Rates of overbank sedimentation on the flood plains of several British rivers during the past 100 years

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Abstract The flood plains of lowland rivers frequently represent important sinks for suspended sediment transported through the river system. However, little is currently known about rates of overbank deposition by British rivers and, more particularly, whether such rates have increased in recent years in response to land use change. The fallout radionuclides ^{137}Cs and ^{210}Pb offer considerable potential for estimating flood plain sedimentation rates over the past 30-35 years and 100 years respectively. Caesium-137 and ^{210}Pb measurements have been employed by the authors to investigate sedimentation rates during the past 100 years at five sites on the flood plains of British rivers. At one site a detailed study of the spatial pattern of deposition within a meander bend was undertaken. The results obtained suggest that no significant changes in sedimentation rates have occurred at these sites during the past 100 years. Further work is, however, required to confirm the general applicability of the findings reported.

BACKGROUND

The flood plains of most lowland rivers in Britain are characterized by extensive deposits of fine sediment resulting from the deposition of suspended sediment during overbank flood events. Such flood plains frequently represent important sinks for fine sediment transported through a river system and Lambert & Walling (1987) have reported that conveyance losses of suspended sediment moving through an 11 km reach of the lower River Culm in Devon could be as high as 28% of the annual load entering the reach. Where it has proved possible to date these deposits, the findings have frequently indicated that deposition has occurred at relatively low rates over extended periods of time. In the case of two British rivers, Shotton (1978) reports an average rate of deposition of 0.5 cm year^{-1} over the past 3000 years on the flood plain of the Warwickshire Avon, and Brown (1987) refers to typical sedimentation rates of 0.14 cm year^{-1} over the past 10 000 years on the flood plain of the River Severn. For some rivers, detailed analysis of sediment stratigraphy has indicated that rates of flood plain deposition increased during periods of forest clearance and agricultural expansion within the upstream basin. For example, Brown (1990) presents evidence from the River Perry, a tributary of the River Severn, which indicates that increased rates of alluviation occurred *c.* 1400 years ago in response to the expansion of agriculture. Little is currently known about more recent trends in rates of overbank deposition and whether they have increased in response to changes in land use, such as the wartime expansion of arable cultivation and the more recent expansion of the area under autumn-sown cereals. Such changes in land use may have resulted in increased suspended sediment yields (cf.

Walling & Quine, 1991), but the lack of long-term records of suspended sediment transport by British rivers precludes detailed analysis of the likely trends involved. In an attempt to provide a preliminary indication of the presence or absence of significant changes in rates of overbank sedimentation during the past 100 years, the authors have used measurements of the content of the fallout radionuclides caesium-137 (^{137}Cs) and unsupported lead-210 (^{210}Pb) in flood plain sediments from several rivers in lowland Britain to estimate sedimentation rates during this period.

USING FALLOUT RADIONUCLIDES TO ESTIMATE RATES OF FLOOD PLAIN SEDIMENTATION

The basis for using measurements of the ^{137}Cs content of flood plain sediments to estimate average rates of sedimentation over the past 30-35 years is described in detail by Walling *et al.* (1992) and Walling & He (1992,1993). In essence, the approach makes use of the global fallout of the human-made radionuclide ^{137}Cs, resulting from the atmospheric testing of nuclear weapons during the middle years of the twentieth century. Most of the fallout occurred in the decade between 1956 and 1965, with maximum deposition occurring in 1963, the year of the Nuclear Test Ban Treaty. In some areas of the world an additional short-term input was received in 1986 as a result of the Chernobyl accident which released radiocaesium into the atmosphere, but in this study attention will focus on bomb-test fallout. Caesium-137 has a half-life of 30.17 years and in most environments fallout inputs were rapidly and strongly adsorbed by clay particles in the surface horizons of the soil. Flood plain surfaces will have received inputs of radiocaesium both directly from atmospheric fallout and in association with deposited sediment eroded from the upstream drainage basin. Estimates of the rate of deposition can be obtained by comparing either the depth distribution or the total inventory of ^{137}Cs in flood plain sediments, with that of a nearby undisturbed site above the level of inundating floodwater. The depth at which peak concentrations are found may be used to determine the level of the flood plain surface in 1963 and the "excess" radiocaesium inventory associated with the flood plain site can be used to determine the mass of sediment deposited and therefore the mean sedimentation rate during the period since the commencement of ^{137}Cs fallout. In the latter case, only a single measurement of the total ^{137}Cs inventory of a flood plain sediment core is required.

Unsupported ^{210}Pb differs from ^{137}Cs in that it is a natural radionuclide. It again reaches the land surface via atmospheric fallout, but the annual fallout may be viewed as being essentially constant through time. It therefore affords a means of estimating deposition rates over somewhat longer time periods (i.e. 50-150 years). Lead-210 is a product of the ^{238}U decay series with a half-life of 22.26 years. It is derived from the decay of gaseous ^{222}Rn, the daughter of ^{226}Ra. Radium-226 occurs naturally in soils and rocks. Diffusion of a small proportion of the ^{222}Rn from the soil introduces ^{210}Pb into the atmosphere and its subsequent fallout provides an input of this radionuclide to surface soils and sediments which is not in equilibrium with its parent ^{226}Ra. This component is termed unsupported ^{210}Pb since it cannot be accounted for (or supported) by decay of the *in situ* parent. The amount of unsupported or atmospherically-derived ^{210}Pb in a sediment sample can be calculated by measuring both ^{210}Pb and ^{226}Ra and subtracting the supported or *in situ* component. As in the case of ^{137}Cs, flood plain

surfaces will receive inputs of unsupported ^{210}Pb as a result of both direct fallout and in association with the deposition of sediment eroded from the upstream basin.

Although ^{210}Pb measurements have been extensively used for establishing lake sediment chronologies extending over the past 50-150 years (cf. Appleby & Oldfield, 1983; Robbins, 1978; Oldfield & Appleby, 1984a,b), their application to flood plain sediments introduces further complexities. Neither the constant flux (CF) (also referred to as the constant rate of supply (CRS)) model nor the constant activity (CA) (also referred to as the constant initial concentration (CIC)) model, which are commonly used to derive age-depth relationships for lake sediments, are directly applicable to flood plain situations. The CA or CIC model assumes that accumulation of unsupported ^{210}Pb in the sediment profile results from the deposition of sediment with a constant ^{210}Pb activity or concentration, but, in the case of flood plain sediments, a substantial proportion of the ^{210}Pb will be deposited directly onto the surface as atmospheric fallout. The CRS or CF model departs less from physical reality. However, although it is possible to represent the atmospheric flux component of unsupported ^{210}Pb input as essentially constant, the annual flux of basin-derived unsupported ^{210}Pb associated with deposited sediment is likely to vary from year to year in response to variations in rates of sediment deposition. In addition, both the above models assume that post-depositional mixing is strictly limited and this is unlikely to be the case with many flood plain sediment deposits.

In order to overcome the limitations of existing models and also to avoid the need for detailed information on the downprofile variation of ^{210}Pb activity in a sediment core (which is both costly and time-consuming to obtain) the authors have employed a constant initial concentration-constant sedimentation rate (CICCS) model to derive the age-depth relationship for flood plain sediments. In this case, the total unsupported ^{210}Pb inventory associated with a sediment core is apportioned into two components, representing that associated with atmospheric fallout and that associated with deposition of sediment-associated ^{210}Pb mobilized from the upstream basin. Values of unsupported ^{210}Pb inventory obtained from neighbouring undisturbed pasture sites above the level of flood inundation can be used to estimate the former component, and the "excess" inventory associated with the latter component can be calculated by difference. The value of "excess" unsupported ^{210}Pb can in turn be used to estimate the sedimentation rate, if the concentration of unsupported ^{210}Pb in the deposited sediment at the time of deposition, otherwise referred to as the initial concentration, is known. Since it assumes a constant sedimentation rate, the model estimates the average rate of deposition over the period involved. The model also has the important advantage that an estimate of the

Table 1 The flood plain sites investigated in this study.

Site/River	Location	Grid reference
1 Exe	Stoke Canon, Devon	SX 923963
2 Culm	Silverton Mill, Devon	SS 983012
3 Stour	Spetisbury, Dorset	ST 024023
4 Avon	Bredonfield, Worcestershire	SO 917388
5 Severn	Tewkesbury, Gloucestershire	SO 887326

average sedimentation rate can be derived from a single measurement of the total unsupported ^{210}Pb inventory of a flood plain core. By undertaking both ^{137}Cs and ^{210}Pb measurements on the same or immediately adjacent flood plain cores, it is possible to estimate average rates of sedimentation relating to both the past 30-35 years (^{137}Cs) and the past 100 years (^{210}Pb). Comparison of the two estimates provides a means of determining whether significant changes in rates of deposition have occurred during this period. This approach has been applied to flood plain sites on five British rivers.

THE STUDY SITES

Further details of the study sites and their locations are provided in Table 1 and Fig. 1. Although the sites investigated relate to only five rivers, these rivers provide a representative sample of the flood plains of British lowland rivers in terms of upstream basin characteristics, hydrological response and the nature of the flood plains themselves. Two cores for ^{210}Pb and ^{137}Cs analysis were collected from the flood plain of the River Culm in Devon, but at the remaining four sites only single cores were analysed. In each case, the coring site was selected as a representative area of active overbank sedimentation, away from the immediate vicinity of the channel. In addition, a more detailed investigation of the pattern of sedimentation within a short reach of the River Culm was undertaken. This involved a grid (7 m × 7 m) of 53 cores located within a meander loop (cf. Walling & He, 1993).
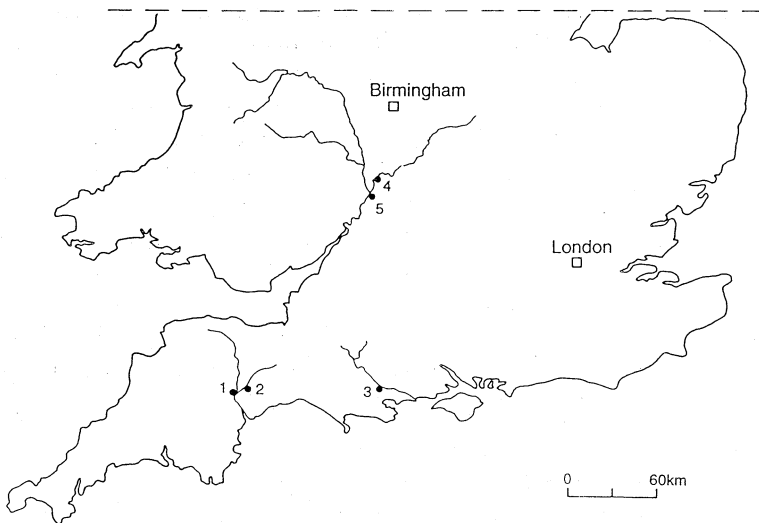

Fig. 1 The location of the flood plain sites investigated in this study.

SAMPLING AND MEASUREMENT PROCEDURES

Cores were collected using a purpose-built motorized percussion corer. A 12 cm diameter core tube was used for the six primary cores, and a 6.9 cm diameter core tube was used for the detailed sampling of the meander site on the River Culm. Coring depths

were *c*. 70 cm and in all instances the cores included the total depth of [137]Cs- and unsupported ^{210}Pb-bearing sediment. The six primary cores were sectioned at 2 cm intervals prior to analysis, but the 53 cores collected from the meander site on the River Culm were analysed as bulk samples, in order to determine their total ^{137}Cs and unsupported ^{210}Pb inventories. All samples were air dried and disaggregated prior to gamma assay using a high purity, low background, low energy, N-type germanium detector linked to a multi-channel analyser. Counting times were typically *c*. 40 000 s. Values of ^{137}Cs activity were measured directly at 662 keV, and concentrations of unsupported ^{210}Pb were calculated from measurements of total ^{210}Pb, [226]Ra and [214]Pb activity according to standard procedures (cf. Joshi, 1987).

Typical analytical results are presented in Fig. 2 which presents ^{137}Cs and unsupported ^{210}Pb depth distributions for two of the six primary cores. In the case of the primary cores, estimates of the depth of the 1963 flood plain surface, and therefore the average sedimentation rate over the past 30 years, were derived from the ^{137}Cs depth distribution using the model proposed by Walling & He (1993). Equivalent estimates of the average sedimentation rate over the past 100 years were derived from the value of the total "excess" unsupported ^{210}Pb inventory for the core, using the CICCS model described above. In the case of the sediment cores collected from the River Culm meander site, estimates of the average sedimentation rate over the past 35 years and past 100 years were derived from the whole core values of "excess" [137]Cs and ^{210}Pb inventory respectively, using the procedure described by Walling & He (1993) for ^{137}Cs and the CICCS model for [210]Pb. Values for the initial unsupported ^{210}Pb content of deposited sediment required by the CICCS model were obtained by radiometric analysis of bulk samples of suspended sediment collected from the five rivers at locations close to the flood plain coring sites.

RESULTS

The five primary sampling sites

Table 2 lists the estimates of average sedimentation rates over the past 30 years and 100 years derived from the ^{137}Cs and ^{210}Pb measurements undertaken on the six cores collected from the five flood plain sites. The contrasts in sedimentation rates between the five sites evident in Table 2 are partly a reflection of the natural spatial variability of flood plain sedimentation and therefore the sampling variability associated with single cores. They will, however, also reflect significant differences between the five rivers in terms of the physical characteristics of their flood plains and their hydrological response. Thus, for example, the relatively high rates of sedimentation reported for the River Severn undoubtedly reflect the relatively high suspended sediment loads transported by this river, the substantial depths of inundation during flood events and the low flood plain gradient. The much lower rates of sedimentation estimated for the River Stour are likely to reflect the relatively low suspended sediment load of this river, the reduced incidence of overbank flooding and the limited width of the flood plain which promotes increased flow velocities.

Despite the substantial variations in sedimentation rates between the individual rivers evident in Table 2, comparison of the average rates for the past 30 and 100 years for the individual sites suggests that rates of sedimentation have remained essentially stable over
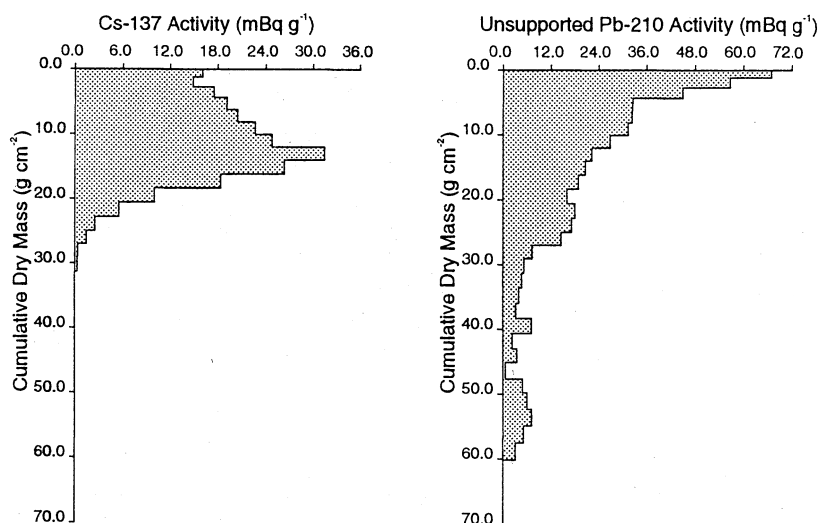
Fig. 2 The vertical distribution of ^{137}Cs and unsupported ^{210}Pb in a sediment core collected from the flood plain of the River Exe at Stoke Canon, Devon.

the past 100 years and that there has been no significant increase during the more recent period.

The River Culm meander site

Maps showing the pattern and rates of sedimentation within the meander bend of the River Culm estimated from ^{137}Cs and ^{210}Pb measurements are presented in Fig. 3. The patterns shown on both maps are very similar and indicate that maximum rates of sedimentation are associated with areas close to the channel and that relatively low rates are found in the depressions within the meander bend. The average rates of sedimentation estimated for the past 35 and 100 years are also very similar, although

Table 2 Average sedimentation rates at the five study sites during the past 30 years and 100 years estimated using measurements of the levels of ^{137}Cs and unsupported ^{210}Pb in the flood plain sediments.

River/location	Average sedimentation rate (g cm^{-2} year^{-1})	
	Past 30 years	Past 100 years
1 Exe at Stoke Canon	0.45	0.42
2 Culm at Silverton Mill	0.22	0.27
	0.35	0.32
3 Stour at Spetisbury	0.04	0.04
4 Avon at Bredonfield	0.17	0.19
5 Severn at Tewkesbury	0.86	0.95

(a)

Sedimentation Rate
(g cm^{-2} year^{-1})

> 0.45
0.35 — 0.45
0.25 — 0.35
0.15 — 0.25
< 0.15

Sedimentation Rate
(g cm^{-2} year^{-1})

> 0.45
0.35 — 0.45
0.25 — 0.35
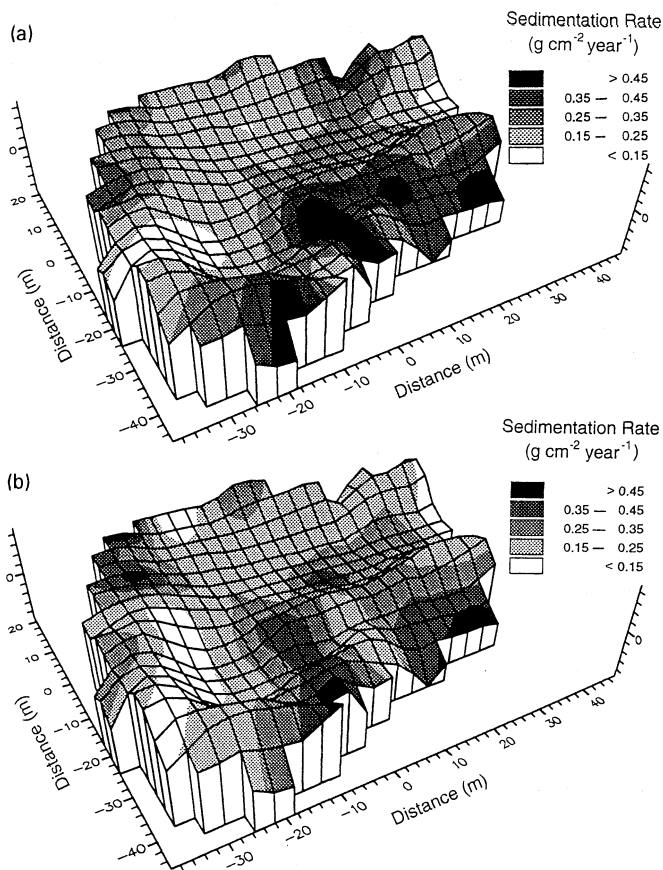0.15 — 0.25
< 0.15

(b)

Fig. 3 A comparison of the average rates of overbank sedimentation during the past 35 years (a) and 100 years (b) within a small area of the flood plain of the River Culm, located inside a meander bend, estimated using measurements of the levels of ^{137}Cs and unsupported ^{210}Pb in the flood plain sediments.

there is some evidence of slightly increased rates during the past 35 years. These results therefore suggest that there has been no substantial change in sedimentation rates at this site over the past 100 years and that the spatial pattern of sedimentation has also remained essentially constant over this period.

PERSPECTIVE

The results presented in Table 2 and Fig. 3 suggest that rates of overbank flood plain sedimentation by rivers in lowland Britain have remained essentially constant over the past 100 years, despite significant changes in land use. The small number of rivers considered and the limited number of cores collected from sites other than that on the River Culm do, however, mean that this conclusion must be viewed as tentative. More work is required to test its general applicability. Furthermore, although fallout radionuclides clearly offer very considerable potential for investigating medium-term rates and patterns of flood plain sedimentation, for which traditional techniques offer little by way of alternative, the limitations of the approach must be recognized. More

particularly, the estimates of sedimentation rates produced represent average values for the period under consideration (ie. 30-35 years or 100 years) and changes could have occurred within these periods. However, the lack of a significant contrast between the average rates estimated for the past 30-35 years and the past 100 years suggests that no clear trend exists. In addition, it should be appreciated that the average sedimentation rates will reflect the magnitude and frequency characteristics of flood plain inundation and differences in the incidence of major flood events between the two periods could mask significant contrasts in the potential for flood plain sedimentation. Similarly, anthropogenic modifications to flood plain environments (e.g. construction and removal of constrictions and obstructions could cause significant modification of flood plain flows and therefore complicate any simple comparison of the estimates of flood plain sedimentation rates for the two periods. Likewise, it is important to recognize that whilst changes in land use may result in significant increases in on-site rates of erosion, these increases may not be so clearly apparent in downstream sediment loads due to the complexity of sediment delivery processes (cf. Walling, 1983).

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