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Storage of fine-grained sediment and associated contaminants within the channels of lowland permeable catchments in the UK

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Abstract Storage of fine-grained (<63 μm) sediment and associated contaminants within river channels frequently represents an important component of a catchment's suspended sediment and geochemical budget. It has also been increasingly identified as a cause of degradation of aquatic habitats. Such problems are particularly evident in lowland permeable catchments in the UK, where the groundwater dominated hydrological regimes with a lack of high magnitude flows are conducive to sediment accumulation. In-channel storage of fine-grained sediment and a range of sediment-associated contaminants (C, Cd, Co, Cr, Cu, N, total P, Pb, Zn) has been documented for a total of 45 sampling sites using the findings of a regular bimonthly field sampling campaign in three contrasting lowland permeable catchments. The data demonstrate the spatial and temporal variability of both sediment storage and its contaminant content and provide a means of estimating the total storage of fine-grained sediment and associated contaminants within the main channel system of each study area.

Key words channel storage; contaminants; fine-grained sediment; sediment budgets

INTRODUCTION

The deposition and storage of fine sediment in river channels is widely considered to be responsible for a number of important environmental problems currently reported for catchments in the UK. Increased sediment accumulation can have numerous deleterious effects on aquatic habitats and is, for example, thought to be a major factor contributing to declining salmonid stocks by virtue of its detrimental impact on spawning gravels (Acornley & Sear, 1999) and to widespread changes in macrophyte (Clarke & Wharton, 2001) and invertebrate (Scullion, 1983) populations. River channel sediment storage frequently poses problems for floodwater conveyance and control works and increasing recognition of the role of fine sediment deposition in the transfer and fate of sediment-associated nutrients (House & Warwick, 1999) and contaminants (Rees *et al.*, 1999) has emphasized its wider significance in relation to nonpoint pollution problems. Improved information on sediment transfer and storage is therefore critical for the sustainable management of UK watercourses within the context of the recently adopted EU Water Framework Directive.

Lowland permeable catchments in the UK are particularly prone to fine sediment storage and the associated impacts, because these systems are typically characterized by stable seasonal flow regimes, which are less episodic than those observed in impermeable areas and which are therefore conducive to sediment accumulation. Groundwater abstraction frequently reduces river discharges and thus sediment transport capacity and these potential problems are further compounded during low-rainfall years. Furthermore, recent land use changes in lowland agricultural regions of the UK, typified by an expansion of cereal and fodder maize cultivation and removal of water meadows, are responsible for generating increased sediment loadings and the excessive macrophyte growth characterizing lowland permeable catchments serves to enhance the potential for deposition and storage of the fines delivered to local river channels. There is, nonetheless, a dearth of information regarding both the magnitude and spatial and temporal variability of fine sediment storage in groundwater-dominated rivers.

To address the need for an improved understanding of the fine sediment dynamics of lowland fluvial systems in the UK, the sediment budgets of three contrasting lowland permeable catchments are currently being investigated as part of a national research programme (LOCAR) funded by the Natural Environment Research Council. One component of this work comprises a detailed study of channel bed storage of fine sediment and associated contaminants and a selection of the findings are summarized in this contribution.

STUDY AREAS

Three lowland permeable catchments, i.e. the Frome/Piddle, Tern and Pang/Lambourn, have been selected for investigation by the LOCAR programme. The rivers Frome (~ 425 km^2) and Piddle (~183 km^2) in Dorset, UK, represent the main study area (see Fig. 1). Both catchments are largely underlain by Chalk, although outcrops of Jurassic limestones and Cretaceous Upper Greensand exist in the headwaters, whilst Tertiary sands and gravels are found in the lower reaches. Drift deposits are widespread and comprise clay-with-flints, head and alluvium. The topography in the upper portions of each catchment is dominated by steep slopes and elevations of ~200 m a.s.l., whilst their lower reaches are characterized by gentle relief and a well-developed floodplain. Land use is predominantly agricultural, with a mixture of grassland and cereals. Average annual precipitation is ~962 mm in the upper Frome and ~888 mm in the upper Piddle.

In contrast, the upper Tern catchment (~ 220 km^2) in Shropshire, UK (see Fig. 1), mainly drains Permo-Triassic sandstones, although an outcrop of Upper Carboniferous mudstones exists in the Coal Brook sub-catchment. Mean annual precipitation is ~707 mm in the lower reaches. Land use is dominated by intensive cereal and root crop production, although dairy farming is widespread in the middle portions of the study area. Altitudes are typically 100 m a.s.l. in the upper reaches, decreasing to 70 m a.s.l. or less in the lower study catchment. Gently undulating relief dominates the topography, with steeper slopes being observed in the Coal Brook sub-catchment.

The Pang (~160 km^2) and Lambourn (~234 km^2) catchments are principally underlain by the main Chalk aquifer of Berkshire, UK (see Fig. 1). Small outcrops of Cretaceous Upper Greensand, river terrace drift deposits and clay-with-flints also exist.

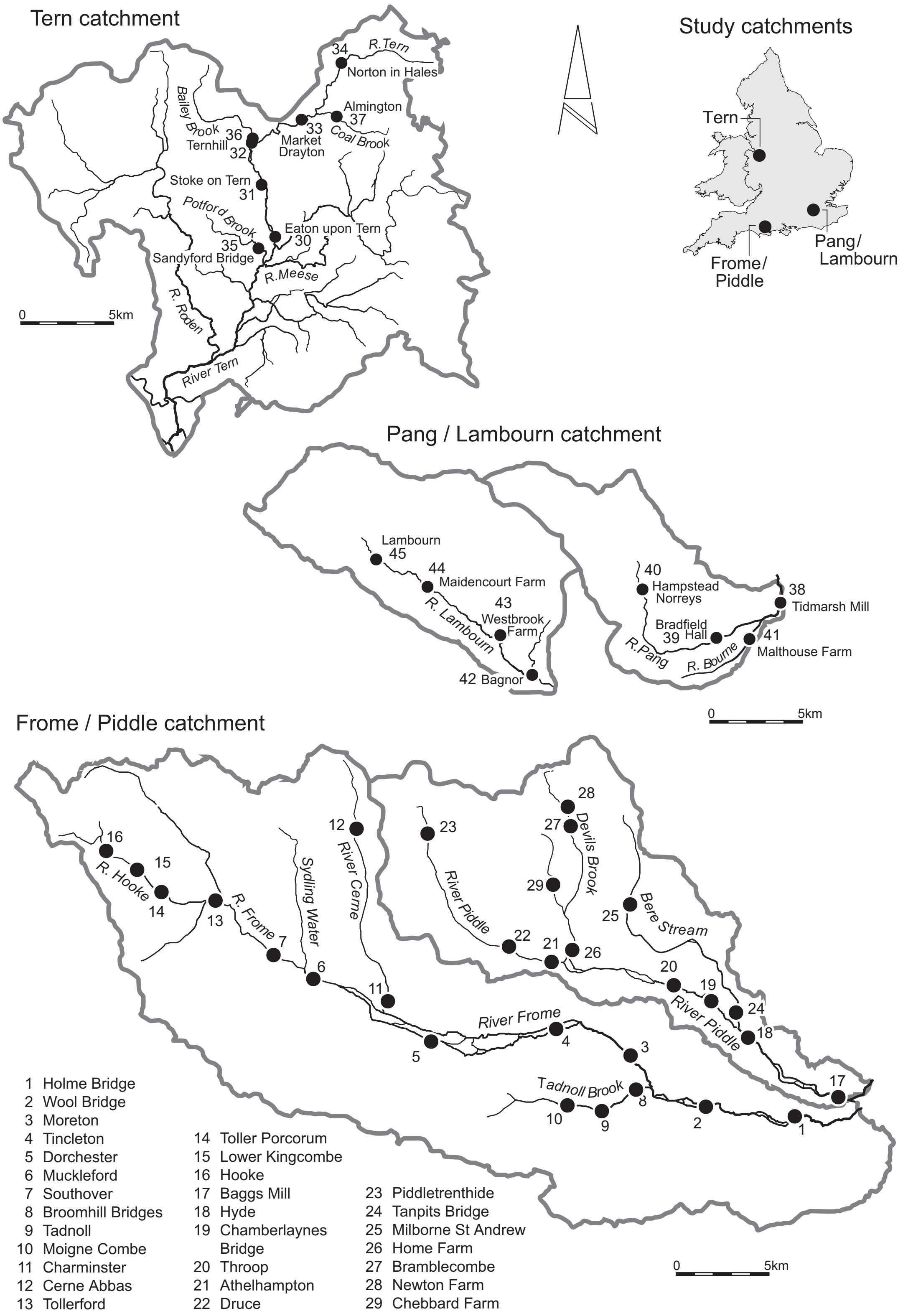

Fig. 1 The location of the study areas and the individual bed sediment sampling sites.

Average annual precipitation lies in the range 692–732 mm. The Pang is intensively farmed for cereals, but outdoor pigs and Christmas tree cultivation have recently expanded. Less intensive mixed farming characterizes the Lambourn. Steeply sloping dry valleys and interfluves with altitudes of >200 m a.s.l. typify the Lambourn, whilst the Pang is less steeply sloping with altitudes of ~120 m a.s.l. in its headwaters.

METHODS

Field sampling

Measurements (total n = 404) of fine-grained bed sediment storage were made approximately bimonthly along the main channels of the study rivers over the period January 2003–September 2004. Each sampling site was selected to be representative of the channel bed in the surrounding reach. The approach employed is described in Lambert & Walling (1988). A metal cylinder (height = 1.0 m; surface area = 0.16 m^2) was carefully lowered onto, and pushed into, the channel bed in order to create a seal and a metal rod was then used to stir the water and agitate the upper 5 cm of the channel bed as a means of mobilizing the fine sediment stored both as a surface drape and within the river bed matrix. A representative aliquot of the turbid water was taken using a 0.5-l bottle and this was used to provide an estimate of sediment storage. This procedure was repeated twice at each sampling site, in order to take account of local spatial variability in sediment storage resulting from variations in water depth and channel bed morphology or texture. One sample was collected in the thalweg, where sediment storage was considered to be lowest, and another adjacent to the river bank visually exhibiting the greatest storage, with the average of the two being taken to provide a meaningful estimate of sediment storage at each location. In addition, a bulk sample of the water and remobilized sediment from the location used to represent the area of maximum sediment storage at each sampling site was pumped into an acid-washed 25-l polyethylene can in order to provide sufficient sample mass for chemical analyses. Flow conditions or safety constraints inevitably resulted in the coverage of the sampling sites being incomplete on some occasions.

Laboratory analyses

The sediment concentrations associated with the 0.5-l sample bottles ($C_s(t)$, g l^{-1}) were determined by filtration and the amount of fine sediment released per unit surface area of channel bed ($B_r(t)$, g m^{-2}), which was used as a measure of sediment storage, was estimated as:

$$B_r(t) = \frac{C_s(t)W_v(t)}{A} \tag{1}$$

where $W_v(t)$ is the volume of water enclosed in the sampling cylinder (l), calculated as the product of the depth of water in the cylinder and its surface area (A: m^2).

The bulk water samples were allowed to settle before the clear supernatant was decanted and the sediment recovered using centrifugation. Following freeze-drying, the sediment samples were gently disaggregated and screened through a 63 μm sieve, because this size fraction is considered to be the most chemically active and appropriate for investigations of sediment-associated contaminants (Horowitz, 1991). Total metal concentrations (Cd, Co, Cr, Cu, Pb, Zn) were determined using ICP-MS after acid digestion with concentrated HNO_3 and HCl (Allen, 1989). The total P content was determined by UV Visible spectrophotometry following extraction using the molybdenum blue method described by Mehta *et al.* (1954). C and N concentrations were measured using a Carlo Erba 1400 ANA automatic analyser.

RESULTS AND DISCUSSION

Channel bed storage of fine sediment and associated contaminants

Mean values for the storage of <63 μm sediment on and within the upper 5 cm of the channel bed within each study catchment during the study period are presented in Table 1. For the Frome, values range from 410 to 2630 g m^{-2}, whilst for the Piddle, estimates lie in the range 260–4340 g m^{-2}. The ranges of the estimates shown in Table 1 demonstrate the considerable spatial variability of fine sediment storage within the study areas and the typical values are directly comparable with those documented for other rivers in the UK (e.g. Walling *et al.*, 1998). The coefficients of variation (*CV*) in Table 1 reflect the temporal variability of the storage estimates at an individual sampling site. The values are typically 80–90%, indicating that such variability can be appreciable.

Table 2 presents values for the mean contaminant content of the <63 μm fraction of fine sediment collected from the channel bed sampling sites within each study catchment. Concentrations of the metal contaminants are comparable with those reported for non-polluted agricultural areas in sediment quality guidelines (e.g. Long *et al.*, 1995) or by individual case studies (e.g. Bubb & Lester, 1994; Kronvang *et al.*, 2003). Total P concentrations range from 783 μg g^{-1} in the Pang to 1355 μg g^{-1} in the Frome. Concentrations of Cd are consistently lower than those measured for the remaining contaminants ranging, for example, from 0.3 μg g^{-1} in the Pang to 1.2 μg g^{-1} in the Tern. The highest metal concentrations are consistently associated with Zn, ranging from 92 μg g^{-1} in the Pang to 179 μg g^{-1} in the Frome (Table 2). Table 3 presents estimates of mean sediment-associated contaminant storage for the study rivers, calculated as the product of the average fine-grained sediment storage (Table 1) and the typical concentrations of each contaminant associated with that sediment (Table 2).

Figure 2 shows temporal variations in the storage of channel bed fine sediment and a selection of associated contaminants for the most downstream sampling site in each study area during the study period. The data serve to illustrate the complexity of temporal variations in sediment and contaminant storage, although some trends are evident. At each site, fine sediment storage is generally lower during the spring/ summer months of March–July/September and varies, for example, from a minimum of 370 g m^{-2} in March 2004 to a maximum of 1630 g m^{-2} in February 2003 with a *CV* of 49%, for the Frome at site 1 and from 400 g m^{-2} in May 2004 to 3980 g m^{-2} in February 2003 with a *CV* of 110%, for the Pang at site 38. The temporal patterns exhibited by the estimates of channel bed storage of total P appear to be primarily

Table 1 Summary information on the channel bed storage of <63 μm sediment at individual sampling sites within each study catchment during the period January 2003–September 2004.

River	*n**	Mean storage (g m^{-2})	Range (g m^{-2})	Mean *CV* (%)
Frome	134	918	410–2630	80
Piddle	116	1580	260–4340	77
Tern	80	2391	860–5500	96
Pang	38	1065	470–2290	85
Lambourn	36	1255	770–1760	78

**n* = total number of samples provided by the field sampling campaign within each study catchment.

Table 2 The mean contaminant content of the <63 μm fraction of the sediment collected from the channel bed at the individual sampling sites within each study catchment during the period January 2003–September 2004.

River	C (μg g^{-1})	Cd (μg g^{-1})	Co (μg g^{-1})	Cr (μg g^{-1})	Cu (μg g^{-1})	N (μg g^{-1})	Total P (μg g^{-1})	Pb (μg g^{-1})	Zn (μg g^{-1})
Frome	102563	1.1	15.1	15.1	21.5	7062	1355.2	38.1	179.1
Piddle	110846	0.9	10.8	15.2	28.8	7000	1151.1	44.5	175.5
Tern	86875	1.2	10.2	29.5	40.4	7000	1337.5	55.8	183.1
Pang	82750	0.3	7.3	12.4	20.4	5500	782.8	38.0	91.8
Lambourn	139500	0.4	5.4	13.1	37.8	8000	920.0	84.5	135.7

Table 3 Estimates of the mean sediment-associated storage of contaminants for the individual sampling sites within each study catchment during the period January 2003–September 2004.

River	C (g m^{-2})	Cd (g m^{-2})	Co (g m^{-2})	Cr (g m^{-2})	Cu (g m^{-2})	N (g m^{-2})	Total P (g m^{-2})	Pb (g m^{-2})	Zn (g m^{-2})
Frome	94.15	0.0010	0.0139	0.0139	0.0197	6.48	1.24	0.0350	0.164
Piddle	175.14	0.0014	0.0171	0.0240	0.0455	11.06	1.82	0.0703	0.277
Tern	207.72	0.0029	0.0244	0.0705	0.0966	16.74	3.20	0.1334	0.438
Pang	88.13	0.0003	0.0078	0.0132	0.0217	5.86	0.83	0.0405	0.098
Lambourn	175.10	0.0005	0.0068	0.0164	0.0474	10.04	1.15	0.1060	0.170

governed by temporal variations in fine sediment storage. Estimates of the total P content of sediment from each sampling site are, nevertheless, highly variable, with the *CV* ranging from 45% for the Piddle at site 17 to 79% for the Lambourn at site 42. No distinct seasonal pattern is observed in the bed sediment-associated storage of total P. Temporal patterns in the storage of Pb and Zn also appear to be principally controlled by corresponding variations in bed sediment storage as opposed to the fluctuating concentrations of these contaminants. Bimonthly estimates of Pb content are more variable than those for Zn, with the *CV* ranging from 25% for the Tern at site 30 to 169% for the Piddle at site 17, compared to 17% for the Lambourn at site 42 and 59% for the Frome at site 1, respectively.

Total channel bed storage of fine sediment and associated contaminants

The data provided by the individual sampling sites were scaled up to estimate the mean total channel bed storage of fine sediment and associated contaminants in the study

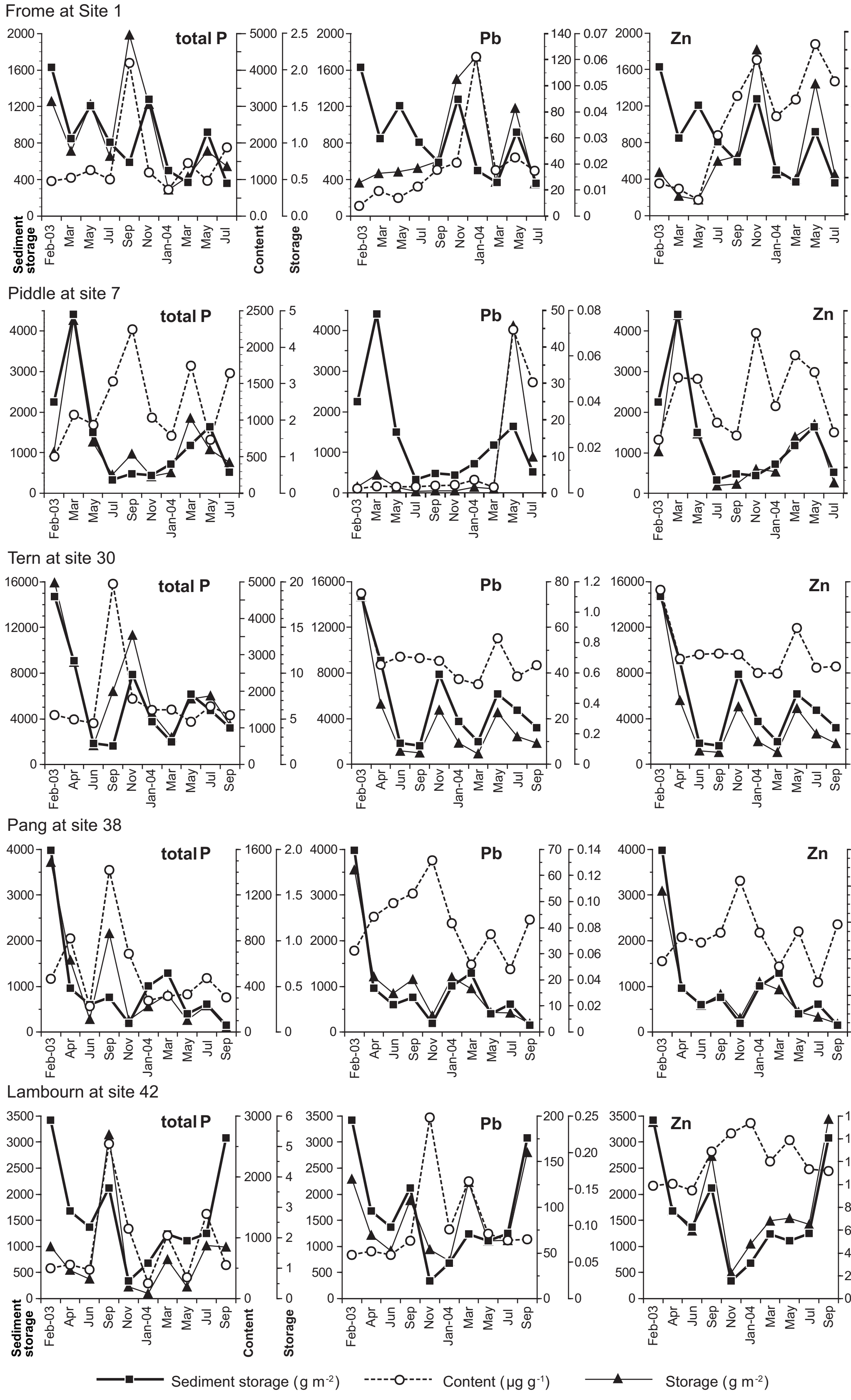

Fig. 2 Temporal variations in fine sediment storage and the content and storage of total P, Pb and Zn for a selection of sampling sites.

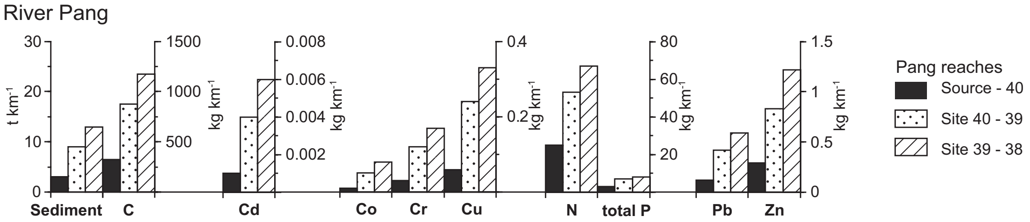

Fig. 3 Downstream trends in mean specific fine sediment and contaminant storage along the channel bed of the Pang study area.

catchments. Each study river was divided into reaches defined by the individual sampling sites and estimates of fine sediment and contaminant storage for the latter were assumed to be representative of those reaches (cf. Walling *et al.*, 2003). The mean total fine sediment or contaminant storage $S_c(t)$ (t or kg) was calculated as:

$$S_c(t) = \sum_{i=1}^{n} \left(S_{bi}(t) + S_{bi+1}(t)\right) / 2\left(W_{br} L_{br} k\right) \qquad (2)$$

where $S_{bi}(t)$ and $S_{bi+1}(t)$ = mean sediment or contaminant storage (g m^{-2}) at sampling site i and $i + 1$ (i.e. the next site upstream); W_{br} = average channel bed width for each reach (m); L_{br} = channel bed length for each reach (m); k = a dimensionless scaling factor.

Figure 3 examines, as an example, downstream trends in the mean specific (i.e. per unit length of bed) fine sediment and contaminant storage within the individual reaches comprising the main stem of the Pang. Specific fine sediment storage increases downstream, rising from 3 to 13 t km^{-1}. Similarly, the specific storage of each contaminant is greatest in the lower reaches of this study area. For example, estimated sediment-associated specific C storage increases downstream from 322 to 1175 kg km^{-1}, total P from 3 to 8 kg km^{-1} and Zn from 0.29 to 1.22 kg km^{-1}.

Estimates of the mean total channel bed storage of fine sediment and associated contaminants within the main channels of each study river are presented in Table 4. In an attempt to place these estimates within the broader context of the overall behaviour of the study rivers, the information summarized in Table 4 was compared with estimates of the mean annual suspended sediment and associated contaminant fluxes at the corresponding catchment outlet. Because continuous records of turbidity and river discharge being assembled by the LOCAR programme were not readily available when these comparisons were made, the suspended sediment loads at the study catchment outlets have been estimated using the probable range of sediment yield scenarios (i.e. 5–15 t km^{-2} year^{-1}) and these estimates have been combined with information on the typical contaminant content of suspended sediment fluxes during the study period provided by a routine suspended sediment sampling programme within each study area.

The estimates presented in Table 5 serve to emphasize the significance of channel bed storage of fine sediment in relation to the suspended sediment flux at the outlet of each study catchment. For example, assuming sediment yields lie in the range 5 to 15 t km^{-2} year^{-1}, channel bed fine sediment storage is estimated to represent between 20–80% and 7–27% of the annual suspended sediment loads in the study areas, respectively. In the case of the contaminants, the corresponding estimates lie in the

Table 4 Estimates of the mean total channel bed storage of <63 μm sediment and associated contaminants for each study river during the period January 2003 – September 2004.

River	Sediment (t)	C (kg)	Cd (kg)	Co (kg)	Cr (kg)	Cu (kg)	N (kg)	Total P (kg)	Pb (kg)	Zn (kg)
Frome	795	78747	0.75	22.14	10.58	15.63	5318	1085	33.98	108.51
Piddle	730	87540	0.84	9.11	12.32	19.88	5638	1003	37.05	147.76
Tern	639	59178	0.82	7.36	20.13	28.31	4787	1050	36.16	126.56
Pang	191	17486	0.08	1.20	2.42	4.74	1051	130	8.00	17.00
Lambourn	229	33807	0.11	1.16	2.98	8.66	2071	222	17.31	30.01

Table 5 Comparison of the estimates of mean total channel bed storage of fine sediment with the estimated total annual suspended sediment fluxes at the study catchment outlets using a range of sediment yield scenarios.

River	Mean total channel bed sediment storage (t)	Estimated mean annual suspended sediment load (t)*	% suspended sediment flux represented by bed sediment storage
Frome	795	2125–6375	37–13
Piddle	730	915–2745	80–27
Tern	639	1100–3300	58–19
Pang	191	800–2400	24–8
Lambourn	229	1170–3510	20–7

* Range estimated assuming a sediment yield of 5–15 t km^{-2} year^{-1}.

ranges, C: 20–77% and 7–26%; Cd: 8–82% and 3–27%; Co: 11–61% and 4–20%; Cr: 4–65% and 1–22%; Cu: 13–58% and 4–19%; N: 19–68% and 6–23%; total P: 9–76% and 3–25%; Pb: 12–41% and 4–14%; and Zn: 12–48% and 4–16%. For most contaminants, the estimate of channel storage represents a smaller proportion of the flux than for the fine sediment itself and this is likely to reflect the enrichment of suspended sediment relative to the bed sediment.

When interpreting the significance of the comparisons of sediment and contaminant storage with annual flux, it is important to recognize that channel bed sediment and contaminant storage are transitory and are therefore unlikely to represent a net conveyance loss at annual or longer timescales. However, where storage is equivalent to a sizeable proportion of the annual flux, such storage is likely to play a significant role in attenuating the downstream transmission of sediment and contaminant fluxes.

PERSPECTIVE

The above findings provide a valuable insight into the magnitude and spatio-temporal variability of channel bed storage of fine sediment and associated contaminants within lowland permeable river systems in the UK. Given the unpolluted nature of the study catchments, the results represent much needed information on reference conditions for sediment-associated contaminants. Future work will endeavour to place the findings within the context of more comprehensive fine sediment and associated contaminant budgets for the study rivers.

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