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Fingerprinting sediment source: The example of a drainage basin in Devon, UK

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ABSTRACT In view of the many difficulties associated with the determination of the source of suspended sediment transported by a stream, the 'fingerprinting' technique which employs sediment properties to identify the source offers considerable potential. Several limitations of the technique must, however, be recognised.

Results of applying this approach to identifying sediment sources within a small agricultural drainage basin in Devon UK are reported. A variety of sediment properties have been employed in order to test the consistency of the results obtained and a simple mixing model has been used to quantify the relative importance of the contributions from surface soil and channel banks.

INTRODUCTION

Over the past few decades, growing awareness of the wide-ranging environmental significance of suspended sediment transport by rivers has generated a considerable body of information concerning the magnitude of sediment yields and their control by climate, human activity and other catchment characteristics (e.g. Jansson, 1982; UNESCO, 1982). More recently, however, recognition of the role of suspended sediment in the transport of nutrients and contaminants and in non-point pollution from land use activities has focussed increasing attention on the sources involved and the pathways associated with the conveyance of sediment from its source to the basin outlet (e.g. Glymph, 1975; Wolman, 1977). In addition to an assessment of the suspended sediment yield from a drainage basin, information concerning the nature, relative importance and spatial distribution of sediment sources is now increasingly required. This requirement has also been promoted by recent attempts to establish sediment budgets for drainage basins (e.g. Swanson *et al.*, 1982), by attempts to develop physically-based distributed models of sediment yield (e.g. Beasley *et al.*, 1982) and by a desire for more meaningful geomorphological interpretation of sediment yield data in terms of landscape evolution (e.g. Finlayson, 1978).

Precise information concerning the nature and relative importance of sediment sources within a drainage basin has, however, traditionally proved difficult to assemble for all but very small basins. Detailed monitoring of potential sources using erosion pins, runoff troughs and similar approaches (e.g. Imeson, 1974) involves many practical difficulties as well as important sampling problems. In some studies, generalised estimates of the relative importance of sheet and channel erosion have been derived by comparing estimates of sheet erosion within a basin obtained using a soil loss equation, such as the Universal Soil Loss Equation (USLE), with the sediment yield at the basin outlet. The latter approach also introduces many problems in terms of the reliability of the soil loss estimate and the uncertainties

associated with estimating the sediment delivery ratio necessary to convert the estimate of on-site erosion to one of downstream sediment yield (cf. Walling, 1983).

The development of the 'fingerprinting' technique as a means of assessing sediment sources within a drainage basin has therefore attracted considerable interest in that it promises to provide a relatively simple means of determining the relative importance of major sediment sources (e.g. Wall and Wilding, 1976; Wood, 1978; Oldfield *et al.*, 1979). In essence this method involves firstly, the selection of a physical or chemical property which clearly differentiates potential source materials and, secondly, comparison of measurements of the same property obtained from suspended sediment with the equivalent values for the possible sources. In the case of a simple distinction between surficial and channel sources, the property could be one that differentiates topsoil (A-horizon) from the underlying parent material and bed rock (C and D-horizons) and Oldfield *et al.*, (1979) suggested that several mineral magnetic parameters offered considerable scope for fingerprinting purposes.

The essential simplicity of the fingerprinting technique is, however, complicated by a number of potential problems which have as yet received relatively little attention. These include, firstly, the enrichment of suspended sediment in fines and organic matter relative to its actual source material; secondly, transformation of sediment properties within the fluvial system, and thirdly, the existence of storage and subsequent remobilisation within the conveyance system. In the case of enrichment, it is well known that many sediment properties are closely controlled by the particle size composition and organic matter content of the material involved (e.g. Forstner and Wittmann, 1981; Lion *et al.*, 1982) and the selective removal of fines and the organic fraction by erosion processes (cf. Young and Onstad, 1976; Alberts *et al.*, 1981) could negate simple comparison of sediment and source material properties. Furthermore, removal of eroded material into the fluvial environment may produce changes in the properties of the transported sediment such that they no longer directly reflect those of source material (cf. Logan, 1978). These transformations could result from changes in pH and redox conditions or from changes in water chemistry and the processes involved could include ion exchange, dissolution and microbial activity. Sediment storage may also affect the fingerprinting of sediment sources by attenuating the linkage between source and downstream sediment yield and more particularly by providing further potential for preferential transport and transformation.

In view of these potential problems it would seem appropriate to suggest that application of the fingerprinting technique should involve several alternative diagnostic properties, rather than a single indicator, in order to establish the consistency of the results obtained, and that further work is required to test a variety of possible fingerprint properties. This paper presents the results of such a study undertaken in a small agricultural drainage basin in Devon, UK.

THE STUDY BASIN

The study basin of the Jackmoor Brook (Fig. 1) has a drainage area of 9.3km² and its altitude ranges from 21.5m at the basin outlet

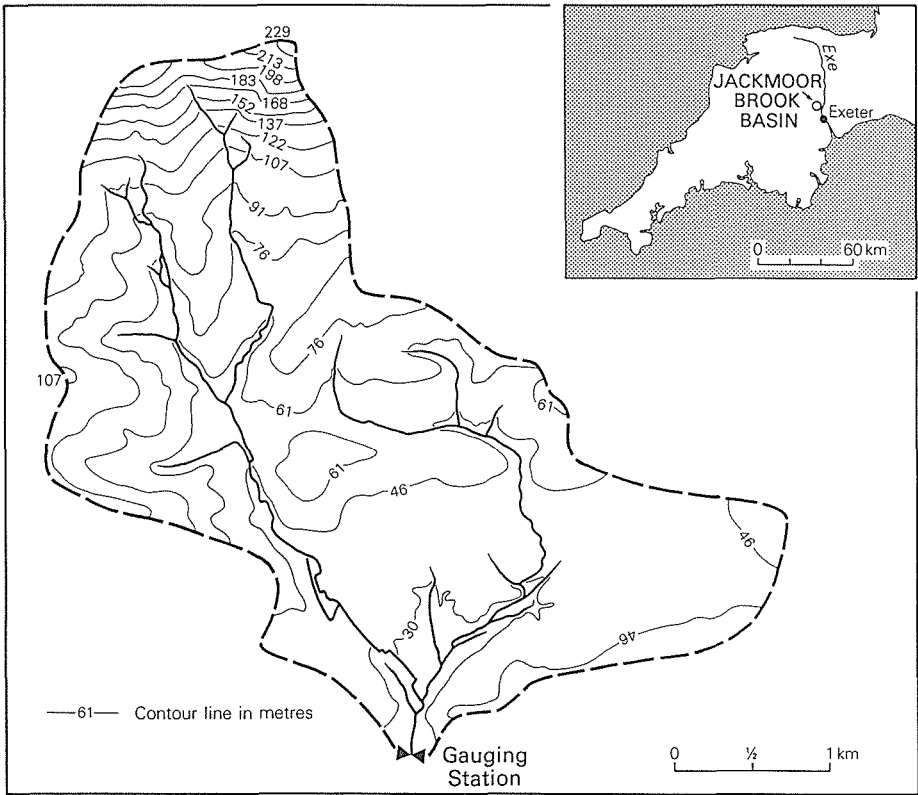


FIG. 1 The Jackmoor Brook study basin.

to 235m on the Raddon Hills which form the northern divide. Slopes are predominantly gentle ($<4^\circ$), although steeper ground occurs towards the northwestern margin (8°). The area is underlain by Permian sandstones, breccias and conglomerates and two major soil types have been identified within the basin (Clayden, 1971). Well-drained brown earths of the Crediton series are found in the extreme north of the basin, and similar soils of the Bromsgrove and Bridgenorth series occur in the southern third of the basin. The central portion is occupied by the gleyed and poorly drained brown earths of the Shaldon and Rixdale series. Extensive tile drain systems exist in this central area.

Land use is predominantly mixed arable farming, with cattle and sheep rearing and rotation of grass, cereals and root crops. The majority of the grassland is in leys. There are some small areas of mixed deciduous woodland, but this occupies less than 4% of the basin.

Mean annual precipitation and runoff are estimated at 825 and 350mm respectively. Within the local area this drainage basin is noteworthy for the relatively high suspended sediment concentrations (up to 3500mg l^{-1}) occurring in the stream during storm events. Based on available records, the mean annual suspended sediment yield from the basin is estimated at 60tkm^{-2} . The stream network is only moderately incised into the valley floors, and bank heights are commonly less than 1m, although

TABLE 1. Sediment properties selected for fingerprinting

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1. Pyrophosphate - extractable iron content
 2. Manganese oxide content
 3. Magnetic susceptibility
 4. Saturation isothermal remanent magnetisation (SIRM)
 5. Total phosphorus content
 6. Organic carbon content
 7. Nitrogen content
 8. Caesium-137 activity
-

deeper incision of 2-3m occurs in places. Floodplain development is limited and active channel incision reaches bedrock in most locations. Neither the channel network nor the agricultural land with its pattern of hedge bank boundaries provide obvious evidence of major sediment sources and in this situation the fingerprinting technique seemingly offered an attractive approach to sediment source identification.

DATA COLLECTION

In an attempt to demonstrate the relative importance of major potential sediment sources, these were initially divided into two basic groups, namely, surface soils and channel banks. Material representative of each of these two sources was collected. In order to characterize the variability of these two populations, each was stratified into a number of sub-populations, reflecting, for example, soil type, land use and different components of the channel network, and each sub-population was sampled on a random basis. In total, more than 100 samples of potential source material were collected. These were returned to the laboratory where they were air dried, disaggregated and stored. Subsequent analysis was restricted to the $<63\mu\text{m}$ fraction in order to minimise differences in particle size composition between source material and suspended sediment. Available evidence indicated that the $>63\mu\text{m}$ fraction of suspended sediment transported by the Jackmoor Brook rarely exceeded 5%. In the knowledge that suspended sediment properties would be likely to vary according to season (e.g. Ongley *et al.*, 1981) and in response to variations in discharge and sediment concentration (e.g. Walling and Kane, 1982), suspended sediment sampling was undertaken over a range of conditions. More than 50 bulk samples of river water (ca. 100 litres) were collected during storm events using a pump sampler and the suspended sediment was recovered using a continuous flow centrifuge (cf. Ongley *et al.*, 1981). The bulk samples of suspended sediment were freeze dried and stored prior to analysis.

In order to differentiate material associated with surficial

TABLE 2. Comparison of mean values of fingerprinting properties obtained from suspended sediment and potential source materials

Property	Bank material	Surface soil	Suspended sediment
Pyrophosphate iron (%)	0.10	0.22	0.34
Manganese (%)	0.17	0.26	0.32
Magnetic suscept. ($\text{mm}^3 \text{kg}^{-1}$)	0.098	0.37	0.41
SIRM ($\text{mAm}^2 \text{kg}^{-1}$)	3.30	7.90	6.42
Total phosphorus (%)	0.065	0.091	0.142
Organic carbon (%)	1.48	3.29	4.30
Nitrogen (%)	0.17	0.36	0.46
Caesium-137 (mBqg^{-1})	1.50	13.3	19.00

and channel sources, a number of properties which distinguished surface soil and channel bank material (mainly C/D horizon material) were sought. The properties finally selected are listed in Table 1 and each exhibited a statistically significant difference at the 0.05 level between surface soils and channel bank material. These properties reflect both the organic and inorganic composition of the source material but, whereas the majority are indicative of the basic chemical and mineralogic nature of the material, the Caesium -137 activity must be seen as reflecting the differential receipt of this radioisotope, as fallout from the atmosphere and its subsequent incorporation into the material. Caesium-137 fallout represents a product of atmospheric testing of nuclear weapons and its receipt at the earth's surface was first detected in 1954 and reached a maximum in 1963/4 prior to the nuclear test ban treaty (cf. Pennington et al., 1973).

Analysis of source material and suspended sediment was carried out using the following methods. Iron extraction was undertaken using the procedure outlined by Bascomb (1968). Manganese content was determined using the selective acid ammonium oxalate extractant technique of Chaco (1972) and phosphorus extraction followed by the methods reported by Williams et al., (1976, 1980). Organic carbon and nitrogen content were measured using a Carlo Erba Nitrogen Analyzer and Caesium-137 activity was determined using a Canberra Ge detector linked to a Canberra Series 35 multi-channel analyzer. Measurements of mineral magnetic properties were made using methods outlined by Oldfield et al., (1979).

RESULTS

A qualitative indication of the relative contributions made by channel and surficial sources to the suspended sediment loads of

TABLE 3. Comparison of mean values of fingerprinting properties for suspended sediment with those of potential source material corrected for enrichment

Property	Bank material	Surface soil	Suspended sediment
Pyrophosphate iron (%)	0.15	0.33	0.34
Manganese (%)	0.26	0.33	0.32
Magnetic suscept. ($\text{mm}^3 \text{kg}^{-1}$)	0.15	0.55	0.41
SIRM ($\text{mAm}^2 \text{kg}^{-1}$)	4.95	11.80	6.42
Total phosphorus (%) ¹	0.098	0.140	0.142
Total phosphorus (%) ²	0.189	0.120	0.142
Nitrogen (%)	0.50	0.47	0.46
Caesium-137 (mBqg^{-1})	2.25	20.0	19.00
1 Corrected using the particle size enrichment factor			
2 Corrected using the organic fraction enrichment factor			

the study basin was initially obtained by comparing the mean values of a given property for the two sources with that for suspended sediment (Table 2). Values for the source material were based on the $<63\mu\text{m}$ fraction. The data listed in Table 2 demonstrate that the properties of suspended sediment are in all cases closer to those of surface source material than to channel bank material, and therefore suggest that the former material provides the dominant, if not exclusive, source of suspended sediment. However, for all properties except saturation isothermal remanent magnetisation (SIRM) the values for suspended sediment exceed those of surface source material. Two possible explanations of this apparent anomaly can be advanced. The first lies in the preferential erosion of the fine fraction and organic material and therefore the enrichment of suspended sediment in fines and organic matter as compared to source material. The second involves transformation of sediment properties during transport. A detailed examination of the latter possibility undertaken by Peart (1984) indicated that, in the case of the properties listed in Table 1, such transformations were unlikely to be important in this small basin. However, clear evidence of enrichment of suspended sediment in fines and organic matter, relative to source material, already existed from other work undertaken in the study basin (cf. Peart and Walling, 1982). Enrichment in fines and the organic fraction would be likely to produce an increase in all the property measurements listed in Table 2.

TABLE 4. The relative contribution of bank material and surface soil sources to the total suspended load of the Jackmoor Brook estimated using a simple mixing model applied to the data in Table 3

Property	Relative Contribution (%)	
	Surface soils	Bank material
Pyrophosphate iron	>100	0
Manganese	86	14
Magnetic suscept.	65	35
SIRM	21	79
Total phosphorus ¹	100	0
Total phosphorus ²	69	31
Nitrogen	>100	0
Caesium-137	94	6

1 Corrected using the particle size enrichment factor

2 Corrected using the organic fraction enrichment factor

Particle size analyses of the mineral fraction of both suspended sediment and potential source material indicated that enrichment in fines was primarily restricted to the <10µm fraction and that the enrichment factor associated with this fraction was commonly of the order of 1.5 for both channel and surficial source materials. If it is assumed that this enrichment factor is also applicable to those properties listed in Table 2 which are likely to be particle-size dependent (i.e. manganese, pyrophosphate iron and total phosphorus concentrations, magnetic susceptibility and SIRM, and ¹³⁷Cs activity) the values may be corrected to be more directly comparable with those for suspended sediment. Similarly, if the organic carbon content of suspended sediment and source material is used as an indicator of their organic matter content, the data contained in Table 2 can be used to calculate organic fraction enrichment factors of 2.9 for bank material and of 1.3 for surface soils. The values for those source material properties likely to be organic matter content-dependent (i.e. total phosphorus and nitrogen concentrations) can also be corrected using these enrichment factors.

Table 3 presents values of source material properties corrected using the enrichment factors described above. In the case of total phosphorus concentration, corrections based on both particle size and organic matter enrichment have been applied since this property is known to be influenced by both. Inspection

of Table 3 reveals that the values for bank material and surface soil properties are more directly comparable with those for suspended sediment than those in Table 2. With the exception of SIRM, all properties suggest that surficial material provides the dominant source of suspended sediment. In order to quantify the relative contribution, a simple mixing model may be used viz.

$$C_s = \frac{P_r - P_b}{P_s - P_b} \times 100$$

where C_s = Contribution from surface soil sources (%)

P_r = Value of selected property for suspended sediment

P_s = Value of selected property for surficial soil

P_b = Value of selected property for bank material

The results of applying this mixing model are listed in Table 4 and provide estimates of surface soil contributions to the suspended sediment yield ranging between 21 and 100%. All values, with the exception of that for SIRM, consistently point to the dominance of surface soil sources. The estimate provided by ^{137}Cs (95%) could be seen as the most convincing, in view of the very clear differentiation between the properties of bank material (2.25 mBqg⁻¹) and surface soils (19.95 mBqg⁻¹), but the mean value for the 8 indicators (80%) could equally be used as a first approximation of the relative importance of the contribution from surficial sources to the suspended sediment load of this basin. However, it must be recognised that the derivation of the data presented in Tables 3 and 4 involved a number of assumptions that may not be entirely justified. Most important is the assumption that enrichment of the individual properties is directly proportional to the enrichment of the fine fraction or of organic matter and therefore than enrichment factors calculated on the basis of particle size data or organic matter content are directly transferable to the individual properties. Existing data suggest that this assumption is largely justified for ^{137}Cs and nitrogen, which consistently point to a very high (≤94%) contribution from surface sources, but more work is required to evaluate fully its validity for the other properties.

An alternative approach to dealing with the uncertainties associated with the application of correction factors to account for the effects of enrichment of suspended sediment in fines and organic matter, involves the use of property ratios. Walling and Kane (1984) have suggested that property ratios may be directly compared, without the need for correction, provided that the two elements or properties involved behave in the same manner with respect to particle size or organic matter enrichment.

Tables 5 and 6 present the results obtained from using a variety of sediment property ratios in the simple mixing model defined previously. In addition to those properties listed in Table 1, values of dithionite extractable iron obtained using the procedures reported by Bascomb (1968) have also been included in calculating the ratios. Caesium-137 activities have not been

TABLE 5. Comparison of mean values of selected property ratios for suspended sediment and potential source materials

Property ratio	Bank material	Surface soil	Suspended sediment
Carbon/Dithionite iron	0.76	2.56	1.53
Phosphorus/Dithionite iron	0.038	0.067	0.054
Carbon/Phosphorus	15.22	36.29	29.29
Nitrogen/Phosphorus	2.44	3.92	3.04
Pyrophosphate/Dithionite iron	0.091	0.170	0.126
Carbon/Nitrogen	7.31	9.83	9.82
SIRM/Mag. susc.	47.74	15.58	17.86
Dithionite iron/Mag. susc.	41.50	7.40	7.92
Manganese/Dithionite iron	0.058	0.116	0.110

suggested that surficial sources contribute more than 90% of the sediment yield of the Jackmoor Brook. This value is encouragingly close to the mean value of 80% obtained from calculations involving enrichment correction of source material (Tables 3 and 4) and to the value of 95% obtained for ^{137}Cs and nitrogen which were judged to be the most reliable indicators in that analysis.

DISCUSSION

The results presented above consistently point to the dominance of surface soil as the source of suspended sediment in the Jackmoor Brook basin and suggest that this source accounts for about 95% of the sediment load. In distinguishing channel bank and surface soils as potential sources, no account is taken of the relative importance of different land use, such as arable cultivation and permanent pasture, in influencing the spatial distribution of sediment mobilisation within the category of surficial sources. Intuitively one might expect arable fields to be more important than areas of permanent pasture as sediment sources in the Jackmoor Brook basin and an attempt was made to verify this hypothesis using the fingerprinting approach. In this case soil properties capable of distinguishing arable topsoil from that in areas of permanent pasture were required. This requirement proved difficult to satisfy, since the majority of the properties listed in Table 1 evidenced no significant difference between these two potential source materials. However, ^{137}Cs activity appeared to offer considerable promise for this purpose, since activity levels employed in calculating ratios since they are known to reflect entirely different controls to those influencing the other properties. Two groups of results can be recognised in Table 6.

TABLE 6. The relative contribution of bank material and surface soil sources to the total suspended load of the Jackmoor Brook estimated using a simple mixing model applied to the property ratio data in Table 5

Property ratio	Relative Contribution (%)	
	Surface soils	Bank material
Carbon/Dithionite iron	43	57
Phosphorus/Dithionite iron	56	44
Carbon/Phosphorus	67	33
Nitrogen/Phosphorus	40	60
Pyrophosphate/Dithionite iron	45	55
Carbon/Nitrogen	99.6	0.4
SIRM/Mag. susc.	93	7
Dithionite iron/Mag. susc.	98.5	1.5
Manganese/Dithionite iron	89	11

The first includes those obtained using the ratios of carbon/dithionite iron, phosphorus/dithionite iron, carbon/phosphorus, nitrogen/phosphorus and pyrophosphate/dithionite iron. This group gave values between 40 and 70% for the contribution of surficial sources to the total load. Secondly, the remaining ratios, including C/N, SIRM/magnetic susceptibility and manganese/dithionite iron, provided values for the surficial contribution of between 90 and 100%. The mean values for this contribution from the first group is 50%, for the second 95% and for all data 70%. All three suggest that surficial material provides a major, if not the dominant, source of the suspended sediment loads of the Jackmoor Brook.

Some explanation of the different results provided by the two groups of ratio indicators identified above can be provided by examination of the properties employed. Ratios which give comparatively low values for the contribution from surficial sources generally involve both inorganic and organic properties. Significantly, those ratios which provide the higher values for the contribution from surficial material employ properties that are either both essentially organic (e.g. C/N) or inorganic (e.g. manganese/dithionite iron). Walling and Kane (1984) suggest that these ratios are likely to provide the more reliable results since they are unaffected by differential enrichment of inorganic and organic material in suspended sediment. On the basis of the results provided by the property ratios, it may therefore be in topsoil associated with permanent pasture were of the order of three times higher than those found in arable topsoil, whilst both topsoil values were in turn very much higher than those found in bank material (Table 7).

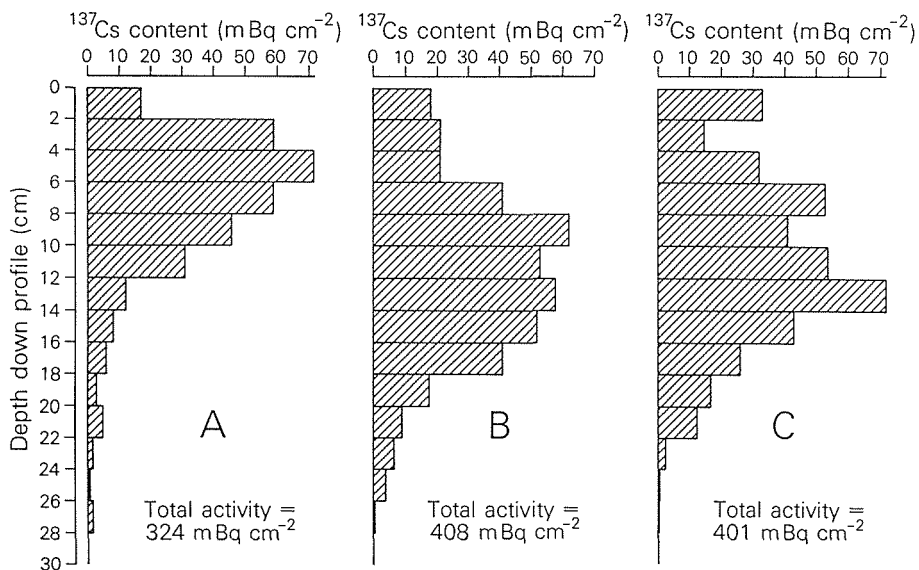


FIG. 2 Typical examples of the vertical distribution of ^{137}Cs in soil profiles associated with undisturbed permanent pasture (A) and arable cultivation (B).

This differentiation of ^{137}Cs activity may be logically explained in terms of the receipt of atmospheric fallout of this radioisotope and its subsequent incorporation in the soil or source material. Channel banks, being essentially vertical receive relatively little ^{137}Cs fallout as compared to field areas and therefore exhibit very low activity levels. Caesium-137 reaching surface soil is strongly adsorbed onto the fine fraction (cf. Rogowski and Tamura, 1965) and will be preferentially concentrated near the surface. Where cultivation occurs, this surface concentration will however be mixed throughout the depth of cultivation (ca. 30cm) and ^{137}Cs concentrations in surface topsoil will be lower than for permanent pasture. Figure 2 provides examples of the distribution of ^{137}Cs in the upper soil horizons of permanent pasture and arable fields within the Jackmoor Brook basin which clearly demonstrates this contrast.

Following the procedures employed previously, the values of ^{137}Cs activity associated with the three potential source materials were corrected using an enrichment factor of 1.5 (Table 7). A simple mixing model was subsequently used to apportion the 94% of the total sediment yield attributed to surficial sources in Table 4 between arable fields and permanent pasture and the results are listed in Table 8. These indicate that arable fields represent the dominant sediment source in this basin and account for approximately 75% of the sediment derived from surficial sources. In this case, the results cannot be confirmed by comparison with those obtained using other properties. However, in view of the clear differentiation between potential sources provided by this indicator (Table 7) and the consistent explanation for its behaviour, it is suggested that the values

TABLE 7. Comparison of the ^{137}Cs activity of suspended sediment with that of potential source material associated with arable fields, permanent pasture and bank material

	Bank material	Arable topsoil	Pasture topsoil	Suspended sediment
A	1.5	9.4	25.0	19.0
B	2.25	14.1	37.5	19.0

A = Raw data
 B = Data corrected for particle size enrichment

represent a meaningful estimate of the relative importance of these three sediment sources within the Jackmoor Brook basin.

With an estimated long-term mean annual suspended sediment yield from the Jackmoor Brook basin of 60 t km^{-2} , the sediment contributed by the areas of arable cultivation represents a soil loss of approximately $600 \text{ kg ha}^{-1} \text{ yr}^{-1}$. This value takes no account of the sediment delivery ratio for the study basin and it would seem likely that average rates of on-site soil loss may be more than an order of magnitude greater. These must, however, still be seen as low by world standards and as confirming to the low rates of soil erosion occurring on cultivated land in the UK reported by Morgan (1985).

PERSPECTIVE

The investigation reported in this paper demonstrates that the fingerprinting approach has provided consistent and meaningful estimates of the relative importance of major sediment sources within the Jackmoor Brook basin and that the method has potential for wider application. It possesses a major advantage over more traditional methods involving on-site monitoring of sediment sources, since it subsumes the linkages interposed between on-site erosion and downstream sediment yield and obviates the need to estimate the sediment delivery ratio applicable to a monitored sediment source.

On the basis of the results obtained from this study it is suggested that further application of the technique should whenever possible involve the use of several, rather than a single, indicator property, in order to establish the consistency of the results obtained. Further attention should be given to the choice of appropriate indicator properties, since those listed in Table 1 undoubtedly represent only a selection of those capable of providing worthwhile results. It must, however, be accepted that in the case of the Jackmoor Brook basin the problems of obtaining indicator properties capable of distinguishing topsoil from substrate material was made easier by the relatively homogeneous geology underlying the basin. Heterogeneous geology will undoubtedly complicate the problem and in such situations ^{137}Cs

TABLE 8. The relative contribution of topsoil from arable fields and permanent pasture and bank material to the total suspended load of the Jackmoor Brook estimated using a mixing model applied to ^{137}Cs activity data

Source	Relative contribution (%)
Channel banks	6
Permanent pasture topsoil	24
Arable topsoil	70

activity may prove particularly useful as an indicator since, unlike many chemical properties, its behaviour is largely independent of rock character.

Based on the results of this investigation, the use of ratio properties is advocated as being particularly valuable, although careful attention is required to ensure that the properties involved will, as far as possible, reflect similar controls. Enrichment of suspended sediment relative to source material as a result of selective erosion of organic matter and the fine fraction, negates the direct comparison of source and sediment properties, but correction of the source material values by using enrichment factors relating to particle size or organic matter content, provides a basis for reducing this problem. Further work is, however, required to establish enrichment factors relating more specifically to the properties concerned. It may also prove more appropriate to restrict analysis of source material and sediment properties to specific particle size fractions, the properties of which will be directly comparable, or to the organic fraction itself.

In this investigation, attention has been restricted to mean or aggregate values of suspended sediment properties, in order to obtain an assessment of the overall importance of particular sediment sources. Scope clearly exists for applying the approach at a more detailed temporal scale in order to evaluate seasonal and intra- and inter-storm variations in sediment sources as advocated by Ongley (1982) and by Oldfield *et al.* (1979) and Walling and Kane (1984).

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