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The deposition and storage of sediment-associated phosphorus on the flood plains of two lowland groundwater fed catchments

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Abstract Overbank sedimentation can result in the accumulation of sediment-associated nutrients on flood plains. This contribution reports the findings of an investigation of sediment-associated phosphorus (P) fluxes within the catchments of the Rivers Frome and Piddle in Dorset, UK, aimed at quantifying deposition of sediment and P on their flood plains associated with individual flood events. Sediment and P deposition were documented using Astroturf synthetic grass mats. Fractionation of the P content of the sediment provided useful information for identifying P sources in the catchments. Depositional fluxes of total P documented for individual flood plain sites in the study ranged from 0.66 g m^{-2} $year^{-1}$ to 19.94 g m^{-2} $year^{-1}$. Comparison of the two rivers shows both contrasts in their sediment budgets and the location of P sources within the catchments.

Key words conveyance losses; phosphorus; river flood plains; sediment deposition

INTRODUCTION

Overbank sedimentation can result in the accumulation of fine sediment and nutrients on flood plains, and while deposition fluxes are generally low, substantial amounts of both sediment and nutrients may be deposited due to the large areas involved. Such deposition can result in a significant reduction of the suspended sediment load transported through a river system, and is therefore an important element of both the catchment sediment and nutrient budgets. The deposition of phosphorus (P), transported in association with fine sediment on flood plains during overbank flows, has two important implications. First, it can result in the accumulation of phosphorus in flood plain environments, which may constitute a problem in terms of the potential for future re-mobilization due to erosion and reintroduction into the system. The resulting enhanced levels of P in surface soils, which effectively equate to a supplementary application of fertiliser, may lead to unwanted growth and change in the ecological structure of both the river and the riparian habitats. Secondly, it can result in a reduction of the phosphorus flux at the catchment outlet, such that the flux measured may significantly underestimate the total mass of P mobilized within the catchment (Walling & Owens, 2003). In consequence, potential environmental problems associated with the transport of nutrient rich sediment through the river system may

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also be underestimated (Walling *et al*., 2003). Other studies have demonstrated the role of river flood plains as a sink for fine sediment and associated nutrients using flood plain sediment cores and ^{137}Cs measurements to establish deposition rates over the last 50 years (e.g. Walling *et al*., 2000). This study aims to contribute further to knowledge of contemporary P deposition on flood plains and to provide an overview of the P content of recent sediment deposits, by documenting spatial and temporal variations in both total P (TP) concentrations in sediment and TP deposition fluxes between sampling sites in the Frome and Piddle catchments, with particular reference to two flood events that occurred in the winter of 2002/2003.

The study area

Two lowland groundwater-fed catchments, the Frome (425 km^2) and the Piddle (183 km^2) in Dorset (Fig. 1) were selected for investigation as part of the UK's Natural Environment Research Council (NERC) LOCAR (LOwland Catchment Research) programme. Both catchments are primarily underlain by chalk (approx. 65% of their area), although outcrops of Jurassic limestone and Cretaceous Upper Greensand occur in the upper reaches, and Tertiary sands and gravels are found in the lower reaches. The headwater areas of both catchments are dominated by chalk outcrops and steep slopes, with maximum elevations of 264 m and 273 m a.s.l. in the upper Frome and upper Piddle, respectively. In contrast, the lower reaches of both catchments are characterized by gentle relief and extensive well-developed flood plains. Agricultural land accounts for >80% of each catchment, and land use is dominated by grassland and cereal cultivation. The mean annual precipitation is ~932 mm in the Frome catchment and ~888 mm in the Piddle catchment. The average daily flows of the Frome and Piddle are 6.44 m^3 s^{-1} and 2.46 m^3 s^{-1}, respectively. The mainly rural catchments are noted as being of high amenity value, with the Frome reported to be the last natural chalk salmon stream in the UK.

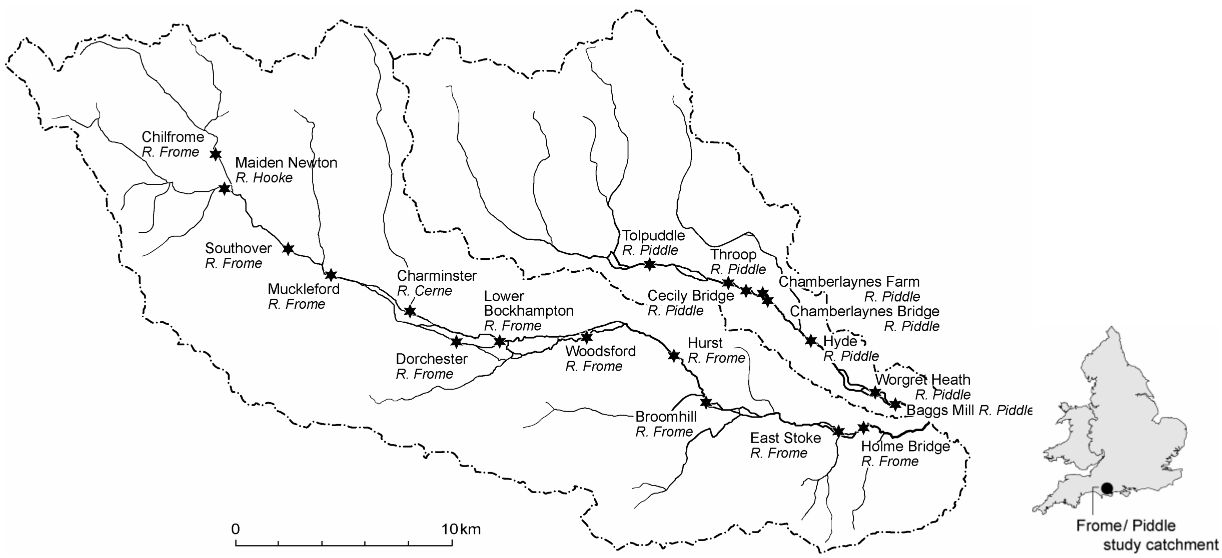

Fig. 1 Location map showing the study catchments and the flood plain sampling sites.

METHODS

Field sampling

To document the deposition of sediment and associated P by individual overbank flood events, Astroturf artificial grass mats (Lambert & Walling, 1987) were deployed at 19 sites along the flood plain bordering the main channels of the Rivers Frome and Piddle (Fig. 1) where overbank deposition was known to occur during flood events. The number of sites was considered large enough to provide a representative assessment of the spatial variation of sediment and P deposition in the study catchments during overbank events. Six Astroturf mats, 20 cm × 30 cm in size and consisting of 1.5 cm tufts on a pliable base, were deployed at each site. The mats were placed on plastic sheets that were slightly larger than the mats and fixed to the flood plain surface, using 15 cm steel nails, passing through both the mat and the underlying plastic sheet. They were positioned on the flood plain to take account of likely variations in deposition fluxes in response to distance from the channel and variability in flood plain topography. After the floodwaters associated with each overbank flood event had receded, the mats were collected and each one transferred to a labelled plastic bag and replaced with a clean one. A total of 71 samples were collected from event 1, and 64 samples were collected from event 2, which occurred on 1 January 2003 and 1 February 2003, respectively.

Laboratory analysis

The total amount of sediment deposited on each mat was recovered by careful brushing (efficiency >95%) after oven-drying at 40°C. The recovered sediment was gently disaggregated and sieved through a 63 μm sieve, in order to separate the silt and clay fraction. The P content (total P (TP), inorganic P (IP), organic P (OP) and the algal available fraction (AAP)) of the <63 μm fraction was determined by UV visible spectrophotometry following chemical extraction with hydrochloric acid and sodium hydroxide, as described by Mehta *et al.* (1954) and Dorich *et al.* (1985). The specific surface area (SSA) of the sediment samples was also estimated from their particle size distribution determined using a Coulter LS130 laser diffraction granulometer, after the removal of organic matter, and chemical and ultrasonic dispersion.

RESULTS

Spatial variations—total phosphorus

Information on the mean TP, IP, OP, and AAP content (μg g^{-1}) of the <63 μm fraction of sediment from the Astroturf mats deployed at each sampling site along the flood plains of the Rivers Frome and Piddle is presented in Table 1. TP concentrations demonstrate considerable spatial variability and, in the case of the River Frome, ranged from 524 μg g^{-1} to 2716 μg g^{-1}, while in the case of the River Piddle, TP concentrations lie in the range 816–1692 μg g^{-1}. For the River Frome, where the TP content in sediment shows a tendency to increase downstream, there is a statistically

Table 1 Average TP, IP, OP and AAP content, IP/OP ratio and SSA of the <63 µm fraction of overbank deposits collected by the mats deployed at the sampling sites in the catchments of the Rivers Frome and Piddle, and estimates of flood plain storage of the <63 µm fraction of sediment and TP. Values in parentheses are 1 SE of the mean.

River	Site	n	TP ($\mu g\ g^{-1}$)	OP ($\mu g\ g^{-1}$)	IP ($\mu g\ g^{-1}$)	AAP ($\mu g\ g^{-1}$)	IP/OP	SSA ($m^2\ g^{-1}$)	Storage ($g\ m^{-2}$)		Reach storage TP (t)		
									TP	Sed.	Event 1	Event 2	Total
Frome	Chilfrome	3	524 (129)	329 (19)	195 (129)	47 (8.4)	0.60 (039)	0.286 (.01)	11.66	1335.72	0.00	1.05	1.05
	Maiden Newton	11	934 (99)	458 (46)	477 (64)	44 (3.4)	1.08 (.14)	0.258 (.01)	4.52	290.36	0.68	1.15	1.83
	Southover	6	1055 (169)	526 (91)	529 (131)	50 (2.8)	1.73 (.85)	0.282 (.02)	2.99	169.92	5.73	1.57	7.30
	Muckleford	11	1330 (183)	690 (108)	640 (133)	86 (13.7)	1.06 (.23)	0.382 (.03)	7.08	319.39	2.96	1.11	4.08
	Dorchester	11	1160 (104)	730 (118)	430 (94)	43 (5.3)	1.02 (.39)	0.274 (.02)	3.69	190.75	12.54	5.63	18.18
	Bockhampton	2	2716 (820)	605 (217)	2110 (602)	0	3.59 (.29)	0.421 (.03)	0.66	14.58	2.63	1.26	3.90
	Woodsford	5	1159 (185)	481 (97)	678 (228)	73 (15.7)	1.91 (.82)	0.355 (.02)	2.12	109.47	4.28	0.00	4.28
	Hurst	7	1118 (144)	479 (117)	639 (138)	62 (14.6)	2.13 (.74)	0.33 (.04)	5.84	313.12	10.33	5.11	15.44
	Broomhill	12	1582 (95)	725 (84)	856 (125)	136 (21.2)	1.76 (.55)	0.432 (.02)	3.02	114.44	8.73	4.88	13.60
	East Stoke	10	1738 (217)	654 (134)	1084 (212)	168 (14.3)	3.96 (1.88)	0.434 (.02)	2.90	100.11	9.80	2.61	12.40
	Holme Bridge	12	1333 (148)	627 (109)	706 (137)	135 (18.3)	1.65 (.46)	0.366 (.02)	4.49	202.04	4.73	1.65	6.38
Piddle	Tolpuddle	6	1692 (128)	1161 (213)	531 (182)	147 (33.3)	1.61 (1.2)	0.428 (.03)	3.44	122.10	0.00	1.50	1.50
	Throop	5	1396 (107)	750 (228)	646 (147)	0	2.12 (1.1)	0.424 (.02)	2.48	106.47	1.18	1.81	2.99
	Cecilybridge	7	1473 (240)	907 (222)	566 (122)	51 (14.7)	1.07 (.51)	0.405 (.01)	6.31	257.10	0.69	0.67	1.36
	Chamber-laynesfarm	5	1272 (488)	944 (374)	328 (120)	36 (3.4)	0.6 (.23)	0.386 (.02)	1.44	68.07	0.29	0.53	0.81
	Chamber-laynesbridge	5	816 (58)	312 (68)	504 (119)	55 (4.1)	2.4 (.98)	0.394 (.02)	1.43	105.47	0.07	0.06	0.13
	Hyde	5	1685 (250)	568 (127)	1118 (255)	93 (2.9)	2.54 (.70)	0.48 (.02)	3.45	122.70	1.37	0.00	1.37
	Wogretheath	6	1141 (147)	365 (44)	776 (155)	139 (3.4)	2.3 (.53)	0.385 (.02)	3.91	205.47	4.42	0.00	4.42
	Baggsmill	5	1683 (311)	749 (150)	934 (319)	127 (24.6)	1.69 (.67)	0.39 (.02)	9.46	337.37	3.54	2.19	5.72

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significant difference between the TP content of sediment collected at sites in the upper reaches, from Chilfrome to Muckleford, and the lower reaches, from Hurst to Holme Bridge, (Kruskal Wallis (KW) $p = 0.000$). In contrast there is no evidence of a downstream increase in the P content of sediment for the River Piddle and there is no significant statistical difference between the TP content of sediment collected at different sites (KW $p > 0.005$).

The low TP concentrations found in sediment collected from the flood plain in the upper reaches of the River Frome may reflect the relatively unpolluted nature of the headwaters. Similarly, the lack of trend in TP concentrations in sediment in a downstream direction in the River Piddle reflects the rural nature of the entire catchment. Variations in TP concentration between sites in this study serve to highlight the impact of point source inputs from sewage treatment works (STW). The high TP concentrations that were noted in sediment deposited at the site at Bockhampton can be attributed to anthropogenic inputs associated with the nearby town of Dorchester and, more particularly, inputs from a STW located upstream of Bockhampton.

Phosphorus transported by rivers is often traceable to diffuse agricultural sources, and the higher TP concentrations observed in flood plain sediment collected in the lower reaches of the River Frome may reflect increased inputs from intensively farmed land in the lower parts of the catchment. Elevated TP levels in flood plain sediment also appear to reflect the influence of inputs of sediment from tributaries. The higher TP concentrations noted in sediment collected at Hyde may reflect the input of sediment with a high TP content from the Bere Stream tributary, which joins the main channel of the River Piddle just upstream from the sampling site at Hyde. Similar effects can be seen at East Stoke due to inputs to the main channel from the Tadnoll Brook tributary. Due to the affinity of phosphorus for the finer sediment fraction, some of the variation in the TP content of flood plain sediment documented in this study undoubtedly reflects variation in the SSA of the sediment. Using all the samples collected during both flood events, there is a significant positive correlation between the TP content of sediment and SSA (Pearson's $r = 0.9$).

Spatial trends—phosphorus fractions

Information on the IP, OP and AAP content of the sediment recovered from the Astroturf mats is shown in Table 1 along with the IP/OP ratio, which shows the contribution of the IP fraction to TP. Most of the variability in the TP content of the sediment reflects variability in the IP fraction. Because the IP fraction is generally associated with point source inputs, from STWs, and diffuse inputs, from intensive agriculture, both the higher values for IP and the increased contribution of this fraction to TP in the sediment from the River Frome reflect the greater importance of inputs from these sources in the Frome catchment compared to the Piddle catchment. The IP/OP ratio is lowest at Chilfrome, again emphasizing the unpolluted nature of the upper reaches of the River Frome, and highest at the Bockhampton site (3.59), due to an increased contribution of IP from inputs from the nearby STW and the town of Dorchester. The higher IP/OP ratios noted at sites in both the lower Frome and Piddle reflect sediment inputs from areas of intensive agriculture in the main catchments and their tributaries. Concentrations of AAP in flood plain sediment vary greatly, ranging from a minimum of zero to a maximum of 168 μg g^{-1}. The average percentage contribution to TP is 6% (range 0% to 12%). AAP concentrations are positively correlated with TP concentrations (Pearson's $r = 0.6$, $p < 0.01$) and more strongly correlated to IP concentrations (Pearson's $r = 0.64$, $p < 0.01$).

The SSA values shown in Table 1 demonstrate that sediment collected in the Piddle catchment is finer than that collected in the Frome, and this is likely to reflect the underlying geology of the catchments. The Piddle is mainly underlain by chalk, which weathers to produce fine sediment, whereas the Frome catchment, though also underlain by Jurassic, Cretaceous and Eocene strata, generates coarser sediment. The Cretaceous Greensand found in the upper reaches of the Frome will weather to produce a coarser textured soil than the chalk found in the middle reaches, and this may help to explain the downstream fining evident in the deposited sediment.

Phosphorus deposition

To gain an insight into the amount of phosphorus deposited on the flood plain, information on the TP concentrations in the sediment must be combined with information on the mass of sediment deposited. Estimates of TP deposition (g m^{-2}) associated with the <63 μm fraction of sediment for each of the flood plain sites are presented in Table 1. Comparison of the two catchments indicates that sediment and TP deposition (g m^{-2}) is higher in the Frome catchment. This reflects the increased supply of sediment, and the higher flows, which have a greater capacity to transport sediment and are more likely to cause overbank flooding. Comparison of the TP concentrations and TP deposition fluxes (g m^{-2}) reported in Table 1 show that maximum and minimum TP concentrations and fluxes do not coincide, which implies that TP deposition is not highly dependent on TP concentrations (Pearson's $r = 0.181$), but is rather governed primarily by the mass of sediment deposited at each site, as demonstrated by the Pearson's $r = 0.521$ ($p < 0.05$). Where sediment deposition is high, P deposition also tends to be high, as demonstrated at the site at Chilfrome in the upper reaches of the Frome. Where, however, the TP concentrations are high, but the amounts of sediment deposited are low, TP deposition fluxes tend be low, as shown at Bockhampton in the Frome catchment.

The estimates of TP deposition flux have been scaled up to establish the total mass of TP storage on the flood plain bordering the main channels of the study rivers using a similar approach to that employed by Walling *et al.* (2003) and the estimates of TP storage within the individual river reaches are shown in Table 1. Reflecting the relationship between fine sediment and TP deposition discussed above, fine sediment deposition and TP deposition are very strongly correlated at the reach scale (Pearson's $r = 0.96$, $p < 0.01$ level). The patterns of P storage at the reach scale mirror that for deposition fluxes, with the greatest P storage occurring in the upper reaches of the Frome, lowest storage in the middle reaches, and storage values increasing again towards the lower reaches. In contrast, in the catchment of the Piddle, storage is highest in the lower reaches. While estimates of TP deposition flux (g m^{-2}) for the two study catchments are comparable, when the estimates of TP storage associated with the entire flood plain system are compared, the total storage on the flood plain of the Frome, estimated at 88.4 t, is considerably higher than total storage on the flood plains of the River Piddle, which was calculated as being 18.3 t. The variation in storage at both the reach and the catchment scale reflects the contrasts in both the extent of the active flood plain, and the magnitude of the suspended sediment load between the two catchments. To emphasise the potential significance of phosphorus storage on the flood plain relative to the sediment-associated TP flux at the outlet of each catchment, if sediment yields are in the range 5 to 15 t km^{-2} $year^{-1}$, phosphorus storage on the flood plains of both catchments can be estimated to represent between 9–26% and 4–11% of the annual sediment-associated P loads of the Frome and Piddle, respectively.

Temporal trends in phosphorus concentration and deposition

Samples of freshly deposited sediment were collected from two overbank events, which occurred on 1 January and 1 February 2003. The maximum discharges for both events, measured at East Stoke in the River Frome and at Baggs Mill in the River Piddle, are shown in Table 2 along with mean values for the TP, IP and OP concentrations in flood plain sediment collected in both catchments after the events. Average TP and IP concentrations were higher in event 1 than event 2, while OP concentrations increased between event 1 and event 2. The higher TP concentrations found in sediment collected from event 1 reflect the higher concentrations associated with high flows. Also, because event 1 was the first significant event of the winter, the elevated TP and IP concentrations in sediment collected may reflect enrichment due to channel storage during the preceding summer and autumn. The higher IP concentrations, further implied by the higher mean IP/OP ratio for event 1, may also reflect short-term inputs from point sources, which are commonly discharged at times of high flow. The higher OP concentrations found in event 2 may reflect fresh sediment introduced to the channel system during the same winter season, and which had not been subject to the same degree of enrichment as the stored sediment transported and deposited in event 1.

Table 2 and Fig. 2 compare mean TP deposition fluxes (g m^{-2}), while Table 1 shows the total storage within each reach of the two catchments associated with each event. These estimates are both higher for event 1, and reflect the higher energy and transport capacity associated with the higher maximum discharge associated with event 1, the increased duration of the event and the greater spatial extent of flooding.

Table 2 Average TP, IP, OP content, IP/OP ratio and SSA of the <63 μm fraction of the sediment deposited on the flood plain and estimates of flood plain storage of TP for two different events in the catchments of the Frome and Piddle.

	TP (μg g^{-1})	IP (μg g^{-1})	OP (μg g^{-1})	SSA ($m^2 g^{-1}$)	IP/OP	TP dep (g m^{-2})	Tot TP storage (t)	Discharge (m^3 s^{-1})	
								Frome	Piddle
Event 1	1472	918	541	0.37	2.42	4.89	73.96	30.66	9.09
Event 2	1213	526	687	0.37	1.24	4.14	32.78	15.22	7.5

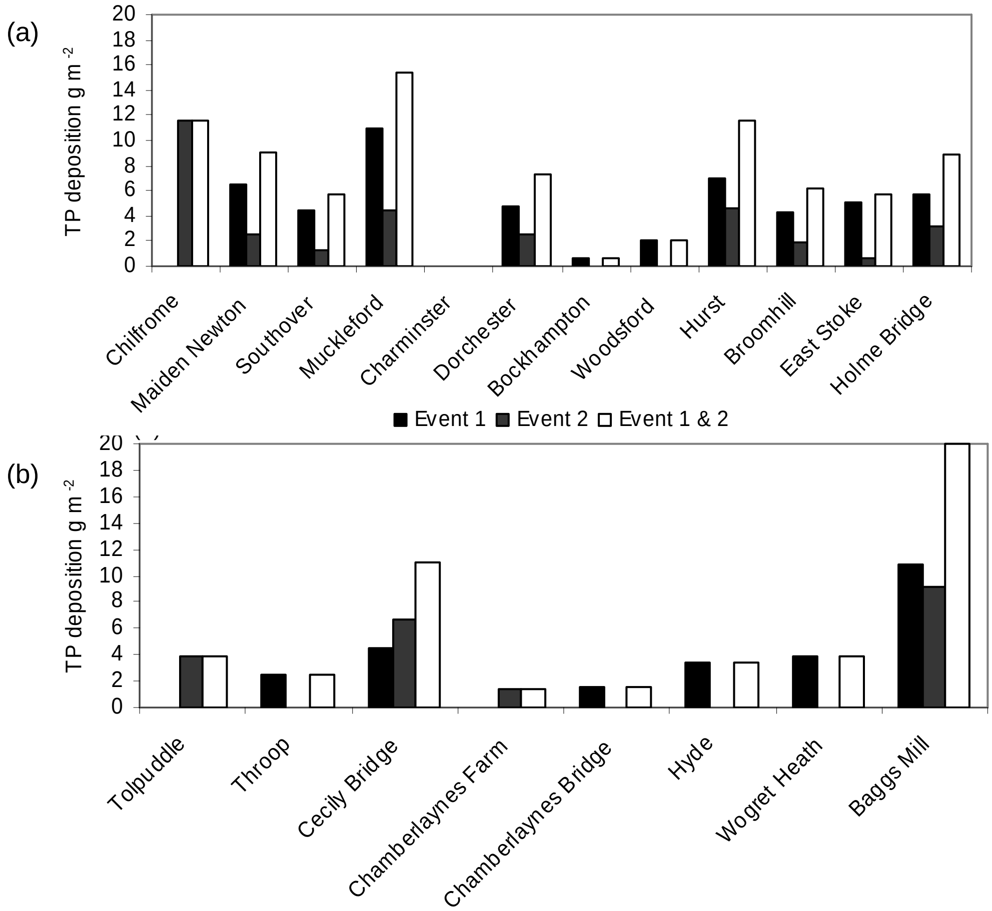

Fig. 2 Estimates of TP deposition (g m^{-2}) at flood plain sites in the catchments of the (a) Frome and (b) Piddle associated with events 1 and 2 and both events.

Also, the first high flows of the winter wet season are likely to transport greater quantities of P enriched sediment, because of the abundant supply that has accumulated over the preceding period of low flows, as represented in this study by event 1, while subsequent high flows, as shown by event 2, will each transport less P enriched sediment until the available supply is exhausted.

PERSPECTIVE

The results presented here show that significant amounts of phosphorus can be deposited on flood plains in times of overbank deposition and the estimates of storage, when viewed in the context of the total sediment-associated P flux of each catchment, emphasize the need to include overbank deposition as a important component of the catchment sediment-associated P budget. Such deposition can be viewed as long term storage, and P is likely to accumulate over time and be stored for periods of between 10^1 and 10^3 years or longer. Under changing conditions, flood plains may become a source of phosphorus in catchments through desorption and transfer to the soluble form, or by remobilisation of the sediment-associated form, if bank erosion or lateral channel migration become important processes in the catchments. Spatial variations in flood plain storage reflect contrasts in the spatial extent of the flood plain both within and between the study catchments and the hydrological conditions, while temporal variations are controlled by the quantity and quality of the sediment involved. The findings from this study provide a useful insight into the spatial and temporal variation of P deposition on the flood plains of two river catchments related to individual overbank events and serve to highlight the important role played by the flood plain in the storage of sediment-associated phosphorus in river basins.

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