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The role of flood plain sedimentation in catchment sediment and contaminant budgets

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Abstract Overbank sedimentation on river flood plains can result in a significant reduction of the suspended sediment load transported by a river and thus represents an important component of the catchment sediment budget. Such conveyance losses will also exert an important influence on sediment-associated contaminant loads and budgets. This contribution reports the results of a study of suspended sediment and sediment-associated contaminant (i.e. total-P, Cr, Cu, Pb and Zn) fluxes in the 1346 km^2 catchment of the River Swale in Yorkshire, UK, aimed at quantifying the role of overbank flood plain sedimentation in the catchment sediment and sediment-associated contaminant budgets. The results indicate that conveyance losses associated with overbank sedimentation on the flood plains bordering the main channel system account for *c.* 27% of the total suspended sediment input to the main channel system, whilst the equivalent values for the sediment-associated contaminants range between *c.* 14% for total-P and 45% for Pb. The variation in the values for the individual contaminants primarily reflects the location of the contaminant sources within the catchment.

Key words river flood plains; sediment deposition; sediment storage; sediment budgets; caesium-137; contaminants; phosphorus; heavy metals; River Swale

INTRODUCTION

Overbank sedimentation during flood events represents an important component of flood plain construction and development. In addition to its importance for flood plain development, overbank deposition of fine sediment during flood events will commonly result in a significant reduction of the suspended sediment load transported through a river system to the catchment outlet. It is important to recognize that many estimates of the magnitude of the conveyance losses associated with overbank deposition cited in the literature relate to specific reaches and specific events (cf. Thoms *et al.*, 2000) and there is a need to establish more precisely the significance of such losses to the longer-term overall sediment budget of a catchment. Recent advances in the use of the fallout radionuclide caesium-137 (^{137}Cs) to obtain estimates of medium-term (e.g. 40-year) accretion rates at different locations along a flood plain have permitted estimation of the total amount of sediment deposited on the flood plains bordering the main channels of a river system. If this value is compared with the measured suspended sediment load at the catchment outlet, it is possible to establish the total conveyance loss associated with the main channel system. In this way, Walling *et al.* (1999a) estimated that the conveyance losses associated with overbank deposition on the flood plains bordering

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the main channel system of the Rivers Ouse and Wharfe in Yorkshire, UK were 39% and 49% of the total sediment input to the main channel system respectively. The same authors provided an equivalent value for the River Tweed in Scotland of 40%. Even greater conveyance losses of 39–71% have been estimated for the Brahmaputra River by Allison *et al.* (1998), using a similar approach.

It is well known that nutrients, such as phosphorus, and many contaminants, including heavy metals and pesticides, are transported in association with fine sediment (cf. Allan, 1979), and these sediment-associated contaminants will also be deposited on river flood plains during overbank flows (cf. Hudson-Edwards *et al.*, 1999; Walling *et al.*, 2000). As with the sediment itself, such deposition has two important implications. First, it can result in the accumulation of nutrients and contaminants in flood plain environments. This may constitute a problem both in terms of enhanced levels of contamination and the potential for future remobilization back into the system (cf. Lecce & Pavlowsky, 1997). Second, it can result in a reduction of the nutrient or contaminant flux at the catchment outlet and the flux measured at the catchment outlet may, therefore, significantly underestimate the total mass of the contaminant mobilized within the catchment. To date, however, there have been few attempts to extend studies of the role of overbank flood plain sedimentation in catchment sediment budgets to include equivalent investigations related to sediment-associated contaminant budgets. The significance of flood plain conveyance losses to sediment-associated nutrient and contaminant budgets will clearly parallel their role in the overall sediment budget, but it will also reflect the location of nutrient and contaminant sources within the catchment and any size selectivity associated with the deposition process. Thus, for example, if the major sources of contaminated sediment are located in the lower reaches of a catchment, there is likely to be limited opportunity for conveyance losses associated with overbank deposition. Equally, it is well known that most sediment-associated nutrients and contaminants are preferentially associated with the finer fractions and preferential deposition of the coarser fractions of transported sediment may reduce the magnitude of the conveyance loss relative to that for the overall suspended sediment load.

This contribution uses the results from studies undertaken by the authors on the River Swale, as part of a wider study of Yorkshire rivers (e.g. Walling *et al.*, 1999a,b; Owens *et al.*, 2001), to investigate the role of overbank sedimentation on the flood plains bordering the main channel system in both the catchment sediment budget and the related sediment-associated contaminant budgets. In the latter context attention focuses on total-phosphorus and several heavy metals (i.e. Cr, Cu, Pb and Zn).

THE STUDY CATCHMENT

The River Swale has a catchment area of *c.* 1346 km^2 above the Environment Agency (EA) gauging station at Leckby (Fig. 1). It drains a predominantly rural catchment with a low population density and is relatively unpolluted along its entire length. The mean annual precipitation for the catchment is 860 mm and the long-term mean discharge for the period 1955–1984 is 20.6 m^3 s^{-1}. The upper reaches of the catchment drain the Pennine Hills, which are underlain by Carboniferous limestone and Millstone Grit and characterized by moorland, rough grazing and permanent pasture, with some cultivated land in the valley bottoms. The lower reaches of the catchment form part of the Vale of York and are underlain by softer Permian (Magnesian limestone), Triassic (New Red sandstone) and Jurassic (limestone) strata. The land use of this portion of the catchment is dominated by temporary pasture and cultivated land. The main channel system is characterized by gravel-bed channels with well-developed flood plains, which are locally up to more than 200 m in width.

The headwaters of the River Swale drain part of the Yorkshire Dales Pb–Zn–fluorite–baryte orefield (Fig. 1(a)) which provides a source of heavy metal contamination. There is evidence that small-scale mining of the orefield began in Roman times, although the major exploitation of the deposits occurred between the

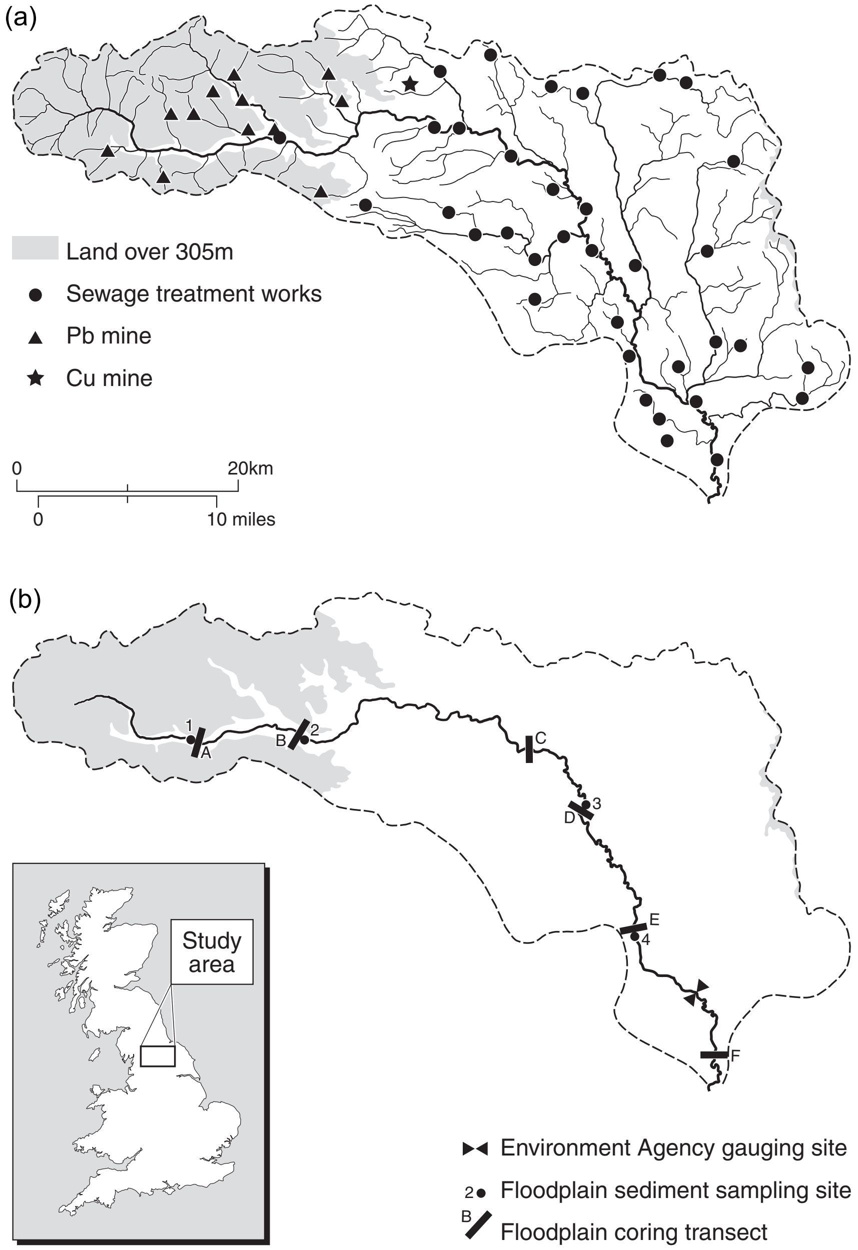

Fig. 1 The study catchment showing (a) the relief and the location of contaminant sources and (b) the network of measuring sites.

mid-eighteenth and early twentieth centuries, peaking in the mid-nineteenth century. Existing studies have shown that both recent and historic overbank deposits on the flood plains located downstream of the mining areas contain elevated levels of Pb and Zn (Hudson-Edwards *et al.*, 1999; Owens *et al.*, 1999). There was also a mine producing Cu on the Gilling Beck, one of the northern tributaries of the River Swale (cf. Fig. 1(a)). Sewage treatment works within the study catchment are located primarily in the middle and lower reaches of the catchment (Fig. 1(a)). These reaches coincide with the main areas of agricultural activity, and thus represent the main area of both point and diffuse source inputs of phosphorus to the river system.

METHODS

The field sampling programme involved two main components. The first focused on the use of ^{137}Cs measurements to obtain estimates of medium-term rates of overbank sediment accretion on the flood plains bordering the main channel of the River Swale. The second involved the use of "astroturf" mats to assemble information on the phosphorus and heavy metal content of the fine sediment deposited on the flood plains during overbank flood events.

Details of the use of ^{137}Cs measurements to estimate medium-term rates of flood plain accretion are provided by Walling & He (1997) and Walling *et al.* (1999a). In this study, attention focused on obtaining estimates of average sediment accretion rates for six transects across the flood plain located at representative sites along the main channel of the River Swale (cf. Fig. 1(b)). At each site, *c.* 10 sediment cores were collected from a transect aligned perpendicular to the river channel and extending from the channel bank to the outer margin of the flood plain. The cores were collected using a 38 cm^2 (for bulked cores) or 98 cm^2 (for sectioned cores) diameter steel core tube inserted to a depth of >50 cm, using a motorized percussion hammer. Most of the cores were bulked, to provide a single sample from each core, but one core from each transect was sectioned into 1 or 2 cm depth increments, in order to determine the ^{137}Cs depth distribution and hence the sedimentation rate at the sampling point. For the bulked cores, a basal slice was retained and analysed separately, in order to ensure that the full depth of the ^{137}Cs profile had been included in the core. Caesium-137 concentrations in the bulked cores and the depth incremental samples were determined by gamma spectrometry using a hyperpure germanium detector coupled to a multichannel analyser. Count times were typically in the range 25 000–58 000 s, providing a measurement precision of between ±5% and ±15% at the 95% level of confidence.

The estimate of sedimentation rate obtained for the sectioned core collected from each transect (R_s, g cm^{-2} year^{-1}) was used to derive estimates of the sedimentation rate associated with the individual bulked cores (R_b, g cm^{-2} year^{-1}) collected from that transect using the relationship:

$$R_b = R_s \left[\frac{Ie_b}{Ie_s} \right] \left(\frac{S_s}{S_b} \right)^{0.75} \tag{1}$$

where Ie_s and Ie_b are the excess ^{137}Cs inventories (Bq m^{-2}) associated with the sectioned and bulked cores respectively and S_s and S_b represent the specific surface areas (cm^2 g^{-1}) of the sediment from the sectioned and bulked cores respectively. The ratio S_s/S_b is used to correct for differences in particle size composition between the sectioned core and the bulked core (cf. Walling & He, 1997) and the exponent 0.75 describes the general relationship between ^{137}Cs concentration and specific surface area reported by He & Walling (1996). The excess ^{137}Cs inventory for a core was determined by subtracting the local ^{137}Cs reference or fallout inventory from the total ^{137}Cs inventory for that core. The local reference inventory was established for each transect by collecting several soil cores from adjacent areas of flat, undisturbed land above the level of inundation. The specific surface area of the sediment from the different coring points was determined from the absolute particle-size distribution of surface sediment (top 1–2 cm) collected immediately adjacent to the coring point, assuming spherical particles. The particle-size distributions of the samples were measured by laser diffraction, after pre-treatment to remove the organic fraction and chemical and ultrasonic dispersion.

Samples of sediment deposited on the flood plain surface during flood events (n = 117) were collected using acid-washed "astroturf" mats (cf. Lambert & Walling, 1987). These mats were deployed at four representative sites along the flood plain bordering the main channel of the River Swale (Fig. 1(b)) between December 1997 and December 1999. At each site, individual mats were placed at points representative of the variations in flood plain morphology and at different distances from the channel. The mats were deployed on the flood plains prior to flood events and were retrieved soon after the flood waters had receded. The sediment collected on each mat was recovered using a stainless steel spatula. In some situations, additional samples of recent overbank sediment deposits were collected shortly after the flood waters had receded by careful scraping of the sediment deposited on the pre-existing vegetation surface.

After recovery from the mats, the samples of sediment deposited on the flood plain were air dried before being disaggregated and screened through a 0.063 mm sieve. The resulting samples were analysed for total-P and for the heavy metals Cr, Cu, Pb and Zn. The total-P content was determined after chemical extraction following the method of Mehta *et al.* (1954). Heavy metal concentrations were measured using a Unicam 939 atomic absorption spectrophotometer after acid (concentrated HCl and HNO_3) digestion (cf. Allen, 1989).

RESULTS

Flood plain sedimentation rates

The mean sedimentation rates of the six flood plain transects shown in Fig. 1(b) are listed in Table 1. The values, which range between 0.13 and 0.53 g cm^{-2} year^{-1}, are similar in magnitude to those that have been reported for the flood plains of other British rivers. For example, based on ^{137}Cs measurements on single cores collected from representative locations on the flood plains of 21 British rivers, Walling & He (1999) reported mean sedimentation rates ranging from 0.04 to 1.22 g cm^{-2} year^{-1}. In most cases, the values of sedimentation rate estimated for the individual cores showed a tendency to decrease with increasing distance from the channel, reflecting the general reduction in flood-water depth with increasing distance from the channel and a reduced frequency of inundation towards the outer limit of the flood plain. The sedimentation rates listed in Table 1 provide some evidence of a downstream increase, but this trend is not clearly marked. The highest sedimentation rate is recorded at site C, which is located in the middle reaches or piedmont zone, where the river emerges from the uplands into the lower-lying Vale of York.

Table 1 Mean overbank sedimentation rates for the individual flood plain transects estimated using ^{137}Cs measurements.

Site*	Mean sedimentation rate ($g\ cm^{-2}\ year^{-1}$)
A	0.16
B	0.13
C	0.53
D	0.23
E	0.19
F	0.22

* see Fig. 1(b) for location of sites.

Sediment storage on the flood plains

An estimate of the total annual storage of fine-grained sediment on the flood plains bordering the main channel of the River Swale has been derived by extrapolating the values of mean sedimentation rate obtained for the individual transects to the adjacent reaches. This extrapolation assumed that the sedimentation rate associated with a particular reach between two transects could be estimated as the mean of the sedimentation rates derived for the two transects, and took account of variations in flood plain width along the reach. For the furthest upstream reach, the sedimentation rate at the source was assumed to be zero. The estimates of sediment storage for the individual reaches and for the entire flood plain area bordering the main channel of the River Swale above the EA gauging station at Leckby are presented in Table 2. These values have been expressed in terms of both total storage ($t\ year^{-1}$) and storage per unit length of main channel ($t\ km^{-1}\ year^{-1}$). The latter values show some evidence of a downstream increase, in response to the general trend for flood plains to increase in width downstream.

Table 2 Mean annual storage of sediment on the individual reaches of the Swale flood plain.

Flood plain reach*	Storage ($t\ year^{-1}$)	($t\ km^{-1}\ year^{-1}$)
Source to A	521	70
A to B	1 069	126
B to C	5 013	167
C to D	5 501	500
D to E	3 307	221
E to gauging station	1 483	171
Total	16 894	210

* see Fig. 1(b) for location of reaches.

The contaminant content of sediment deposited on the flood plains

Table 3 lists the average total-P and heavy metal content of the sediment collected by the flood plain mats deployed at the four sites along the River Swale. The Pb and Zn concentrations must be seen as high for fluvial sediment, since they exceed the guidelines for "severe" effects (250 and 820 μg g^{-1}, respectively) documented by the Ontario Ministry of Environment and Energy in Canada (Persaud *et al.*, 1993). Overall, there is little evidence of major variations in the total-P and heavy metal content of the flood plain sediment along the river, although both Pb and Zn concentrations show a tendency to increase immediately downstream of the headwaters, as the river enters the main area of past metal mining activity. However, there is little evidence of a significant decline in Pb and Zn concentrations further downstream towards the catchment outlet, such as might be expected to result from dilution of the contaminated sediment by sediment from other sources. Copper concentrations do, however, show some sign of a downstream reduction, whereas total-P concentrations show evidence of a significant increase downstream, in response to increased inputs from both point and diffuse sources.

Table 3 Mean values for the contaminant content of the <63 μm fraction of overbank deposits collected by the mats deployed at the sampling sites on the River Swale flood plain.

Site*	Cr (μg g^{-1})	Cu (μg g^{-1})	Pb (μg g^{-1})	Zn (μg g^{-1})	Total-P (μg g^{-1})
1	13	54	361	884	452
2	12	62	1602	1070	470
3	29	38	1476	1007	695
4	13	42	1486	1094	566

* see Fig. 1(b) for location.

Estimating contaminant deposition fluxes

By combining the information on sediment deposition fluxes presented in Table 2 with the information on the total-P, Cr, Cu, Pb and Zn content of the deposited sediment presented in Table 3, and taking account of grain-size effects, it is possible to estimate the mean annual total deposition flux for the individual sediment-associated contaminants to the flood plains bordering the main channel of the River Swale. These calculations were undertaken for the individual reaches defined by the sites used for the deployment of the "astroturf" mats and totalled to provide a value for the entire river. The total values are listed in Table 4 and the patterns shown by the values for the individual reaches expressed as a deposition flux per unit channel length (kg km^{-1} year^{-1}) are presented in Fig. 2. The patterns shown by the individual contaminants in Fig. 2 demonstrate the importance of both the varying sediment deposition fluxes to the flood

Table 4 Estimates of the mean annual deposition flux of sediment-associated contaminants on the flood plain bordering the main channel of the River Swale upstream of Leckby.

Cr (kg year^{-1})	Cu (kg year^{-1})	Pb (kg year^{-1})	Zn (kg year^{-1})	Total-P (kg year^{-1})
328	858	24 489	17 503	9830

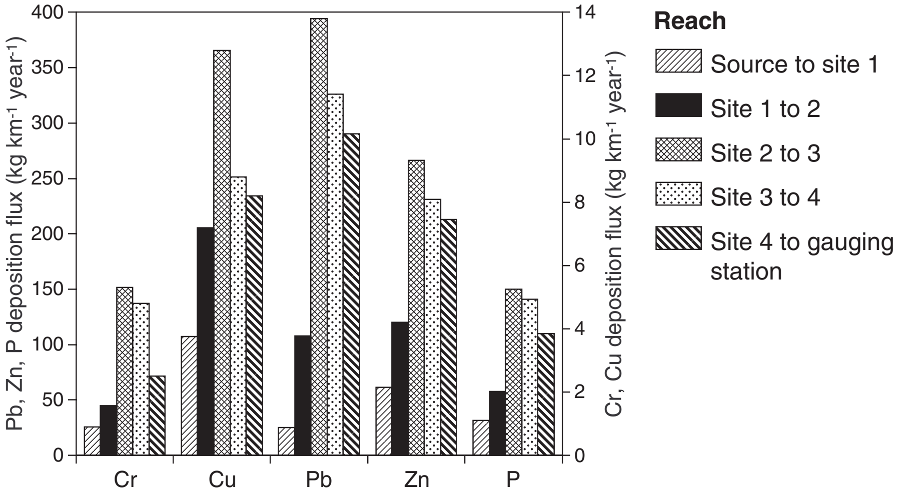

Fig. 2 Downstream variation in the deposition of sediment-associated contaminants on the flood plains bordering the main channel of the River Swale.

plain surface in different reaches and variations in the contaminant content of the deposited sediment, which will in turn reflect the location of the main contaminant sources within the river basin. The importance of Cu, Pb and Zn inputs from the mining areas in the upper reaches of the catchment and of total-P inputs associated with the sewage works and agricultural areas in the middle and lower parts of the catchment are clearly evident.

Conveyance losses associated with overbank flood plain sedimentation

In order to place the estimates of flood plain storage of both sediment and sediment-associated contaminants within the broader context of the sediment and contaminant budgets for the study catchment, it is useful to compare them with estimates of the suspended sediment and sediment-associated contaminant flux for the gauging station at the outlet of the catchment (Table 5). An estimate of the mean annual suspended sediment flux for the River Swale at Leckby has been provided by Wass & Leeks (1999), based on continuous discharge and turbidity records, and preliminary estimates of the mean annual sediment-associated contaminant fluxes have been derived by combining this value with information on the contaminant content of suspended

Table 5 Mean annual conveyance losses associated with the deposition of sediment and sediment-associated contaminants on the flood plain bordering the main channel of the River Swale upstream of Leckby.

Substance	Mean annual flood plain deposition flux	Mean annual load	Conveyance loss (%)
Suspended sediment	16 894 t year^{-1}	45 158 t year^{-1}	27
Cr	328 kg year^{-1}	1174 kg year^{-1}	22
Cu	858 kg year^{-1}	3658 kg year^{-1}	19
Pb	24 489 kg year^{-1}	29 398 kg year^{-1}	45
Zn	17 503 kg year^{-1}	32 514 kg year^{-1}	35
P	9830 kg year^{-1}	62 544 kg year^{-1}	14

sediment samples collected from the flow gauging station over a wide range of flows as part of other studies (cf. Owens *et al.*, 2001). The results presented in Table 5 indicate that flood plain deposition accounts for 27% of the suspended sediment input to the main channel system above Leckby, and between 14% and 45% of the equivalent sediment-associated contaminant flux. The higher conveyance losses for Pb and Zn (45% and 35% respectively) reflect the location of their main sources in the former mining areas in the headwaters of the catchment and thus the opportunity for conveyance losses along a major proportion of the river's length. In contrast, the appreciably lower value for total-P (14%) reflects the importance of the middle and lower reaches of the catchment as the source of P and thus the reduced opportunity for conveyance losses.

PERSPECTIVE

The results presented above must be seen as providing only an approximate indication of the role of overbank sedimentation in the catchment sediment and sediment-associated contaminant budgets for the River Swale. A greater number of flood plain transects and mat sampling sites, as well as a more rigorous sampling programme to estimate contaminant fluxes at the catchment outlet, would be required to provide more precise values for the deposition fluxes and conveyances losses involved. Nevertheless, the results obtained emphasize the important role played by overbank deposition on flood plains in catchment sediment budgets and sediment-associated contaminant budgets and demonstrate the importance of the location of contaminant sources in influencing the precise magnitude of the conveyance losses associated with the latter. Furthermore, the approach described could provide a basis for implementing similar, if more detailed, studies in other catchments.

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