The Role of Erosion and Sediment Transport in Nutrient and Contaminant Transfer (Proceedings of a symposium held at Waterloo, Canada, July 2000). IAHS Publ. no. 263, 2000.

River flood plains as phosphorus sinks

D. E. WALLING, Q. HE & W. H. BLAKE
School of Geography and Archaeology, University of Exeter, Exeter EX4 4RJ, UK
e-mail: d.e.walling@exeter.ac.uk

Abstract Recent research has emphasized the importance of conveyance losses associated with the deposition of suspended sediment on river flood plains during flood events. Such deposition also has important implications for the accumulation of sediment-associated nutrients in flood-plain sinks. Use of ^{137}Cs measurements in combination with information on downcore variations in the total-P content of flood-plain sediment cores affords a means of documenting recent rates of phosphorus accumulation and of investigating recent changes in the total-P content of the suspended sediment deposited on river flood plains. Results are presented for sediment cores collected from the flood plains of 20 British rivers. Average rates of total-P accumulation since 1963 range from 1.3 to 11.6 g m^{-2} $year^{-1}$, and estimates of the increase in the total-P content of suspended sediment deposited on the individual flood plains over the period 1950–1992 range from 10 to 170%.

INTRODUCTION

Recent studies of the role of river flood plains as sediment sinks have demonstrated that a significant proportion of the suspended sediment flux transported through a river system may be deposited on the flood plain bordering the main channel during overbank flood events. For example, Walling *et al.* (1998) estimated that *c.* 40% of the total suspended sediment load delivered to the main channel system of the 3315 km^2 catchment of the River Ouse in Yorkshire, UK was deposited on the adjacent flood plains. This and similar estimates of the magnitude of the conveyance losses associated with overbank sedimentation on river flood plains (e.g. Walling & Quine, 1993; Middelkoop & Asselmann, 1994) serve to emphasize the importance of overbank flood-plain sedimentation both as a conveyance loss within the overall catchment sediment budget and as a component of contemporary flood-plain evolution.

When such evidence of the importance of river flood plains as sediment sinks is coupled with recognition of the significance of fine sediment in the transport of nutrients and contaminants through river systems (cf. Allan, 1986), it is clear that river flood plains may also represent important sinks for sediment-associated nutrients and contaminants. Data presented by Walling *et al.* (1997) and Withers *et al.* (1999) have, for example, shown that sediment-associated transport can typically account for *c.* 25–93% of the annual total-P load of British streams and rivers and loss of a substantial proportion of the suspended sediment load to overbank deposition would result in a significant reduction in the phosphorus flux. Deposition of fine sediment on the flood plain will equally result in an increase in the P stock of the flood-plain soils. Furthermore, the progressive accumulation of overbank sediment deposits on a flood plain could also offer potential for providing a record of past changes in the P content of deposited sediment, in response to changes in land use and land use practices and to increases in effluent discharges to the river system.

Further investigation of river flood plains as P sinks and, more particularly, the assembling of information regarding rates of P accumulation and temporal changes in the P content of deposited sediment requires information on rates of sediment accumulation and a means of establishing the age–depth relationship for overbank deposits. This need can be met by recent developments in the use of the fallout radionuclide caesium-137 (^{137}Cs) to estimate sedimentation rates over the past *c.* 40 years and to define the associated age–depth relationships for individual sediment cores (cf. Walling & He, 1997). This paper reports the findings of a reconnaissance study, involving the coupling of estimates of sedimentation rates obtained from ^{137}Cs measurements with information on the P content of flood-plain sediments, aimed at developing an improved understanding of the role of the flood plains of British rivers as P sinks.

THE APPROACH

The approach adopted in this study can be usefully demonstrated by considering the measurements undertaken on a sediment core collected from the flood plain of the River Stour near Shillingstone, Dorset, UK, in late 1994. The core was collected from a representative area of the flood plain using a motorized percussion corer equipped with a 12 cm diameter steel core tube. The core was subsequently sectioned into 2 cm increments prior to analysis of the ^{137}Cs and total-P content of the resulting depth-incremental samples. Caesium-137 concentrations were measured by gamma spectrometry using an HPGe coaxial detector and total-P concentrations were

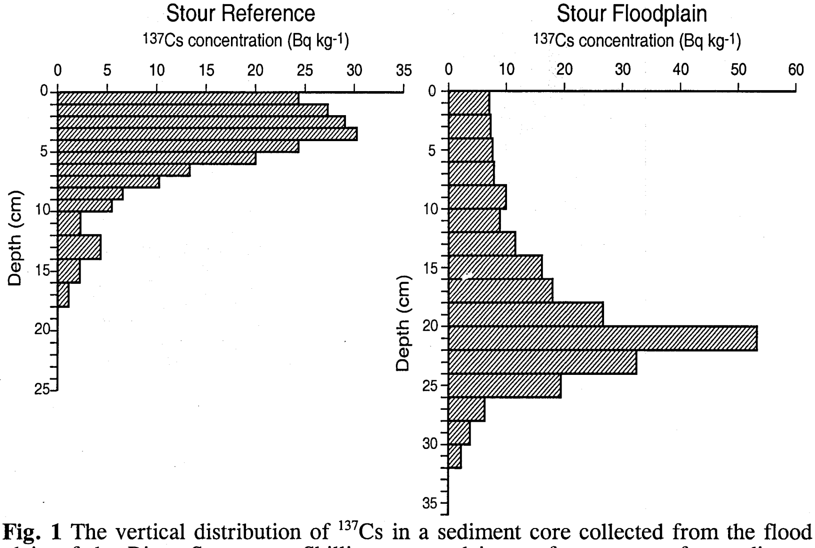

Fig. 1 The vertical distribution of ^{137}Cs in a sediment core collected from the flood plain of the River Stour near Shillingstone and in a reference core from adjacent pasture above the level of flood inundation.

determined colorimetrically after perchloric digestion. Figure 1 presents the results of the ^{137}Cs measurements undertaken on the flood-plain core. These may be compared with equivalent measurements for a core collected from an undisturbed "reference" site located adjacent to the flood plain, but above the level of inundating floodwater, also shown in Fig. 1. The ^{137}Cs depth distribution associated with the flood-plain core conforms closely with that normally recorded for aggrading flood-plain sites (cf. Walling & He, 1997). The total ^{137}Cs inventory of the flood-plain core (6970 Bq m^{-2}) is considerably in excess of that found in the reference core (2250 Bq m^{-2}), reflecting the additional input of ^{137}Cs associated with deposited sediment, and the peak ^{137}Cs concentration is found at depth, again reflecting the progressive aggradation of the site since the period of peak fallout in 1963. The depth of the 1963 peak can be used to estimate the amount of deposition occurring since 1963 and thus the average deposition rate for the period extending from 1963 until the time that the core was collected (i.e. 1994) (cf. Walling & He, 1997). In this case, the average deposition rate at the coring point has been estimated to be 0.83 g cm^{-2} $year^{-1}$.

Figure 2 provides information on the total-P concentrations associated with both the flood-plain sediment core and the natural soil profile from the adjacent reference site above the flood plain. Figure 2 indicates that the total-P concentrations associated with the flood-plain core are considerably in excess of those associated with the upper horizons of the natural soil. This reflects both the selectivity of erosion and sediment delivery processes, which causes the sediment eroded from the upstream catchment and subsequently deposited on the flood plain to be enriched in fines and organic matter and thus in total P, relative to the soil, and the additional inputs of P

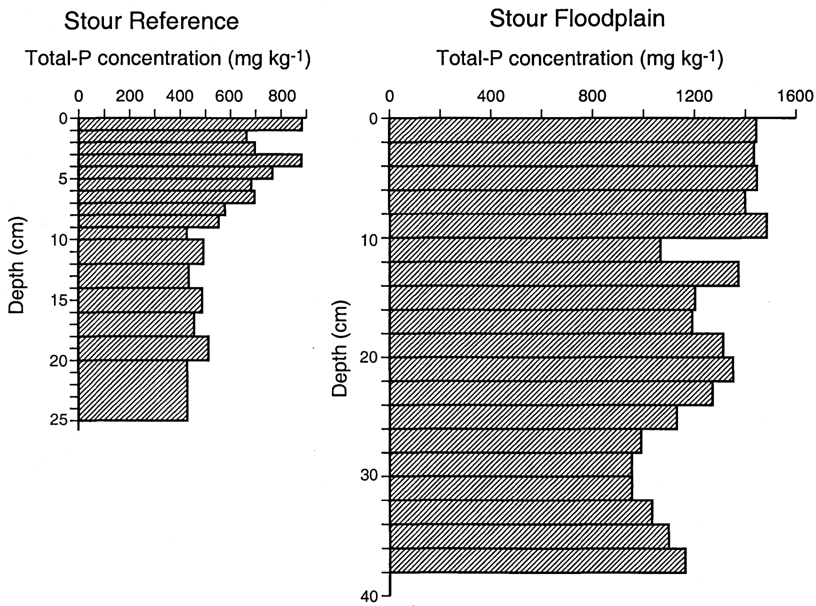

Fig. 2 The vertical distribution of total-P concentrations in a sediment core collected from the flood plain of the River Stour near Shillingstone and in a reference core from adjacent pasture above the level of flood inundation.

to the transported sediment, associated with effluent discharges from sewage treatment works. In addition, total-P concentrations in the natural soil profile decline rapidly with depth, such that concentrations below a depth of 10 cm are only *c.* 50% of those encountered at the surface. In contrast, relatively high total-P concentrations extend to the bottom of the flood-plain core, reflecting the fact that the core is composed entirely of sediment deposited over the recent past. By combining the information on sedimentation rates provided by the ^{137}Cs measurements with the phosphorus concentration data shown on Fig. 2, it is possible to estimate both the total and the mean annual input to total-P storage since 1963. In this case the overall increase in the total-P stock since 1963 can be estimated to be 372 g m^{-2}, which represents a mean annual input of 11.6 g m^{-2} $year^{-1}$.

Consideration of the downcore changes in the P content of the flood-plain sediment core presented in Fig. 2 also affords a means of deriving some information concerning past changes in the total-P content of suspended sediment transported by the river. In this case, it is important to recognize the potential for post-depositional changes in the total-P content of the flood-plain sediment, due to mobilization into solution, plant uptake and related mechanisms. However, most of the sediment-associated P is likely to be firmly fixed to the sediment and not readily mobilized and the downcore reduction in the total-P concentrations found in this core is thought to reflect a progressive increase in the P content of deposited sediment towards the present, in response to increased fertiliser application and, to a lesser extent, increased effluent output from sewage treatment works. Support for this interpretation is provided by the work of Fustec *et al.* (1995), who have reported studies of sediments from the flood plain of the River Seine in France, which indicate that *c.* 80% of the total-P content of recently deposited sediment is not readily bioavailable and that the relative contribution of this fraction to the total-P content of sediment from flood-plain cores shows only a small increase downcore. Such results suggest that post-depositional mobilization is likely to be of limited importance. By combining information on the age–depth relationship provided by the ^{137}Cs measurements with that on downcore changes in total-P concentration, it is possible to estimate that the total-P content of sediment deposited by the River Stour on its flood plain at the study site near Shillingstone has increased by *c.* 50% over the period 1950–1992 (i.e. from *c.* 950 to 1450 mg kg^{-1}). Furthermore, it is possible to produce a tentative reconstruction of the trend of the increase over this period based on the generalized age–depth relationship and the downcore variation in total-P concentration.

THE STUDY

The approach outlined above was applied to sediment cores collected from the flood plains of 20 British rivers over the period 1992–1996. The locations of the rivers and the sampling sites are shown on Fig. 3. The rivers were selected to embrace a wide range of catchment characteristics (e.g. underlying geology and land use) and the coring sites were selected to be generally representative of the flood plains at those locations. The use of a single core from each site necessarily introduces some limitations, but these are judged to be of limited significance, since the emphasis of

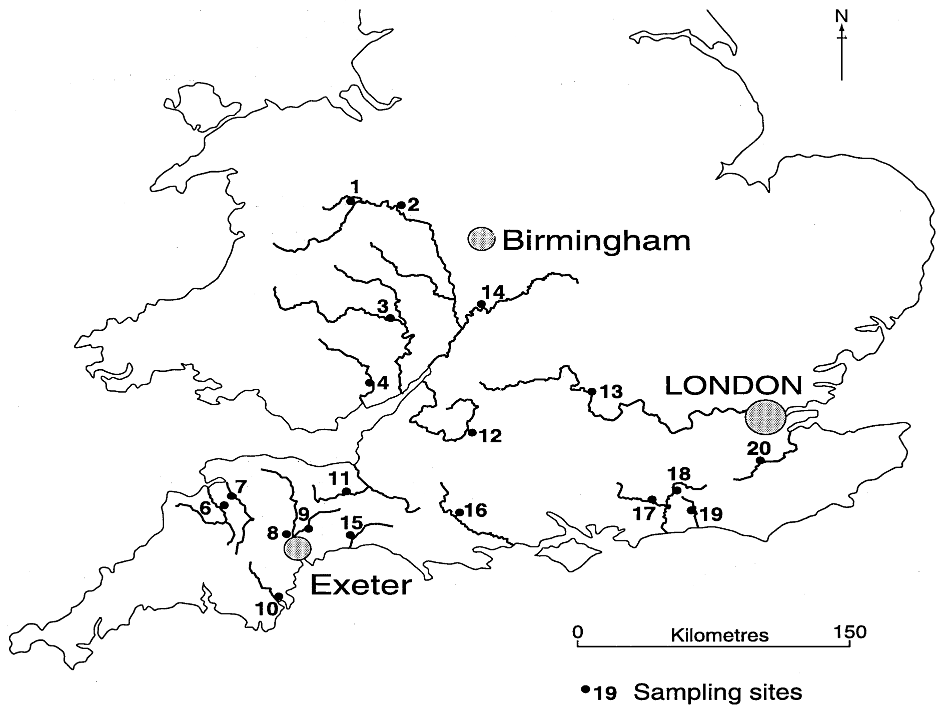

Fig. 3 The location of the flood-plain study sites listed in Table 1.

the study is on reconstructing temporal variations in the P content of deposited sediment, rather than spatial variability.

RESULTS

Table 1 presents values for the mean total-P concentration of sediment deposited since 1963 (mg kg^{-1}), the mean annual increase in the total-P stock of the flood-plain sediments since 1963 (g m^{-2} $year^{-1}$) and the magnitude of the overall increase in the total-P content of the deposited sediment over the period 1950–1992 (%), for each flood-plain site. The values for the mean total-P concentration of sediment deposited at each flood-plain site since 1963 range from 417 to 2660 mg kg^{-1}. This large range reflects variations between the individual rivers in the nutrient status of catchment soils, in suspended sediment sources, in land use and fertiliser application rates and in the magnitude of effluent discharges. As might be expected, the lowest values are found in rivers with upland catchments, such as the rivers Usk, Teme and Vyrnwy and the upper River Severn. Most of the catchments of these rivers are occupied by upland sheep pasture with thin soils. The limited fertiliser application associated with upland grazing and the low population density also result in low anthropogenic nutrient inputs to these river systems. In contrast, the highest values of total-P content (i.e. >1500 mg kg^{-1}) are associated with the flood plains of rivers draining areas of intensive agriculture characterized by high rates of fertiliser application and

Table 1 Phosphorus storage on the flood plains of British rivers.

River/Location		Mean total-P concentration of post-1963 sediment (mg kg^{-1})	Total-P storage since 1963 (g m^{-2} $year^{-1}$)	Increase in total-P content of deposited sediment 1950–1992 (%)
1.	River Vyrnwy near Llanymynech	760	1.7	9
2.	River Severn near Atcham	717	9.0	23
3.	River Wye near Preston on Wye	1031	1.6	17
4.	River Usk near Usk	417	3.8	25
5.	River Teme near Broadwas	507	2.0	45
6.	River Torridge near Great Torrington	955	6.5	45
7.	River Taw near Barnstaple	830	4.8	75
8.	River Exe near Stoke Canon	1090	4.8	65
9.	River Culm near Silverton	2660	8.2	33
10.	River Start near Slapton	1931	8.4	40
11.	River Tone near Bradford on Tone	1047	5.8	55
12.	Bristol Avon near Langley Burrell	1266	5.0	28
13.	River Thames near Dorchester	1532	7.8	30
14.	Warwickshire Avon near Pershore	2374	10.6	23
15.	River Axe near Colyton	1466	7.6	170
16.	Dorset Stour near Shillingstone	1321	11.6	53
17.	River Rother near Fittleworth	1895	2.0	33
18.	River Arun near Billingshurst	1436	5.7	94
19.	River Adur near Partridge Green	795	4.0	147
20.	River Medway near Penshurst	913	1.3	10

with high population densities and associated effluent inputs. These include the rivers Culm, Start, and Thames and the Sussex Rother and Warwickshire Avon.

Table 1 also presents estimates of the rate of total-P accumulation at the individual flood-plain sites. The magnitude of these values will reflect both the total-P content of the deposited sediment and the rate of sediment accretion and it is difficult to identify broad spatial trends, since the latter values will vary locally in response to the flood-plain morphology and microtopography. However, as might be expected, there is a general distinction between the flood plains of rivers draining upland catchments, which are commonly characterized by lower values of total-P accumulation, and the flood plains of lowland rivers which are characterized by significantly higher accumulation rates. The values of total-P accumulation for these lowland rivers are of a similar magnitude to that of 9 g m^{-2} $year^{-1}$ cited by Fustec *et al.* (1996) for a flood-plain site on the River Seine at Maizières, France, and further underscore the potential importance of river flood plains as P sinks.

The evidence for recent changes in the total-P content of suspended sediment fluxes provided by downcore changes in P concentration are usefully summarized in Fig. 4, which presents a representative selection of findings for five of the rivers. In all cases there is a close relationship between the trend of the total-P content of the deposited sediment over the period since 1950 and likely changes in the intensity of agricultural activity in the upstream catchment. For the upland catchments (i.e. rivers Usk and upper Severn) the limited increase in total-P concentration of deposited sediment over this period (25% and 23%, respectively) is consistent with the low intensity agriculture and the limited fertiliser application. The marked increases

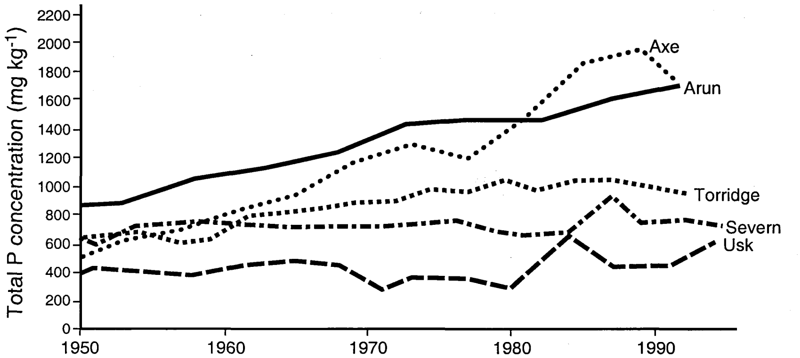

Fig. 4 A tentative reconstruction of variations in the total-P content of suspended sediment deposited on the flood plains of five British rivers over the past 40 years, based on information obtained from flood-plain cores.

evident for the rivers Axe (170%) and Arun (94%) are similarly consistent with the more intensive agriculture in these catchments, which includes a substantial proportion of arable cultivation, and which is likely to have been associated with significant increases in fertiliser application over the past 40 years. The more limited increase shown by the River Torridge (45%) is again consistent with the land use of this catchment, which is primarily permanent pasture. In all cases, the increases in total-P concentration of deposited sediment evident over the period since 1950 are also likely to reflect increases in population density and associated increases in effluent inputs to the river systems. Equivalent values for the increase in the total-P concentration of deposited sediment for the other 15 rivers over the period 1950–1992 are listed in Table 1 and these are broadly in accord with the trends demonstrated by Fig. 4.

PERSPECTIVE

The results presented above clearly underscore the importance of river flood plains as phosphorus sinks and demonstrate the potential for using the evidence provided by flood-plain cores to reconstruct recent changes in the P content of the suspended sediment transported by British rivers. Further work is required to confirm the trends reported and the explanations advanced on the basis of the results from the 20 flood-plain sites investigated.

Acknowledgements The financial support of the UK Natural Environment Research Council for the work presented in this paper through Research Grant GR3/8633 is gratefully acknowledged. The study also represents a contribution to IAEA Co-ordinated Research Project F3.10.01 through Research Agreement 9090.

REFERENCES

Allan, R. J. (1986) *The Role of Particulate Matter in the Fate of Contaminants in Aquatic Ecosystems*. Inland Waters Directorate, Environment Canada, Scientific Series 142.

Fustec, E., Bonté, P., Fardeau, J.-C., Khebibeche, L., Chesterifoff, A. & Carru, A. M. (1996) La rétention des MES et des pollutants associés dans les zones inondables. In: *Piren-Seine Rapport* 1996/II, Thème Corridor Fluvial, 3-3–3-16. Laboratoire de Géologie Appliquée, Université Pierre et Marie Curie, Paris, France.

Fustec, E., Enguerran, F., Bonté, P. & Fardeau J.-C. (1995) Rétention et biodisponibilité du phosphore dans les zones inondables. In: *Piren-Seine Rapport* 1995/II, Thème Corridor Fluvial, 3-22. Laboratoire de Géologie Appliquée, Université Pierre et Marie Curie, Paris, France.

Middelkoop, H. & Asselmann, N. E. M. (1994) Spatial variability of floodplain sedimentation at the event scale in the Rhine–Meuse delta, the Netherlands. *Earth Surf. Processes and Landforms* **25**, 561–573.

Walling, D. E. & He, Q. (1997) Use of fallout ^{137}Cs in investigations of overbank sediment deposition on river floodplains. *Catena* **29**, 263–282.

Walling, D. E. & Quine, T. A. (1993) Using Chernobyl-derived fallout radionuclides to investigate the role of downstream conveyance losses in the suspended sediment budget of the River Severn, United Kingdom. *Phys. Geogr.* **14**, 239–253.

Walling, D. E., Owens, P. N. & Leeks, G. J. L. (1998) The role of channel and floodplain storage in the suspended sediment budget of the River Ouse, Yorkshire, UK. *Geomorphol.* **22**, 225–242.

Walling, D. E., Webb, B. W. & Russell, M. A. (1997) Sediment-associated nutrient transport in UK rivers. In: *Freshwater Contamination* (ed. by B. Webb) (Proc. Rabat Symp., April–May 1997), 69–81. IAHS Publ. no. 243.

Withers, P. J. A., Dils, R. M. & Hodgkinson, R. A. (1999) Transfer of phosphorus from small agricultural basins with variable soil types and land use. In: *Impact of Land-use Change on Nutrient Loads from Diffuse Sources* (ed. by L. Heathwaite) (Proc. Birmingham Symp., July 1999), 41–50. IAHS Publ. no. 257.