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Techniques for establishing suspended sediment sources in two drainage basins in Devon, UK: a comparative assessment

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Abstract There is an increasing need for information concerning the source of the sediment load leaving a drainage basin. However, such information is difficult to obtain. Traditional methods include both direct and indirect approaches. The "fingerprinting" technique, based on measurements of sediment and source material properties, has been developed more recently. Several of these methods of sediment source determination have been applied in two drainage basins in Devon, UK. Some of the problems encountered are described.

Techniques pour établir les matières d'origine des sédiments en suspension dans deux bassins versants au Devon, RU: une étude comparative

Résumé Il y a un besoin croissant d'information en ce qui concerne l'origine des sédiments transportés en dehors des bassins. Cependant de telles informations sont difficiles à obtenir. Les méthodes traditionnelles incluent non seulement des approches directes mais aussi des approches indirectes. La technique des "empreintes digitales", basée sur les mesures des propriétés des sédiments et des matières d'origine, a été mise au point plus récemment. Plusieurs de ces méthodes pour déterminer l'origine des sédiments ont été mises en pratique sur deux bassins situés au Devon, RU. Quelques problèmes qui ont été rencontrés sont décrits.

INTRODUCTION

Measurements of sediment yield at the outlet of drainage basins have been made for well over 100 years. The data provided by such measurements are of considerable value to the hydrologist and geomorphologist, but, their essentially lumped nature introduces a number of problems when more searching questions are posed. For example, it is now becoming increasingly important to assemble information on the source of the sediment, as well as on the magnitude of the load. Information on sediment source may be required for a number of purposes including: firstly, the construction of sediment budgets to elucidate the sediment system; secondly, as an input to the development of sediment yield models; thirdly, to permit the more meaningful interpetation of sediment yield data, both in terms of the magnitude and spatial distribution of denudation rates, and of patterns of landscape development; and finally, for the assessment of sediment quality and pollution loadings. In many instances a simple assessment of the relative contribution of surface and channel erosion to the sediment yield at a catchment outlet would be of great value, but such data are remarkably difficult to obtain. The increasing need for information on sediment sources is paralleled by a general lack of effective techniques for providing such data. Traditional approaches to determining sediment source can be conveniently divided into two, namely, direct and indirect methods.

In the case of the direct approach, an attempt is made to isolate major sediment sources within the drainage basin and to monitor the rate of sediment production. Thus, for example, erosion pins could be used to document surface lowering; and pins, surveying and terrestrial photogrammetry could be used to estimate sediment production by bank erosion. A number of indirect methods exist for evaluating sediment source. For example, it may be possible to estimate the total sheet and rill erosion within a drainage basin using a soil loss equation, such as the USLE, and to estimate the downstream yield from this source by applying a sediment delivery ratio. Subtraction of the calculated soil erosion loss, corrected for sediment delivery, from the measured yield, gives an estimate of the contribution from other sources such as gully and channel erosion.

One of the most common methods of studying storm-period suspended sediment concentration/discharge relationships involves the construction of storm-period hysteretic rating loops. If a specific form of rating loop can be seen as diagnostic of a given sediment source, its occurrence could be used to infer sediment origin. For example, Arnborg *et al.* (1967) and Bogen (1980) ascribe clockwise hysteresis to the entrainment, on the rising limb, of sediment which was deposited on the bed of the stream during the previous recession flow, and this may, therefore, afford evidence of sediment derived from within the channel.

A number of traditional approaches to the evaluation of sediment source have been described. An alternative, and comparatively new, method of determining sediment origin involves the use of suspended sediment properties as natural tracers. If the materials of potential sediment source areas are sampled and characterized, and in addition, information is available on the properties of sediment transported by the stream, the latter can be used to "fingerprint" the sediment source. This approach relies upon potential sources being differentiated in terms of a given property. The distinction between sediment of surficial and channel or geologic origin was made by Wall & Wilding (1976) using carbonate content and clay mineralogy, while Grimshaw & Lewin (1980), utilized sediment colour.

A comparative study of sediment source determination, using both indirect and direct traditional approaches, and the "fingerprinting" technique, has been undertaken in Devon, UK. The results are presented in this paper.

THE STUDY BASINS

The results presented here were derived from measurements made in two small drainage basins located in Devon, UK. Figure 1 indicates that the Jackmoor Brook basin (9.8 km^2) is essentially undulating in character and the highest point (235 m) occurs on the northern divide, formed by the Raddon Hills. Slopes are generally less than 4°, although steeper slopes, of around 8°, do occur in the Raddon Hills. The bedrock geology consists of Permian sandstone, breccia and conglomerates. Land use is mainly arable with ley pasture and some permanent woodland. The mean annual sediment yield is about 50 t km^{-2} $year^{-1}$. The second drainage basin is that of the River Dart which has an area of 46 km^2. This basin has a well dissected, incised terrain, which is illustrated in Fig. 1. The slopes in this catchment are steeper than those of the Jackmoor Brook basin. Much of the drainage basin is underlain by sandstones, shales and mudstones of Upper Carboniferous age and some

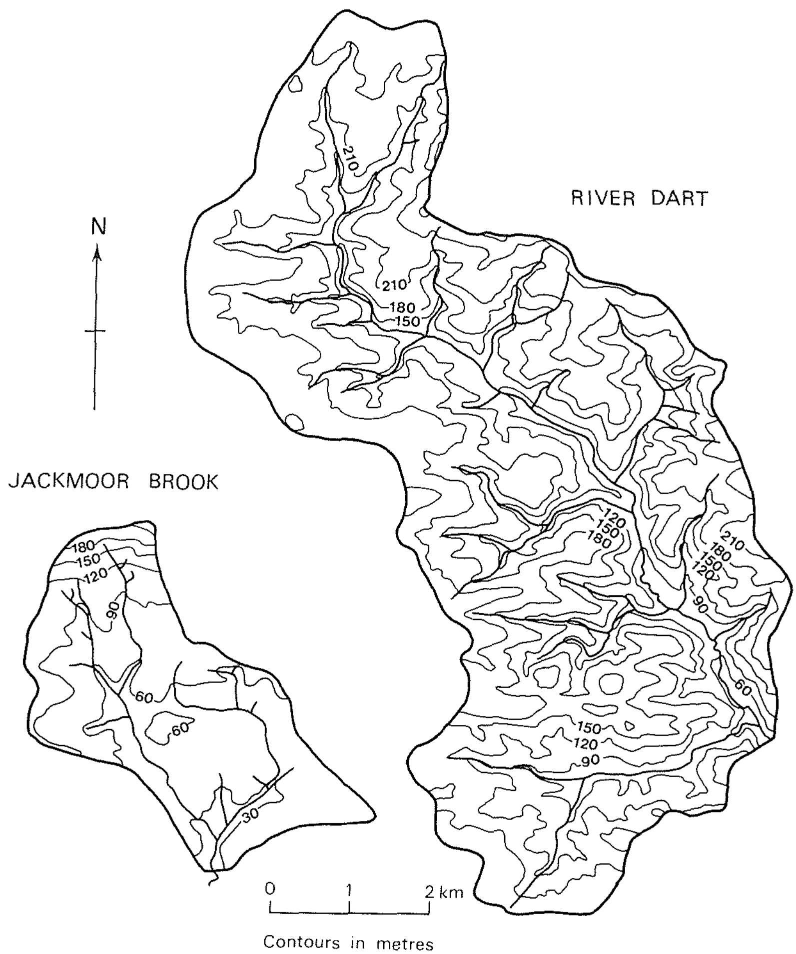

Fig. 1 Topography of the study basins.

alluvial deposits occur in the valley bottoms. Permanent pasture is the most important land use and on the steeper slopes permanent woodland occurs. The mean annual suspended sediment yield is estimated at 75 t km^{-2} $year^{-1}$. Much of the hydrological and sedimentological monitoring for this study was conducted during the period October 1977 to May 1979.

AN INDIRECT METHOD OF SEDIMENT SOURCE EVALUATION

The availability of detailed records of suspended sediment concentration, derived from the continuous monitoring of turbidity for both basins, permits the construction of sediment concentration/discharge hysteresis relationships.

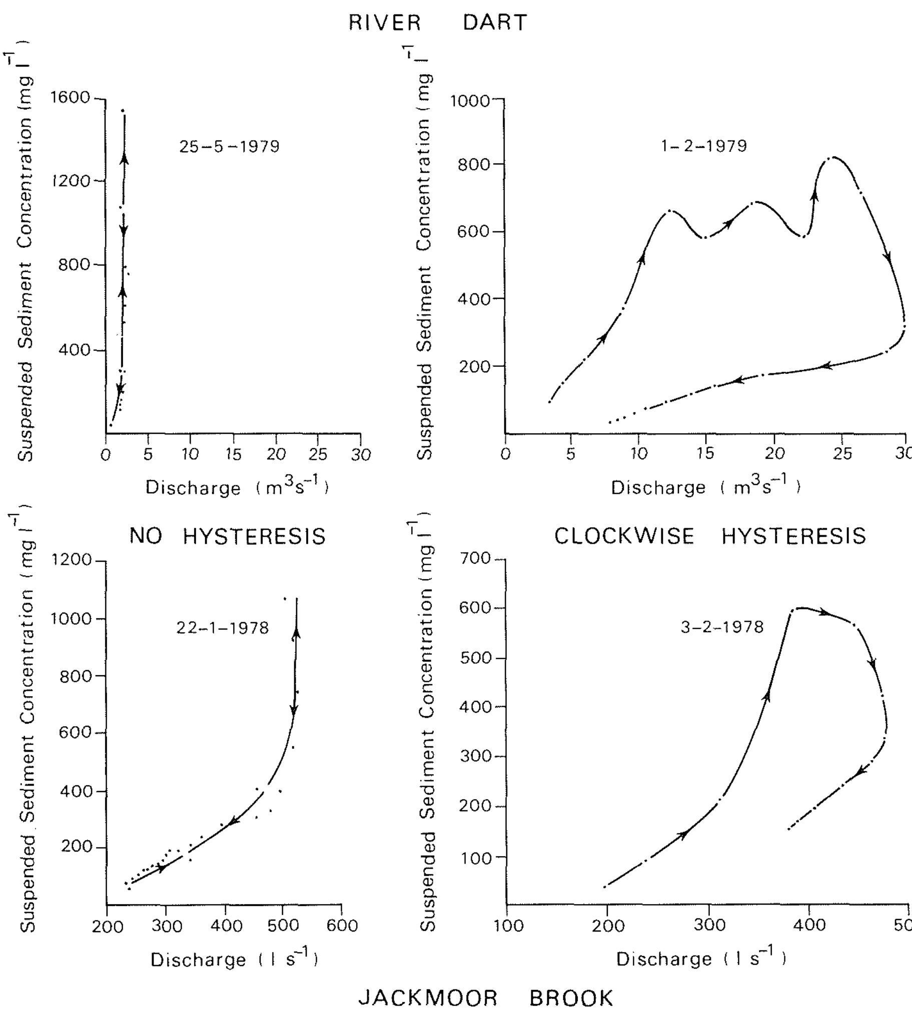

Fig. 2 Suspended sediment-discharge rating loops for the study basins.

Analysis of the rating loops for the drainage basins reveals that, for single peaked storm events, two general forms exist. These are: no hysteresis, when a single line describes the relationship between sediment concentration and flow, and clockwise hysteresis, caused by sediment depletion on the recession limb of the storm hydrograph. Examples of these two types of rating loop are shown in Fig. 2. The clockwise hysteretic relationship between flow and sediment is the most common form. If these two storm-period hysteresis relationships can be shown to reflect sediment derived from a particular source, their occurrence can be used to infer sediment origin. As a result of the dominance of storm events exhibiting clockwise hysteresis, attention will focus upon this as a potential indicator of sediment source.

The literature indicates that clockwise hysteresis is generally interpreted in terms of variations in sediment supply, which are not necessarily confined to any specific sediment source. For example, Doty & Carter (1965) have shown that production of sediment from surface erosion declines through time from an early peak, while Novotny (1980) indicates that the cessation of rainfall causes the reduced detachment and transport of soil particles. These observations could explain clockwise hysteresis in storms where the sediment was derived from surface sources. However, Arnborg *et al.* (1967) and Bogen (1980) ascribe clockwise hysteresis to the entrainment on the rising limb of sediment which was deposited on the bed of the streams during the previous recession flow. Furthermore, Carling (1983) provides evidence that depletion of channel sources of sediment may generate clockwise hysteresis loops. The preceding discussion indicates that it is possible to explain clockwise hysteresis in terms of sediment derived from either, within-channel or surface sources. In consequence, in the absence of additional evidence, it is not possible to use the occurrence of clockwise hysteretic rating loops in the study basins to infer sediment source.

A DIRECT METHOD FOR THE DETERMINATION OF SEDIMENT ORIGIN

An attempt has been made to utilize the direct monitoring of erosion to evaluate sediment source. In order to avoid the need to measure all the potential sources of sediment in the study basins, attention focussed on evaluation of the contribution from one source, namely, channel bank erosion. The contribution from surface sources can be estimated indirectly by subtracting the contribution made by bank erosion from the measured-suspended-sediment load. Erosion pin-sites were established such that a mean value of channel bank erosion could be derived. Sampling was stratified in that only sites undergoing erosion were monitored. In order for the contribution from channel bank erosion to be quantified a number of factors, in addition to the rate of erosion, had to be determined. These were firstly, the area of eroding bank; secondly, bulk density of the channel bank material and finally, the percentage of the eroded bank sediment capable of being removed in suspension. The determination of these factors affords a source of error additional to those associated with the accuracy and representativeness of the erosion pin measurements.

All the values necessary for the determination of the bank erosion contribution to the sediment load of each basin were obtained. However, values for the percentage derived from this source are not presented here, since further investigations identified several factors which may seriously affect the reliability of the results. Firstly, the great variation amongst the individual measurements of bank retreat recorded by the erosion pins introduced considerable uncertainty into the estimation of a mean erosion rate. The standard error of the mean rate of bank recession was sufficiently large to make this estimate unreliable. Secondly, there was evidence that the natural bank erosion processes delivered some material to the stream in the form of blocks or peds. This was especially so where cantilever failure, frost wedging or slumping were involved. Before this material can be transported out of the basin it must be broken down to a size suitable for transport in suspension. In consequence, there may be delay between erosion and the eventual removal of the material from the basin. As a result of such storage of sediment within the channel, it is difficult to relate erosion rates for a given time to the sediment passing the basin outlet during the same period. More information on this potential storage effect is required before the erosion data obtained can be used to assess the proportion of the total sediment load derived from bank erosion sources.

THE USE OF SEDIMENT PROPERTIES AS A NATURAL TRACER

In addition to the use of sediment/discharge hysteretic rating loops, and the direct monitoring of channel bank erosion, an attempt was made to determine sediment origin using the natural properties of soil, channel substrate and suspended matter to fingerprint sediment source. Two categories of sediment source were identified, namely, surface soil and channel bank material. In each of the study basins, samples of surface soil were obtained so as to be representative of the range of land-use, topography and geology. Channel bank material sampling was statified to incorporate the effects of geology and soil profile development. Upon return to the laboratory the samples were air dried and the <63 μm fraction separated for analysis. Screening at 63 μm was carried out because little material coarser than this is transported in suspension in these basins. Bulk storm water samples were collected in polyethylene containers at the outlets of both study basins. The samples were transported back to the laboratory and the sediment was separated by continuous flow centrifugation. The recovered sediment was freeze dried and stored for analysis. At each site in excess of 50 samples were collected in an attempt to reflect variations of flow, storm hydrograph and season. Laboratory analysis of the potential source materials and the suspended matter included the determination of total carbon and nitrogen using a Carlo Erba elemental analyser, total phosphorus by the method of Williams *et al.* (1980), pyrophosphate and dithionite extractable iron using the technique of Bascomb (1968) and manganese oxide by selective extraction following the methodology of Chaco (1972). Caesium-137 measurements were undertaken by gamma spectrometry using a germanium co-oxial detector.

The "fingerprinting" technique of sediment source evaluation can only be used where potential source material is clearly differentiated by a physical or chemical property. For the study basins mean values of a number of sediment property ratios were significantly different at the 0.05 level for the two potential sources of sediment. These are listed in Table 1 which also presents mean values of these ratios for channel bank material, surface soil and suspended sediment. In order to quantify the relative contribution of the two sediment sources the mean values of the property ratios were incorporated into a simple mixing model viz.:

$$C_s = \frac{P_r - P_b}{P_s - P_b} \times 100 \qquad (1)$$

where C_s = contribution from surface source (%); 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.

Table 1 Comparison of mean values of selected property ratios for suspended sediment and potential source materials

Property ratio	*Jackmoor Brook:*			*River Dart:*		
	Bank material	*Surface soil*	*Suspended sediment*	*Bank material*	*Surface soil*	*Suspended sediment*
Carbon/dithionite iron	0.76	2.56	1.53	0.73	3.55	3.39
Phosphorus/dithionite iron	0.038	0.067	0.054	0.034	0.090	0.083
Carbon/phosphorus	15.22	36.29	29.29	21.51	47.36	43.07
Nitrogen/phosphorus	2.44	3.92	3.04	2.64	4.44	3.88
Pyrophosphate/dithionite iron	0.091	0.170	0.126	0.174	0.312	0.287
Carbon/nitrogen	7.31	9.83	9.82	7.63	10.46	12.10
Manganese/dithionite iron	0.058	0.116	0.110	0.037	0.113	0.220

The results of applying this model to each of the sediment property ratios are presented in Table 2. Ratios have been used to quantify sediment source in an attempt to overcome the problems caused by the enrichment of the suspended sediment in fines and organic matter in comparison to the source material. Such enrichment means that the direct comparison of individual properties of suspended sediment to source material is impossible (cf. Peart & Walling, 1986). Walling & Kane (1984) suggest that property ratios may be directly compared, because, providing the two components of the ratio are influenced in the same manner by changes in particle size or organic matter content, the ratios are independent of the effects of enrichment. The results presented in Table 2 indicate that the two contrasting sources of sediment may contribute different proportions of the total sediment yield in each basin. For example, in Table 2 all property ratios consistently indicate that surface sources provide a greater proportion of the sediment load in the River Dart than in the Jackmoor Brook. In addition, the mean values for the percentage of the suspended sediment derived from the two sources indicate that surface sources are more important in the Dart basin.

Table 2 *The relative contribution of surface soil and bank material to the suspended load of the study basins estimated using a simple mixing model applied to the property ratio data in Table 1*

	Jackmoor Brook relative contribution (%)		*River Dart relative contribution (%)*	
	Surface soil	*Bank material*	*Surface soil*	*Bank material*
Carbon/dithionite iron	*42.8*	*57.2*	*94.3*	*5.7*
Phosphorus/dithionite iron	*55.2*	*44.8*	*87.5*	*12.5*
Carbon/phosphorus	*66.8*	*33.2*	*83.4*	*16.6*
Nitrogen/phosphorus	*40.5*	*59.5*	*68.9*	*31.1*
Pyrophosphate/dithionite iron	*44.3*	*55.7*	*81.6*	*18.4*
Carbon/nitrogen	*99.6*	*0.4*	*100*	-
Manganese/dithionite iron	*89.7*	*10.3*	*100*	-
MEAN	*62.7*	*37.3*	*88.0*	*12.0*

The use of sediment property data to evaluate sediment source is not without difficulties. Problems arise in relating source material to suspended sediment, because of the selective nature of the erosion and transportation process, which causes the enrichment of suspended sediment in fines and organic matter, thereby resulting in higher concentrations of nutrients and contaminants in the suspended sediment. However, as stated previously, sediment property ratios facilitate the direct comparison of suspended matter and source material properties and they have been adopted for use in this study. Chemical transformation and alteration of the suspended sediment may also occur during transport in the fluvial system such that the suspended sediment no longer reflects the original source material (e.g. Logan, 1978). Peart (1984), however, presents evidence which suggests that suspended sediment property transformation may not be significant in the study basins. Ideally, properties used as tracers in the fluvial system should be chemically inert or conservative in behaviour. Caesium-137, a product of atmospheric fallout, may provide one such chemically conservative tracer. Caesium-137 is strongly adsorbed onto the clay mineral fraction of drainage basin soils and once sorbed further movement by natural chemical processes is limited (e.g. Ritchie *et al.*, 1974).

Caesium-137 concentrations for source materials and suspended sediment are presented in Table 3 for both basins. For the study basins particles size analysis of the mineral fraction of soils and suspended sediment indicates that enrichment of the latter is primarily restricted to the <10 μm fraction and is generally of the order of 1.5 in relation to both surficial and channel sources. The values of ^{137}Cs for the potential source materials were therefore corrected using an enrichment factor of 1.5 and the results are presented in Table 3. In order to quantify the relative contribution from channel bank and surface soil sources, the corrected ^{137}Cs data were incorporated into the mixing model used for the sediment property ratios. The results of applying this model are listed in Table 4 and suggest that surface sediment sources are dominant, supplying 70% and 94% of the suspended sediment transported by the River Dart and the Jackmoor Brook respectively. The dominance of surface sources in both basins suggested by ^{137}Cs is in agreement with the findings of the sediment property ratios introduced above.

Table 3 *Comparison of the caesium-137 activity of suspended sediment with that of potential source material*

Material	*Caesium-137 content (mBq g^{-1})*			
	Jackmoor Brook:		*River Dart:*	
	A	*B*	*A*	*B*
Suspended sediment	*19.00*	*19.00*	*30.0*	*30.0*
Surface soil	*13.3*	*20.0*	*28.0*	*42.0*
Bank material	*1.5*	*2.25*	*1.5*	*2.25*

A = Uncorrected.
B = Corrected using the particle size enrichment factor.

Table 4 *The relative contribution of bank material and surface soil sources to the suspended load of the study basins estimated using a simple mixing model applied to the data in Table 3*

Drainage basin	*Relative contribution (%):*	
	Surface soils	*Bank material*
River Dart	*70*	*30*
Jackmoor Brook	*94*	*6*

The mean values of surface soil contribution provided by the seven property ratios and by ^{137}Cs point to the dominance of surface sources in both basins. Whilst this agreement is encouraging it must be recognized that there is considerable variation between each of the natural tracers in terms of the estimates of the relative importance of channel and surface sources provided. An independent methodology for evaluating suspended sediment origin is required so that the most reliable natural tracers can be identified. It is believed that at the present time erosion process studies afford the most practical means of achieving this aim.

CONCLUSION

There is a need to determine sediment source and three different methodologies have been evaluated in this study. The construction of suspended sediment concentration/discharge hysteresis rating relationships do not, without additional information, permit the evaluation of sediment source in terms of a within-channel, surface soil division. The channel bank erosion study indicates that this source provides sediment to the channel system. However, because of problems associated with sediment storage and evaluating erosion it is difficult to quantify the contribution made by bank erosion. Nevertheless, it is believed that process studies afford the best method of evaluating new techniques of sediment source evaluation, such as "fingerprinting". In the study basins the "fingerprinting" methodology proved most capable of determining sediment source. However, in the case of the Jackmoor Brook and the River Dart the relatively homogeneous geology underlying the basins may have simplified the problem of finding properties capable of distinguishing topsoil from substrate material. In drainage basins with heterogeneous geology this will be more difficult. In such situations ^{137}Cs may be the better tracer since its behaviour is largely independent of rock character.

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