultivated</td>
<td>10.6</td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>19.8</td>
<td>24.2</td>
</tr>
<tr>
<td>Triassic</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pasture</td>
<td>12.3</td>
<td></td>
</tr>
<tr>
<td>Cultivated</td>
<td>29.5</td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>41.8</td>
<td>51.2</td>
</tr>
<tr>
<td>Permian</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pasture</td>
<td>6.7</td>
<td></td>
</tr>
<tr>
<td>Cultivated</td>
<td>19.7</td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>26.4</td>
<td>17.3</td>
</tr>
<tr>
<td>Channel banks</td>
<td>12.0</td>
<td>3.8</td>
</tr>
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</table>

\(^A\) Assuming a mean annual yield of suspended sediment of 32 t km\(^{-2}\) year\(^{-1}\) for the basin and catchment area proportions of 26.2%, 26.1%, and 47.7% for the areas underlain by Cretaceous/Eocene, Triassic and Permian rocks respectively.

The seven source types varied from sample to sample in response to hydrometeorological conditions, including the antecedent conditions, the time of year, the distribution of storm precipitation over the drainage basin, and the timing of sampling during flood events. Values representing the mean contributions from the seven individual source types for all sediment samples are listed in Table 2. These suggest that surface erosion from cultivated areas represents the dominant sediment source within the Culm catchment, with surface erosion from pasture areas representing an important secondary source and channel banks providing a mean contribution of about 12%. This value of 12% is in reasonable agreement with the value of about 19% provided by Ashbridge (1990) on the basis of reconnaissance measurements of river-bank recession within the study catchment.

The results obtained for the individual samples of suspended sediment can be considered further by plotting the source contributions on ternary diagrams. To facilitate such plotting, the sources have been consolidated into three major categories, namely the surface of cultivated areas, the surface of pasture areas, and channel banks. Fig. 3 indicates that, on the occasions when samples of suspended sediment were collected, the relative contributions from surface erosion of cultivated areas and pasture areas ranged between 45% and 91% and between 7.5% and 45% respectively and the contribution from bank erosion ranged between 1.5% and 23.5%. On average, surface erosion contributed 88% of the suspended sediment load. If attention is restricted to the contributions from surface erosion it is possible to evaluate the spatial distribution of sediment sources within the study catchment in terms of the relative contributions provided by three major rock types (i.e. Cretaceous/Eocene, Triassic and Permian).

These results are presented in Fig. 4. On average, the Cretaceous/Eocene outcrops contribute about 22.5% of the total suspended sediment derived from surface erosion, and the values for the Triassic and Permian areas are 47.5% and 30% respectively. In terms of the areas of the catchment underlain by the three major rock types, it is evident that the sediment contribution from the Triassic areas is considerably more than what might be expected (Table 2). If it is assumed that conveyance losses associated with the delivery of suspended sediment through the upper and middle reaches of the study basin are of limited significance, and if the substantial

Fig. 3. Ternary plot of the estimates of the relative importance of contributions from cultivated and uncultivated topsoil and channel erosion to samples of suspended sediment collected from the outlet of the study basin.
conveyance losses associated with the floodplain reaches in the lower part of the basin are taken into account, it is possible to estimate the sediment yields associated with surface erosion on the three major rock types (Table 2).

Ternary plots also afford a convenient means of demonstrating intra-storm variations in the relative importance of sediment source types. Fig. 5 presents results from two flood events on the River Culm that show how the proportions of sediment derived from surface sources on the three major rock types changed during the events in response to the arrival of water and sediment from different parts of the basin. During the initial stages of the events, most of the sediment was, as might be expected, derived from the area of Permian rocks in the lower areas of the basin. As water from more distant parts of the basin arrived at the basin outlet, the proportions of sediment derived from Triassic and subsequently from Cretaceous/Eocene outcrops increased. This clear relationship between the timing of the sampling during the events and the travel times of water and sediment derived from different areas of the basin further demonstrates that channel storage of fine sediment is of limited importance in this drainage basin. If large amounts of fine sediment were stored in the channel between events, this relationship between travel time and sediment source would tend to be obscured.

Although, as noted previously, the mixing model consistently provided a good fit between the measured and the predicted values of the suite of fingerprint properties for individual samples of suspended sediment, it is also important to consider the reliability of the resultant partitioning of sediment sources. No ‘known’ values are available against which to compare the estimates of source contributions generated by the mixing model, but a preliminary attempt has been made to examine the sensitivity of the estimates obtained to the precise values used for the source fingerprint properties. Because mean values were used to represent the fingerprint properties of individual sources, and in view of the assumptions made concerning the comparability of source materials and samples of suspended sediment, some degree of error must be associated with the values used in the mixing model to characterize individual sources. To examine the potential impact of such errors on the stability of the partitioning estimates, three sensitivity tests were undertaken. In the first, all values of one fingerprint property (SIRM) were increased by 5%; in the second, the values of all fingerprint properties for one source (Cultivated C in Table 1) were increased by 5%; and in the third, all values for the four mineral magnetic parameters were increased by 5%. In each case, the partitioning estimates remained reasonably stable relative to the original values. The rank order of the source contributions generally remained unchanged, and the partition estimates typically altered by less than ±10% (relative deviation). This stability further confirms the value of using composite fingerprints based on values of several essentially independent fingerprint properties.

**Perspective**

The methodology and results presented above clearly demonstrate the potential of a multivariate fingerprinting approach for identifying sediment sources. The relative contributions both of different areas of the River Culm catchment and of different sediment source types have been established. Such data could be of considerable
value in investigating non-point pollution, in designing and establishing sediment control programmes, and in providing a basis for improved interpretation of data on sediment yield in terms of long-term landscape evolution. Further refinement of the approach is possible. This could involve further subdivision of the seven sediment source types used in this study in order to distinguish, for example, areas of the Permian and Triassic outcrops underlain by different lithologies and surface erosion from areas of permanent pasture and ley pasture. This would, however, necessitate the use of additional fingerprint properties capable of discriminating such sources. A more detailed programme for sampling suspended sediment could also provide the basis for a more rigorous examination of the factors influencing temporal variations in the relative contributions of the major sediment sources to the suspended sediment load at the outlet of the basin.

A number of limitations to the results presented must, however, be identified. Firstly, it should be recognized that the values indicating the relative contributions of the major sediment sources listed in Table 2 are based on a simple average for the 27 sediment samples collected. Since these samples provided an essentially random selection of both flood events and sampling times within flood events, the values obtained are likely to provide an acceptable approximation of reality. However, more accurate estimates could be provided by ensuring that samples afford a good representation of intra-event sampling times and by weighting the values obtained for source contributions by the magnitude of the event and its contribution to the long-term sediment load. Secondly, the multivariate mixing model in this study used average values of the fingerprint properties for each source type. Future refinement could take account of the variability of fingerprint properties within source types and provide confidence limits for the estimates of the relative contributions from each source type. Thirdly, a number of simplifying assumptions were made in this study regarding the comparability of values of fingerprint properties for suspended sediment and potential source materials. Some corrections for contrasts in particle size and for enrichment of organic matter were incorporated into the analysis, but further scope clearly exists for dealing with variations in particle size composition, for example by considering only specific size fractions of both suspended sediment and source material. Finally, it must be accepted that the characteristics of the River Culm catchment make it well suited to fingerprinting of sediment sources. More particularly, the varied geology of the basin makes it possible to distinguish sediment derived from different areas as well as from different source types. In areas of more uniform geology, it may prove more difficult to discriminate spatial sources.

Much will depend on the range of fingerprint properties employed, and more work is clearly required to identify properties that are likely to be useful for discriminating spatial sources.

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