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Suspended sediment sources in British rivers

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Abstract Sedimentation problems have traditionally been viewed as being of limited importance in Britain. As a result there is no national sediment monitoring programme and relatively little is known about the suspended sediment loads of British rivers. The recent growth of awareness of the wider environmental significance of fine sediment and its important role in the sediment-associated transfer of nutrients and contaminants and in degrading aquatic ecosystems has emphasized the need for sediment control and management programmes. The design of such programmes requires an improved knowledge and understanding of the suspended sediment budgets of British catchments. In addition to information on sediment loads and sediment yields, there is a need for information on sediment source. Such information is difficult to obtain using traditional techniques, but source fingerprinting procedures offer an effective and reliable means of assembling such data. The authors and their co-workers have undertaken a number of source tracing investigations in British catchments and the findings from 48 catchments are synthesized in this contribution. The results are reviewed and their implications for the sediment budgets of British catchments and for the design and implementation of effective sediment management programmes are discussed.

Key words British rivers; sediment sources; source fingerprinting; source tracing; suspended sediment

INTRODUCTION

Sedimentation problems, such as reservoir sedimentation and the siltation of canals and navigable waterways, have traditionally been viewed as being of limited importance in Britain. As a result, there is no national sediment monitoring programme and relatively little is known about the magnitude of the suspended sediment loads of British rivers. The recent growth of awareness of the wider environmental significance of suspended sediment transport by rivers has focused attention on its important role in the transport of nutrients and contaminants (cf. Walling *et al*., 1997; Warren *et al*., 2003) and the degradation of aquatic habitats, through, for example, the siltation of salmon spawning gravels and the clogging of aquatic vegetation (cf. Soulsby *et al*., 2001; Wood & Armitage, 1997, 1999). Table 1 serves to emphasize the potential significance of the suspended sediment load in accounting for a substantial proportion of the nutrient load of a river, by providing information on the proportion of the annual total P load transported in association with fine sediment (i.e. as particulate-P) for several British rivers. Concern for the important role of fine sediment in nutrient and contaminant transport through river systems and in degrading aquatic habitats has been further heightened by recognition of its key role in influencing the ecological status of rivers and streams and thus the need to treat it as a key factor within assessment procedures linked to the EU Water Framework Directive.

Table 1 Phosphorus export from selected UK catchments and the proportion transported in particulate form (based on data reported by Withers *et al.*,1998).

River	Catchment area (km^2)	Total P export ($kg\ ha^{-1}\ year^{-1}$)	Particulate (%)
Avon (Warwickshire)	2674	2.10	26
Severn	6850	1.62	43
Exe	601	1.64	68
Dart	46	1.87	75
Ouse	3315	2.07	55
Swale	381	0.84	33
Calder	899	6.40	34
Don	1320	0.93	67
Dee	2100	0.26	69
Ythan	689	0.73	79

Against this background, there is increasing interest in the potential for implementing sediment control or management programmes in British catchments, linked, for example, to improved land management practices and the promotion of catchment sensitive farming. In this context, fine sediment is increasingly viewed as a key component of diffuse source pollution from agricultural land. The design and targeting of sediment control programmes must necessarily be based on a sound knowledge and understanding of existing sediment loads and sediment yields and this requirement has highlighted the need for improved information on the suspended sediment loads of British rivers. In addition to information on the magnitude of suspended sediment loads and yields, there is also a need for information on the source of the transported sediment. If effective catchment management strategies, aimed at controlling suspended sediment mobilization and transport, are to be implemented, it is essential that the main sediment sources should be identified and their relative contributions assessed, in order to target control measures in a cost-effective manner. Control of sediment mobilization and delivery from agricultural fields will, for example, require a very different approach from control of degrading channel banks and channel erosion. Equally, it is important to recognize that, even if one group of sediment sources (e.g. surface sources) is successfully controlled, significant sediment mobilization and transport could still occur and generate problems, if other sources (e.g. eroding channel banks) remain uncontrolled.

In an environment such as the UK, where erosion rates and sediment yields are relatively low, it is frequently difficult to identify the main sediment sources from field and aerial surveys and this has led to uncertainty and even disagreement as to the relative importance of surface and channel erosion. Traditional approaches to establishing the relative importance of a number of potential sources also face important problems related to temporal and spatial sampling (cf. Peart & Walling, 1988; Collins & Walling, 2004). Sediment source tracing using fingerprinting techniques has, however, proved an increasingly valuable tool for providing information on the relative importance of a range of potential suspended sediment sources within a catchment. In essence the approach is founded on a comparison of the “fingerprint” of transported sediment with those of potential sources and involves, firstly, the selection of one or more physical or chemical properties which clearly differentiate potential source materials and, secondly, comparison of measurements of the same property obtained from suspended sediment with equivalent values for potential sources, in order to identify the likely source of that sediment. By using composite fingerprints involving a variety of fingerprint properties, multivariate statistical techniques to test source discrimination, and quantitative mixing (or unmixing) models, the fingerprinting approach can provide reliable quantitative information on the sources of the sediment transported by a river or stream and their relative contributions. Furthermore, the approach can be applied to a range of rivers or catchments to generate data that permit comparisons between individual catchments at both the local and national scale. Work undertaken by the authors and their co-workers over the past 10 years, using an effectively common approach, has generated a growing body of information on suspended sediment sources in British rivers, including the relative importance of surface and channel sources and the range of variation of these contributions. This information will be reviewed and its implications for the sediment budgets of British catchments and the development of sediment management strategies discussed.

THE FINGERPRINTING PROCEDURE

An essentially similar approach has been employed in 11 studies, and the resulting data have established the relative contributions of a range of potential sources to the suspended sediment yields of 48 British catchments, located in many different parts of the country and ranging in size from 0.31 to 4390 km^2. Further details of the approach employed are provided by the reports on the original studies. In brief, this involved collecting samples of suspended sediment at the catchment outlet and comparing the properties of these samples with equivalent information for a range of potential sources within the upstream catchment, in order to establish the relative contributions of those sources. In most cases, the samples of suspended sediment were collected as discrete instantaneous bulk samples and the sediment was recovered by continuous flow centrifugation. In some studies, however, time-integrating trap samplers (cf. Phillips *et al.*, 2000) were employed to collect time-integrated samples over periods of several weeks. In all cases, sampling continued throughout a period of 12 months or more, in order to provide samples representative of a range of different flow conditions and seasons. The samples of potential source material were collected from a large number of representative sites in the catchments and, in most cases, the sources included the surface of areas under cultivation, permanent pasture (or moorland) and woodland, as well as channel banks, ditches and other subsurface sources. In a few cases, field drains were included as a potential source, and these were characterized by collecting samples of the sediment issuing from the drains. In order to take account of the influence of grain size composition on the values obtained for the fingerprint properties for individual samples and the likely contrasts in grain size composition between the sediment samples, which were generally <63 μm, and the coarser source material samples, all samples were sieved to <63 μm prior to analysis.

In all studies, a wide range of potential fingerprint properties were analysed, including base cations, heavy metals, nutrients and environmental radionuclides (e.g. ^{137}Cs, excess ^{210}Pb, ^{226}Ra), and a two-stage statistical procedure was employed to select the optimum set of properties for inclusion in the final composite fingerprint.

This procedure commonly involved use of the Kruskal-Wallis test, to identify those fingerprint properties capable of discriminating between the potential sources, and stepwise multiple discriminant function analysis, to select from these the optimum set of properties for the composite fingerprint. The composite fingerprint was then used in a mixing model, which was optimized by minimizing an objective function R_{es}, based on the sum of squares of the deviations from the measured concentrations of the concentrations estimated for individual tracer properties, for given relative contributions P from the m individual sources s, viz:

$$R_{es}=\sum_{i=1}^{n}\left(\frac{C_{ssi}-\left(\sum_{s=1}^{m} C_{si}P_{s}\right)}{C_{ssi}}\right)^{2} \tag{1}$$

where: C_{ssi} is the concentration of tracer property i in the suspended sediment sample, C_{si} is the mean concentration of tracer property i in source group s and P_s is the relative proportion from source group s.

The mixing model provides estimates of the relative contributions of the potential sources to individual sediment samples. In many cases, a particle size correction factor was incorporated into the mixing model to take account of contrasts in the grain size composition of the <63 µm fraction between the sediment and the source materials and in a few cases an additional correction factor was used to also take account of differences in the organic matter content of the source material and sediment samples. Where the sediment samples were instantaneous samples, collected over a range of flow conditions and seasons, an estimate of the overall contribution of the individual sources to the longer-term sediment load of the stream or river was obtained either by averaging the results for the individual samples or by calculating the load-weighted mean contribution, and thereby taking account of the magnitude of the sediment load at the time of sampling. Where the sediment sample had been collected using a time-integrating trap sampler, the resulting source apportionment was representative of the period of deployment of the sampler and the values obtained for individual samples/periods were either averaged or used to calculate a weighted average, based on the relative magnitude of the sample mass or the total sediment flux for the period of deployment, obtained from an ongoing sediment monitoring programme.

Since the results obtained for the individual studies were generated using a common fingerprinting procedure, they are seen to be directly comparable and thus as providing a nationally-consistent data set. However, it must be recognized, that the estimates of the relative contributions from the individual sources involve a number of uncertainties and that, although, for convenience, they are presented as absolute values they necessarily involve a degree of imprecision. These uncertainties include, for example, the precision of the laboratory analysis of sediment and source material properties, the use of single mean values to represent the properties of a given potential source and the representativeness of such mean values, the number and nature of the sediment samples used to derive the estimate of the overall contribution of a given source to the longer-term sediment yield from a catchment, and the procedure used to calculate this contribution, based on the estimates obtained for the individual samples.

SEDIMENT SOURCES IN BRITISH CATCHMENTS

The results of the fingerprinting investigations carried out in 48 British catchments are summarized in Table 2. In two cases, a particular river was investigated by two separate studies and results are presented for both studies. The differences apparent between the two sets of results are not unexpected, due to differences in the study periods involved, the numbers of suspended sediment samples collected, the sediment sampling procedures employed, the source material sampling strategies and the fingerprint properties involved. The locations of the individual catchments listed in Table 2 are shown on Fig. 1.

The results presented in Table 2 are consistent with existing understanding of the role of forests in limiting both surface runoff and erosion, since, in the majority of cases, the relative contribution from areas of the catchment surface under forest are low. These low contributions will, however, also reflect the relatively small proportion of most catchments occupied by forest and woodland. The exceptions, namely catchments 2 and 14–17, where contributions are much higher, ranging from 11 to 78%, reflect catchments with much larger areas of forest, where both planting and harvesting activities can increase erosion and sediment mobilization. It is, nevertheless, important to recognize that the proportions contributed by individual sources reported in Table 2 are effectively independent of the magnitude of the sediment yield. A *high proportion* contributed from the surface of forested areas within a catchment does not itself indicate that a *large amount* of sediment is contributed from the forested areas, since the overall sediment yield from the catchment could be low. Similar considerations must be borne in mind when evaluating the relative contributions from other sources.

Any attempt to interpret fully the results presented in Table 2 regarding the relative importance of the areas of the catchment surface under cultivation and permanent pasture/moorland, as sediment sources, would require information on the relative proportions of the catchment occupied by these two land use classes. In the absence of such information, it must be assumed that the results presented reflect, at least in part, the relative spatial extent of the two land use classes in the individual catchments. Thus, the surface of areas under permanent pasture and moorland are seen to be a major sediment sources in those areas in the north and west of the country, where permanent grassland and moorland represent the dominant land use. Similarly, the surface of cultivated areas contributes >50% of the suspended sediment load in several of the catchments located in southern England, where arable cultivation represents an important land use.

In four cases (catchments 12, 13, 23, 24) field drains (tile drains) were included as potential sources and the results of the fingerprinting investigations indicated that these were an important source, accounting for ~30% of the sediment yield from two small catchments in Leicestershire and ~50% for two small catchments in Herefordshire. These relatively high contributions undoubtedly reflect the extensive underdrainage in both catchments, but nevertheless emphasize that field drains can represent an important sediment source in lowland catchments. Detailed investigations of the properties of the fine sediment discharged from the drains indicated that these were very similar to those of surface soil and therefore that the drains served as an additional pathway for sediment mobilized from the catchment surface to reach the stream

Table 2 Estimates of source type contributions for a selection of British catchments obtained using the source fingerprinting technique.

Catchment no.[1]	River/ catchment	Area (km^2)	% Contribution[2] from topsoil from areas under:			% Contribution[2] from channel:		Study
			Wood-land	Pasture/ moorland	Cultiv-ation	Banks	Drains	
1	Ettrick Water	500	3	49	–	48		Owens *et al.* (2000)
2	Teviot	1110	15	21	24	39		Owens *et al.* (2000)
3	Tweed	4390	7	20	35	39		Owens *et al.* (2000)
4	Swale	1350	–	42	30	28		Walling *et al.* (1999)
5	Ure	914	0.7	45	17	37		Walling *et al.* (1999)
6	Nidd	484	6.9	75	2.8	15		Walling *et al.* (1999)
7	Ouse	3315	–	25	38	37		Walling *et al.* (1999)
8	Wharfe	814	4.4	70	3.6	23		Walling *et al.* (1999)
9	Aire	282	–	45	–	55		Carter *et al.* (2003)
10	Aire	–	–	57	–	43		Carter *et al.* (2003)
11	Aire[3]	1932	–	7	20	33		Carter *et al.* (2003)
12	New Cliftonthorpe	0.96	–	30	33	6	31	Russell *et al.* (2001)
13	Lower Smisby	2.6	–	26	37	6.2	31	Russell *et al.* (2001)
14	Upper Hore	1.6	11	63	–	26		Collins *et al.* (1997a,b)
15	Hafren	–	78	28	–	4		Collins *et al.* (1997a,b)
16	Upper Severn	8.7	22	68	–	12		Collins *et al.* (1997a,b)
17	Upper Severn	580	48	29	–	23		Collins *et al.* (1997a,b)
18	Rhiw	140	2	89	2	7		Collins *et al.* (1997a,b)
19	Vyrnwy	778	2	83	4	11		Collins *et al.* (1997a,b)
20	Perry	181	2	71	22	5		Collins *et al.* (1997a,b)
21	Severn	4325	2	65	25	8		Collins *et al.* (1997a,b)
22	Tern	852	1	40	53	5		Collins *et al.* (1997a,b)
23	Jubilee	0.31	–	3.1	37	12	48	Russell *et al.* (2001)
24	Belmont	1.5	–	3.9	30	11	55	Russell *et al.* (2001)
25	Frome	77	–	14	38	48		Walling *et al.*(unpubl.)
26	Stretford Brook	55	–	9	48	43		Walling *et al.*(unpubl.)
27	Dore	42	–	2	56	42		Walling *et al.*(unpubl.)
28	Worm	69	–	25	20	55		Walling *et al.*(unpubl.)
29	Garron Brook	93	–	14	46	40		Walling *et al.*(unpubl.)
30	E. Avon	89	–	19	64	17		Walling *et al.*(unpubl.)
31	W. Avon.	85	–	25	71	4		Walling *et al.*(unpubl.)
32	Till	55	1	46	33	20		Walling *et al.*(unpubl.)
33	Chittern	16	–	30	69	1		Walling *et al.*(unpubl.)
34	Sem	21	–	10	78	12		Walling *et al.*(unpubl.)
35	Ebble	109	–	37	52	11		Walling *et al.*(unpubl.)
36	Nadder	221	–	4	54	32		Walling *et al.*(unpubl.)
36	Nadder	221	1.3	16	69	14		Heywood (2003)
37	Upper Avon	324	1.8	12	78	8.2		Heywood (2003)
38	Wylye	446	1.7	14	73	11		Heywood (2003)
39	Lower Avon	1477	1.4	16	64	19		Heywood (2003)
40	Waldon	78	4	48	27	21		Nicholls (2001)
41	Upper Torridge	115	2	48	29	21		Nicholls (2001)
42	Torridge	258	2	47	28	23		Nicholls (2001)
43	Barle	128	6	85	1	8		Collins *et al.* (1997a,b)
44	Bathern	64	1	87	3	9		Collins *et al.* (1997a,b)
45	Lowman	54	2	54	40	4		Collins *et al.* (1997a,b)

Catchment no.[1]	River/ catchment	Area (km^2)	% Contribution[2] from topsoil from areas under:			% Contribution[2] from channel:		Study
			Wood-land	Pasture/moorland	Cultiv-ation	Banks	Drains	
46	Dart	46	3	82	11	5		Collins *et al.* (1997a,b)
47	Exe	601	3	72	20	5		Collins *et al.* (1997a,b)
48	Culm	276	–	30	60	10		Walling & Woodward (1995)
48	Culm	276	–	35	53	12		He & Owens (1995)

[1] See Fig. 1.

[2] In several cases contribution values were abstracted from histogram plots and represent approximate values.

[3] There were additional contributions from urban sources in this catchment i.e. STW solids 18% and road dust 22%.

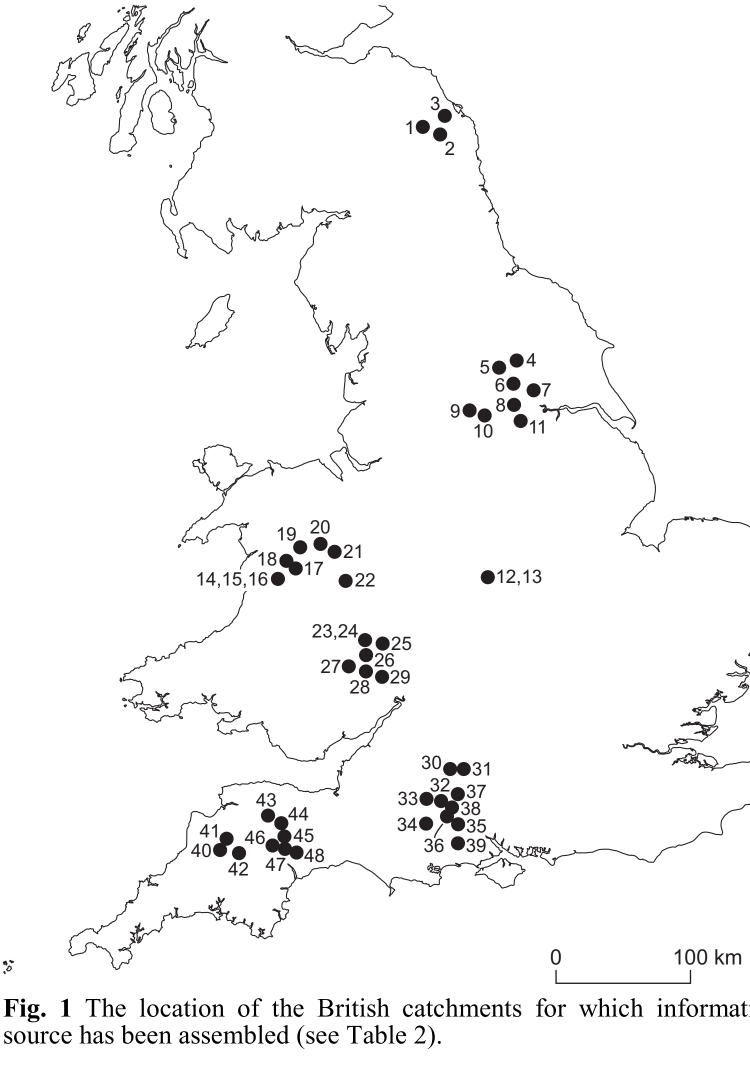

Fig. 1 The location of the British catchments for which information on sediment source has been assembled (see Table 2).

channels. Deep cracking of the clay soils in dry weather produced large macropores through which sediment mobilized from the soil surface could enter the field drains (see Walling *et al.*, 2002). Based on these findings, the sediment discharged from drains should therefore be seen as a contribution from the catchment surface, rather than from the channel system or subsurface sources.

The contribution of channel/subsurface sources to the sediment yields of the catchments included in Table 2, shows a substantial variation, ranging from <5% in several catchments to >50% in two catchments. Again, it is important to recognize that these values represent *relative* contributions, and therefore that, in absolute terms, the amount of sediment contributed by these sources could be much greater in a catchment with a high sediment yield, even though, when expressed as a proportion, its magnitude was significantly lower than in many other catchments. The range of values presented in Table 2 shows evidence of several controls. As might be expected, catchment size appears to exert a significant influence on the magnitude of the contribution from channel/subsurface sources, in that values for the very small catchments are all relatively low. This reflects the lack of well developed alluvial channels with eroding banks in most small catchments. Equally, there is a clear trend for channel/subsurface sources to assume greater relative importance as a sediment source in northern and western areas of the country, where contributions in excess of 30% are common. This trend could reflect two different but complementary controls. Firstly, the higher drainage densities, storm runoff intensity and channel mobility associated with upland areas could be expected to increase the importance of channel and bank erosion. Secondly, however, the denser, and often undisturbed, vegetation cover, the thin soils and the lack of cultivated areas, associated with upland areas, could be expected to limit sediment mobilization from the slopes of upland catchments and thereby result in an increase in the relative importance of channel/subsurface sources.

In attempting to generalize the data presented in Table 2, it is probably most useful to consider the relative importance of the catchment surface and channel and subsurface sources, as representing a key indicator of the sediment sources in a catchment. As indicated above, there continues to be considerable uncertainty as to the precise importance of channel/subsurface sources in contributing to catchment sediment yields in British catchments. Thus, whereas most attempts to develop risk assessment procedures, aimed at identifying those areas of the country where sediment inputs to the river system are likely to be high, have focused on estimating soil loss from the catchment surface (e.g. McHugh *et al*., 2002; Walling & Zhang, 2004), others, such as Hooke (1987), have emphasized the importance of channel bank erosion as a sediment source. The information regarding the relative importance of surface and channel and subsurface sources provided by the 48 British catchments listed in Table 2 has been summarized in Fig. 2, which presents frequency distributions for the contributions of the two contrasting source types. In this analysis, sediment issuing from field drains has been treated as having originated from surface sources. Although the sample of catchments used to produce Fig. 2 cannot be seen as entirely representative, either in terms of its spatial distribution, or its coverage of different terrain types and catchment sizes, it, nevertheless, affords a useful preliminary indication of the national scene.

Figure 2 highlights the wide range of the relative contributions of the catchment surface and channel/subsurface sources to the sediment yields of British rivers, with both sources accounting for up to 60% of the sediment yield in different catchments. There are a significant number of catchments where the channel/subsurface contribution exceeds 40% and also where the catchment surface contribution exceeds 90%.

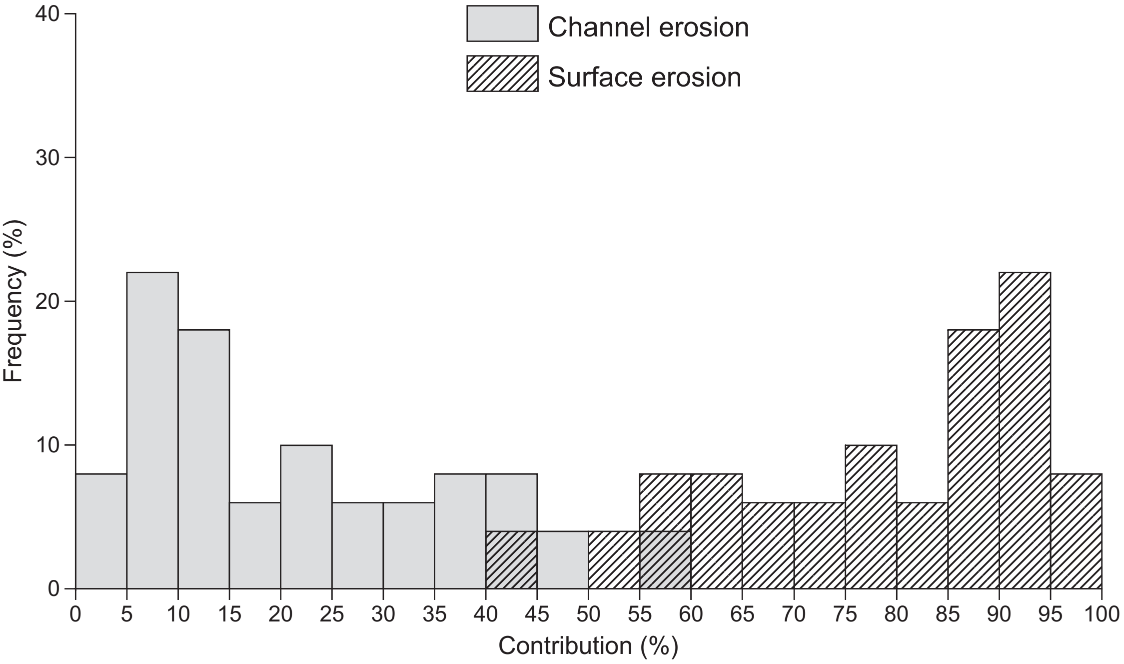

Fig. 2 Frequency distributions of the percentage contributions from surface sources and channel/subsurface sources for the study catchments.

This diversity emphasizes the many controls that influence the relative importance of these two main source types. These controls act both directly, by influencing the magnitude of the contribution from a particular source, and indirectly, by influencing the magnitude of the contribution from the alternative source, which will be reflected in the relative importance of the first source. In addition to the wide range of relative contributions, Fig. 2 also indicates that contributions in the range 85–95% from the catchment surface and 5–15% from channel/subsurface sources are probably most typical of British catchments, if such a generalization is required.

SOME IMPLICATIONS

The results presented above represent the first attempt to provide an assessment of suspended sediment sources in British catchments. The source fingerprinting approach represents the only effective and reliable means of undertaking such an assessment and the application of this approach in a consistent way across a substantial number of catchments has provided valuable new information. This information is important in providing an improved understanding of the sediment budgets of British catchments, although it needs to be combined with reliable information on the sediment yields of the catchments investigated, in order to evaluate the absolute magnitude of the contributions from the individual sources. A knowledge of the magnitude of these contributions would, in turn, provide valuable information on rates of erosion and sediment generation. In the case of surface contributions, however, the efficiency of slope–channel transfers (cf. Walling & Zhang, 2004) would need to be considered, such that the on-site erosion rates or rates of sediment mobilization could be substantially greater than those estimated from the proportion of the sediment yield.

The findings also have important implications for the design of sediment control or management strategies, in that they emphasize the need to consider measures to control both surface erosion and channel erosion, if a substantial reduction in the sediment yield from a catchment is to be achieved. In some areas of southern Britain, emphasis can reasonably be placed on surface erosion, but in many other parts of the country it will also be important to control channel erosion. In some locations this could be achieved by fencing off river channels to prevent stock access, since, in areas with relatively high stocking densities, degradation of channel banks by livestock trampling, rather than "natural" channel erosion, may be the main cause of increased sediment mobilization from channel sources. Much current work, aimed at implementing measures for the control of diffuse source pollution from agriculture, places emphasis on control of erosion and sediment mobilization from the catchment surface and thus agricultural fields. Although this is likely to prove effective in reducing fluxes of sediment-associated nutrients and contaminants, the findings presented above show that even total control of surface sources will, in most cases, not reduce such fluxes to zero, since channel sources could continue to supply appreciable amounts of sediment if they are not controlled. In some areas of the country, channel sources alone could be responsible for sediment mobilization equivalent to approximately 20–25 t km^{-2} year^{-1} and particulate-P exports of a similar magnitude to those from uncontrolled surface sources and of the order of 150 kg P ha^{-1}. These will need to be controlled if the overall P flux is to be appreciably reduced. The importance of field drains as a sediment source or transfer pathway in many lowland areas also introduces new challenges for sediment control, since tile drain networks must be seen as efficient delivery systems, such that it will be difficult to reduce sediment transfer once sediment has entered the tile drains.

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