Investigating the remobilization of fine sediment stored on the channel bed of lowland permeable catchments in the UK

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Abstract The bed of the main channel system represents an important store of fine sediment in lowland groundwater-fed catchments, in the UK, on account of the deposition promoted by their naturally subdued hydrological regimes, low channel gradients and the reduction of flows caused by water abstraction. Although a number of recent investigations have contributed to an improved understanding of the magnitude and spatio-temporal variability of fine sediment storage, much less is known about the role of remobilization of fine sediment from the channel bed in the suspended sediment fluxes from lowland permeable catchments. To address this shortcoming, the authors report the use of a composite fingerprinting technique, incorporating uncertainty analysis, to investigate the magnitude and timing of the remobilization of fine sediment sequestered on the channel bed of three lowland permeable catchments in the UK. The findings are used to assess the relative contributions of three principal potential sediment sources to the sediment loads sampled at the catchment outlets, namely: fine sediment remobilized from the channel bed of the main stem; suspended sediment inputs from tributary sub-catchments; and sediment originating from channel banks along the main channel.

Key words remobilization; sediment fingerprinting; u sediment storage; ncertainty analysis

INTRODUCTION

Storage of fine-grained (<63 μm) sediment on the channel bed of river systems has become increasingly well-documented (e.g. Walling *et al.*, 1998; Wood & Armitage, 1999) and is considered to be responsible for a number of important environmental problems. By virtue of its detrimental impact on fluvial habitat quality, increased deposition and sediment storage can, for example, contribute to changes in macrophyte (Clarke & Wharton, 2001) and macroinvertebrate (Richards & Bacon, 1994) communities, as well as to declining Salmonid populations (Rabeni & Smale, 1995).

On account of their stable seasonal flow regimes, growing pressures from water abstraction and increasing fine sediment loadings due to land-use change associated with the expansion of cereal or fodder maize cultivation and the removal of buffering water meadows, lowland groundwater-fed catchments in the UK are especially susceptible to bed storage of fine-grained sediment (Walling & Amos, 1999; Collins *et al.*, 2005). Bed sediment storage can have a profound influence on the transfer and fate of nutrients and contaminants (e.g. Jain & Ram, 1997), thereby emphasizing its wider significance in important catchment diffuse pollution issues.

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Despite recent advances in our understanding of the magnitude of fine-grained sediment storage on the channel bed of lowland groundwater-fed systems in the UK and its importance in relation to the catchment suspended sediment yield, far less is understood with respect to the remobilization of such sediment. Research undertaken outside the UK has, nevertheless, demonstrated that remobilization of fine sediment from the channel bed can represent an important component of the catchment sediment budget (Meade, 1982) and can be equally important in governing contaminant dispersal (Macklin & Klimek, 1992).

To address the need for an improved understanding of the remobilization of fine sediment sequestered on the main channel bed of lowland groundwater-fed catchments in the UK, this contribution reports the findings of a preliminary investigation based on the fingerprinting approach, undertaken as part of the LOCAR (Lowland CAtchment Research) thematic programme funded by the Natural Environment Research Council.

STUDY AREAS

The investigation of the remobilization of fine sediment from the channel bed was undertaken in the Frome and Piddle catchments in Dorset and the upper Tern catchment in Shropshire, UK (Fig. 1). The Frome (~437 km^2) and Piddle (~183 km^2) study areas are underlain by complex geology dominated by Chalk, but with outcrops of Jurassic limestones and Cretaceous Upper Greensand in the headwaters and extensive Tertiary sands and gravels in the lower reaches. Steep slopes dominate the upper portions of each catchment, whilst a well-developed flood plain exists further downstream. Average annual rainfall decreases eastwards from 1040–860 mm in the Frome and 1020–840 mm in the Piddle. Land use is predominantly mixed arable and grassland farming.

The upper Tern (~231 km^2) catchment is underlain by Permo-Triassic sandstones and a small outcrop of Upper Carboniferous mudstones. Land use is dominated by cereal and root crop farming, but dairying is widespread in the middle portions of the study area. Mean annual precipitation is 730 mm in the upper and middle, and 707 mm in the lower reaches. The topography is characterized by gentle slopes.

METHODS

The approach

The remobilization of fine sediment sequestered on the main channel bed of each study river was investigated using the fingerprinting approach. Sediment fingerprinting relies upon the link between the geochemical properties of suspended sediment and those of its potential sources. Assuming the potential sources can be distinguished on the basis of their geochemical properties or "fingerprints", the provenance of suspended sediment fluxes at a catchment outlet can be established using a comparison of the properties of that sediment with those of the individual potential sources. Although a range of fingerprint properties has been successfully employed as means of discriminating

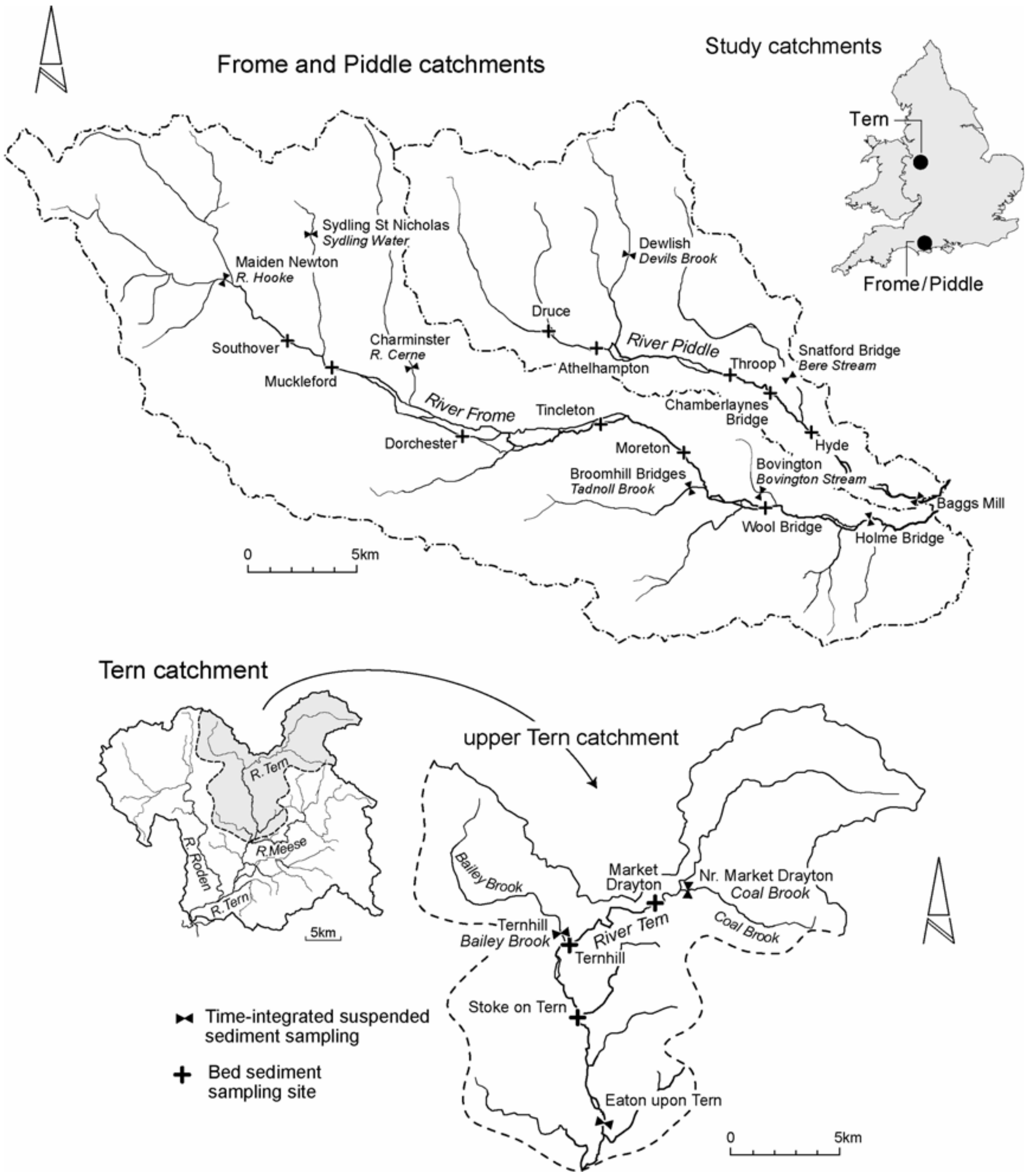

Fig. 1 The location of the study areas and the tributary, channel bed and catchment outlet sampling sites.

potential sediment sources, including mineralogy, colour, mineral magnetism, environmental radionuclides and geochemical composition, it is now considered essential to use "composite fingerprints" comprising a range of different diagnostic properties (Collins & Walling, 2004). For the purpose of this investigation, the provenance of suspended sediment sampled at the study catchment outlets was characterized in terms of three principal potential sources, namely: fine sediment sequestered on the bed of the main channel; suspended sediment transported by the main tributaries; and eroding channel banks along the main stem. It was assumed that potential changes in the geochemical properties of fine sediment associated with its storage on the channel bed would provide the basis for discriminating such sediment from the remaining two principal potential sources.

Fieldwork

Representative samples of fine sediment stored on the bed of the main channel of each study river were collected using the method proposed by Lambert & Walling (1988). A purpose-built metal cylinder (height = 1 m; area = 0.16 m^2) was carefully lowered onto, and pushed into, the channel bed in order to create a seal and minimize the winnowing of fines. A metal rod was used to agitate the water and the upper 5 cm of the channel bed enclosed within the cylinder and a bulk (25 L) sample of the re-suspended sediment was collected using a submersible pump powered by a portable generator. Channel bed sampling sites (see Fig. 1) were selected to be representative of the different reaches comprising the main stem of each study river.

Representative samples of suspended sediment were collected from the individual tributaries and the outlet of each study river (see Fig. 1) using a time-integrating sampler (Phillips *et al.*, 2000). Two samplers were installed at each sampling site. Sampling of channel banks (n = 20 (Frome); 20 (Piddle); 29 (Tern)) along the main stem of each study river targeted actively eroding channel margins. Composite samples (approx. 500 g each) were collected using a trowel.

Laboratory analyses

Upon return to the laboratory, all bulk samples of fine bed and suspended sediment were allowed to settle for 48 h. The sediment was subsequently recovered by centrifugation, freeze-dried, disaggregated and homogenized using a 63 μm sieve. Channel bank samples were oven-dried at 40^{o}C, disaggregated and sieved through a 63 μm mesh. Selection of potential fingerprint properties was based on the need to include a range of determinands responding to differing environmental controls and which therefore provided a substantial degree of independence and more reliable source discrimination. The total concentrations of Al, As, Ba, Bi, Ca, Cd, Ce, Co, Cr, Cs, Cu, Dy, Er, Eu, Fe, Ga, Gd, Ge, Hf, Ho, La, Li, Mg, Mn, Mo, Na, Nd, Ni, Pb, Pd, Pr, Rb, Sb, Sc, Sm, Sn, Sr, Tb, Ti, Tl, V, Y, Yb, Zn and Zr were analysed using ICP-MS, following acid digestion. C and N were measured by pyrolysis using an automatic analyzer. Total P was determined colorimetrically using UV/Visible spectrophotometry, after extraction using a molybdenum blue procedure. The absolute grain size composition of all samples was measured using a laser diffraction granulometer, following pre-treatment to remove the organic fraction with hydrogen peroxide and chemical/ultrasonic dispersion.

Data processing

Application of the fingerprinting approach to investigate the remobilization of fine sediment sequestered on the main channel bed of the study rivers involved two key stages, namely: source discrimination; and source apportionment. The ability of fingerprint properties to discriminate the three primary potential sediment sources identified for this particular investigation was tested statistically using the two-stage procedure proposed by Collins *et al.* (1997). In stage one, the Kruskal-Wallis H-test was used as a basis for eliminating redundant fingerprint properties, by examining the ability of individual determinands to distinguish the three principal sediment sources in an unequivocal manner. In stage two of the source discrimination procedure, Discriminant Function Analysis (DFA) was used to identify from the properties passing the Kruskal-Wallis H-test, the optimum composite fingerprint for correctly classifying all the samples collected to represent each primary potential sediment source. The minimization of Wilks' lambda provided a stepwise selection algorithm for identifying the optimum composite fingerprint. Table 1 shows the final results of the DFA for identifying the optimum composite fingerprint for distinguishing the samples collected to represent the three primary potential sediment sources contributing to the suspended sediment sampled at the outlet of the Frome study catchment during the period 5 February 2003–12 March 2003.

Table 1 The final results of the stepwise Discriminant Function Analysis for identifying the optimum composite fingerprint for discriminating the three principal potential sediment sources contributing to the suspended sediment flux sampled at the outlet of the Frome study catchment during the period 5 February 2003–12 March 2003.

Step	Fingerprint property selected	% samples collected to represent the three principal sediment sources classified correctly
1	C	86.2
2	Ba	89.7
3	Al	93.1
4	Ga	96.6
5	Zn	100.0

The two-stage statistical source discrimination procedure was repeated for each catchment outlet suspended sediment sampling period because the bed sediment stored along the main stem and the tributary suspended sediment outputs were re-sampled during the time period represented by the time-integrated outlet sediment samples. Consequently, a total of seven composite fingerprints were identified to discriminate the three primary sources contributing to the samples of suspended sediment collected at the outlets of each of the Frome and Piddle catchments, whilst eight composite fingerprints were used for the same purpose in the Tern study area. The individual composite fingerprints correctly distinguished between 89.7–100% of the samples collected to represent each of the three primary sediment sources for the discrete time-integrated sampling periods at the study catchment outlets.

Sediment source apportionment was estimated using the multivariate sediment-mixing model described by Collins *et al.* (1997). The mixing model optimized estimates of the relative contributions from the three primary sediment sources by minimizing the sum of squares of the weighted relative errors, viz.:

$$\sum_{i=1}^{n}\left\{\left(C_i-\left(\sum_{s=1}^{m}P_s S_{si} Z_s O_s\right)\right)/C_i\right\}^2 W_i \qquad (1)$$

where: C_i = concentration of fingerprint property (i) in catchment outlet time-integrated suspended sediment sample; P_s = the optimized percentage contribution from source category (s); S_{si} = mean concentration of fingerprint property (i) in source category (s); Z = particle size correction factor for source category (s); O = organic matter content correction factor for source category (s); W_i = tracer specific weighting; n = number of fingerprint properties comprising the optimum composite fingerprint; m = number of sediment source categories.

Two linear boundary constraints were imposed on the mixing model calculations to ensure that the relative contribution from each potential sediment source was non-negative (equation (2)) and that the contributions from the three primary sources summed to unity (equation (3)):

$$0 \leq P_s \leq 1 \tag{2}$$

$$\sum_{s=1}^{n} P_s = 1 \tag{3}$$

A Monte Carlo routine (cf. Rowan *et al.*, 2000) was used to quantify the uncertainty associated with estimates of the mean relative contributions of the three primary sediment sources to each sample of suspended sediment collected at the study catchment outlets. The mean and standard deviation of the measurements of each fingerprint property made on the samples collected to represent the three primary sources during each sampling period were used to construct cumulative normal distributions within a random number generator. The mixing model was repeatedly solved for a total of 1000 realizations by randomly sampling values for each property comprising a composite fingerprint from the corresponding normal distributions. 95% confidence limits for the relative contribution from each individual source to each sample of suspended sediment collected at each catchment outlet were estimated using the standard error of the mean associated with the results of the 1000 repeat iterations.

The load-weighted mean relative contribution of each of the three primary sources to the samples of suspended sediment retrieved at each study catchment outlet over the entire duration of the sampling period was calculated as:

$$P_{sw} = \sum_{s=1}^{n} P_{sx} \left[\frac{L_x}{L_t} \right] \tag{4}$$

where: P_{sw} = weighted relative contribution from source category (s); P_{sx} = relative contribution from source category (s) for catchment outlet time-integrated suspended sediment sample (x); L_x (g m^{-2}) = the suspended sediment load estimate in association with catchment outlet time-integrated suspended sediment sample (x); L_t (g m^{-2}) is the sum of the suspended sediment load estimates associated with (n) time-integrated sediment samples collected at the catchment outlet.

RESULTS AND DISCUSSION

The estimated relative contributions from the three primary sources to the time-integrated suspended sediment samples collected at the outlet of each study catchment are presented in Fig. 2. These estimates can be readily used in conjunction with

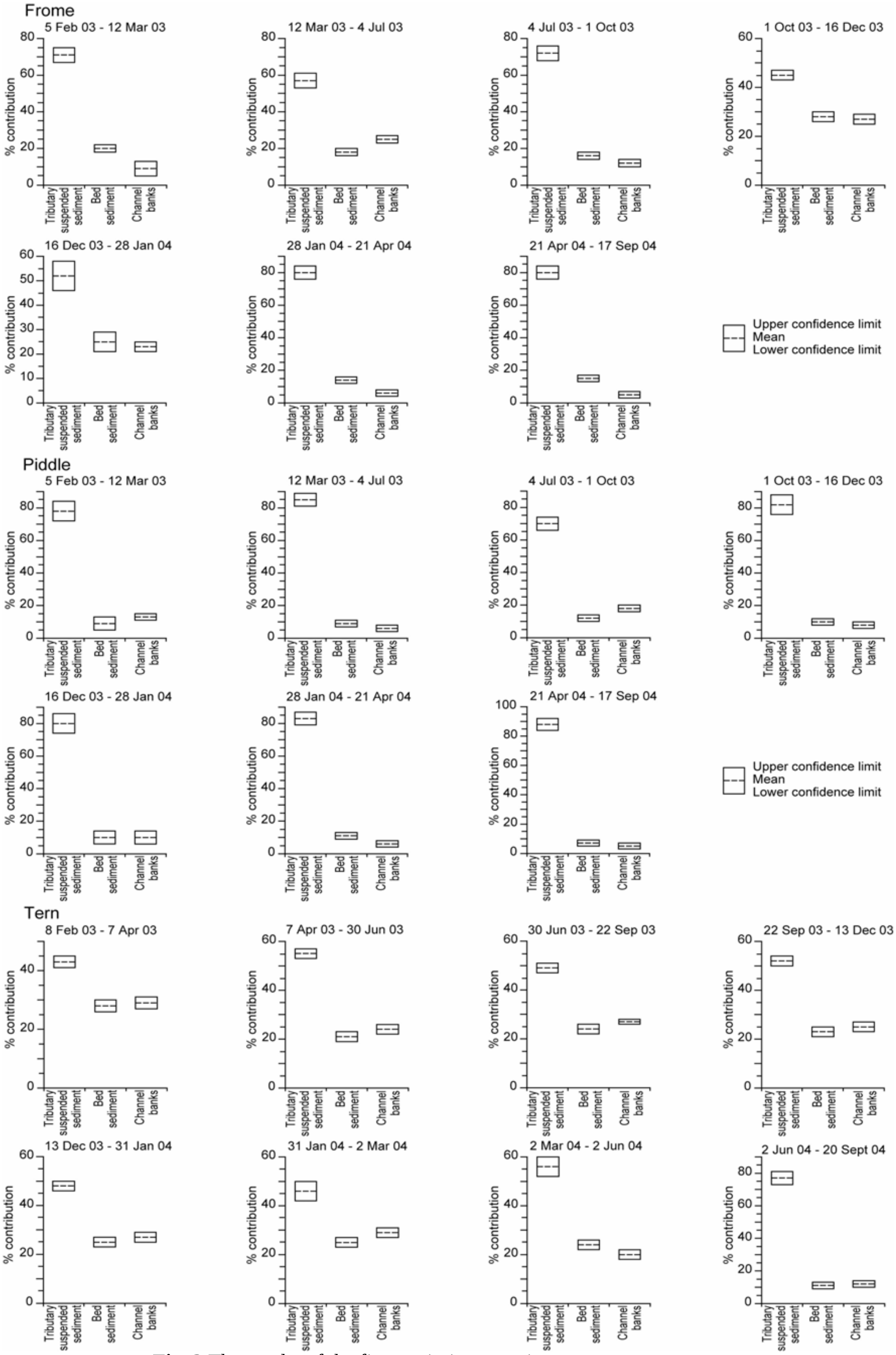

Fig. 2 The results of the fingerprinting exercise.

sediment flux measurements at the outlet to assess the actual load derived from a particular source per unit time. It is therefore important to recognize that a smaller relative contribution can be more significant in terms of its absolute magnitude and *vice versa*. The provenance of the suspended sediment samples collected at the outlet of the Frome catchment is dominated by tributary inputs, with their contributions representing, for example, 52 ± 6% (426–537 t) and 80 ± 4% (547–605 t) during the periods 16 December 2003–28 January 2004 and 28 January 2004–21 April 2004, respectively. Eroding channel banks along the main stem contributed between 5 ± 2% (11–25 t) and 23 ± 2% (195–232 t) during the periods 21 April 2004–17 September 2004 and 16 December 2003–28 January 2004, respectively. The remobilization of fine bed sediment does, however, also represent an important source of the suspended sediment flux sampled at the catchment outlet. For example, during the periods 1 October 2003–16 December 2003 and 16 December 2003–28 January 2004, bed sediment remobilization contributed 28 ± 2% (186–214 t) and 25 ± 2% (213–250 t). The load-weighted mean relative contribution from bed sediment remobilization over the duration of the entire sampling period was 20 ± 2% (796–973 t).

For the Piddle study catchment, suspended sediment inputs from the tributary sub-catchments again represent the principal source of sediment flux at the outlet, contributing, for instance, 78 ± 6% (158–185 t) and 85 ± 4% (167–183 t) between 5 February 2003–12 March 2003 and 12 March 2003–4 July 2003, respectively (see Fig. 2). Eroding channel banks bordering the main stem contributed between 5 ± 2% (1–2 t) during 21 April 2004–17 September 2004 and 13 ± 2% (24–33 t) during 5 February 2003–12 March 2003. The remobilization of fine bed sediment stored along the main stem represented a less significant source in the Piddle study area, with its contribution varying between 7 ± 2% (1–2 t) during the period 21 April 2004–17 September 2004 and 9 ± 4% (11–29 t) during the period 5 February 2003–12 March 2003. Over the duration of the sampling period, the load-weighted mean contribution from bed sediment remobilization was 10 ± 2% (62–93 t).

In the Tern study catchment, the remobilization of fine sediment sequestered on the bed of the main stem represents a significant source of the suspended sediment sampled at the catchment outlet, contributing, for example, 25 ± 2% (173–203 t) and 25 ± 2% (172–201 t) during the periods 13 December 2003–31 January 2004 and 31 January 2004–20 March 2004, respectively (see Fig. 2). Main stem channel banks contributed 27 ± 2% (188–218 t) and 29 ± 2% (201–231 t) and tributary inputs 48 ± 2% (346–376 t) and 46 ± 4% (313–373 t) during the same periods. During the sampling period, the load-weighted mean contribution from bed sediment remobilization was 24 ± 2% (500–591 t).

PERSPECTIVE

The remobilization of fine sediment stored on the main channel bed represents a significant source, both in relative terms and absolute magnitude, of the suspended sediment flux sampled at the study catchment outlets. Remobilization of fine bed sediment is therefore an important component of the suspended sediment budgets of lowland groundwater-fed catchments in the UK. The findings of this novel application of sediment fingerprinting have important implications for the transfer and fate of sediment-associated nutrients and contaminants.

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