Assessing the remobilisation of recently deposited sediment from river flood plains during single overbank flood events, using caesium-134 and cobalt-60 as tracers

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Abstract River flood plains can represent important stores of fine sediment and sediment-associated contaminants and there is therefore a need to develop an improved understanding of the rates and patterns of fine sediment deposition during overbank flood-events and its subsequent fate. Most existing studies have focused on deposition rates and only limited attention has been given to the potential for remobilisation of the recently deposited sediment during subsequent events. This communication reports an attempt to develop a tracing technique to address this problem. The approach employed involves placing small quantities of fine sediment, pre-labelled with artificial radioisotopes, on the flood plain surface and documenting the changes in the tracer inventories after subsequent overbank flood events. Reduced inventories provide evidence of sediment remobilisation. The magnitude of the reduction in the inventory provides information on the extent of the remobilisation, which can be related to the local physical conditions. This approach has been applied on two river flood plains in Devon, UK, where it was possible to document the change in tracer inventories after two subsequent overbank flood events. Remobilisation occurred at 80% and 87% of the measuring points on each flood plain during the first inundation event and at 67% and 73% during the second. The results confirm the potential importance of remobilisation of recently deposited sediment during subsequent overbank flood events.

Key words caesium-134; cobalt-60; flood plain; sediment remobilisation; deposition; single overbank flood event; *in situ* gamma spectrometer

INTRODUCTION

Recognition of the importance and environmental significance of river flood plains as stores of fine-sediment and sediment-associated nutrients and contaminants (e.g. Nakamura & Kikuchi, 1996; Walling *et al*., 1998; Owens *et al*., 1999) has directed attention to documenting the sediment storage capacity of flood plain systems, sediment residence times, and rates and patterns of deposition during overbank flood events. Although it has proved possible to quantify deposition rates and sediment residence times, most studies have involved medium-term timescales and the relative importance of sediment deposition and remobilisation over shorter timescales remains uncertain. There is a need to investigate the extent of remobilisation of recently deposited sediment, but this has proved difficult due to the problems of tracking its fate at the scale of individual events and taking account of the complex, site-specific interactions that will influence the potential for sediment remobilisation (e.g. Nicholas *et al*., 2006).

Where rates and patterns of flood plain sedimentation have been successfully documented over short timescales (e.g. Simm, 1993; Simm & Walling, 1998), the findings have indicated that the macro and micro-scale variability of sediment deposition is controlled by a number of factors, including the physical characteristics of the flood plain, the depth of inundation and the magnitude of the suspended sediment load (e.g. Lambert & Walling, 1987; Simm & Walling, 1998; Walling & He, 1994, 1997). The study reported in this communication has attempted to develop a new approach for documenting the remobilisation of recently deposited sediment over the timescale of individual events, in order to establish the importance of such remobilisation within the overall sediment budget of the flood plain system and to identify the key controls on both the magnitude and spatial variability of sediment remobilisation rates. The approach is based on the use of the artificial radionuclides caesium-134 (^{134}Cs) and cobalt-60 (^{60}Co) as sediment tracers.

EXPERIMENTAL DESIGN

The use of Caesium-134 and Cobalt-60 as tracers

Caesium-134 ($t_{0.5}$ = 2.06 years) has been successfully used as a sediment tracer in a number of existing studies, and its characteristics and environmental conservatism have been documented elsewhere (e.g. Quine *et al*., 1999; Syversen *et al*., 2001). In contrast, the use of ^{60}Co ($t_{0.5}$ = 5.26 years) as a sediment tracer remains largely untested. However, its characteristics and environmental conservatism have been investigated (Khan, 2003; Shinonaga, *et al*., 2005) and its potential as a sediment tracer has been recognised (Alam *et al*., 2001; Galabov *et al*., 2003). It was therefore selected for use in this study as a complement to ^{134}Cs.

Method

Surface sediment was collected from each flood plain under investigation and wet-sieved to obtain the <63 μm fraction. The excess water was removed from the <63 μm fraction by centrifugation and the resulting sediment was subdivided into approx. 200 g aliquots and labelled with either ^{134}Cs or ^{60}Co. Labelling was achieved by adding solutions containing 80 Bq of the radionuclide to 250 ml of tap water. The water was then added to the sediment and the contents were mixed into a slurry. A method of depositing the labelled sediment onto a predetermined area of the flood plain was devised, in order to simulate the deposition of suspended sediment on the flood plain surface during a flood event. This was achieved by removing the base from a 300 mm diameter flexible rubber bucket. The bucket was then embedded into the flood plain surface to a depth of approx. 50 mm and the soil was firmed against the bottom of the sides of the bucket to obtain a watertight seal. Each aliquot of labelled sediment was then added to a further 25 L of tap water and vigorously shaken to ensure that the labelled sediment was in suspension. The contents were poured into the container (Fig. 1(a)) and left until the water infiltrated into the flood plain and the sediment was deposited onto its surface. The container was then carefully removed, leaving a "plot" of labelled sediment with a thickness (e.g. approx. 2 mm) typical of the amount of sediment deposited during overbank floods on the flood plains of local rivers (Simm & Walling, 1998).

At each study site, three labelled aliquots were used to establish control plots located above the maximum flood level and 15 labelled aliquots were used to establish "active plots" at a range of representative locations across each flood plain. Documenting the fate of the deposited sediment was based on measuring the areal activity density (AAD) of the plots after deposition of the labelled sediment and after successive subsequent overbank flood events. Reduction in the AAD was seen as reflecting remobilisation of sediment from the plot during the flood event. Plot inventories were determined using a field-portable EG&G ORTEC High Purity Germanium (HPGe), high resolution N-type coaxial gamma spectrometer (relative efficiency 40%), mounted on an adjustable cradle (Fig. 1(b)) and equipped with a 5-L liquid N_2 Dewar and coupled to a NOMAD Plus power supply and multi-channel analyser system and a lap-top computer. Five assays, each with a 500 s counting time, were undertaken at predetermined positions on the plot in order to cover the majority of the surface of the plot and to provide a representative value for the total inventory, or AAD, of the tracer radionuclide within each plot. The fixed positions facilitated re-measurement of the plot inventory after individual overbank flood events. During measurement, the detector head was positioned approx. 10 mm above the surface. After each re-measurement, the mean AAD value of the three control plots was subtracted from the value obtained for the individual active plots, as a means of accounting for reductions in the AAD values caused by processes other than remobilisation by inundating floodwater. (e.g. in-washing, rain splash or bioturbation, etc.). After adjustment, based on the control plots, the changes (reductions) in the AAD values for the active plots were attributed to remobilisation of the sediment by the floodwater.

The study was undertaken at two flood plain sites in Devon, UK. The first was on the flood plain of the River Taw and the second on the flood plain of the River Culm. In order to test the two different radionuclide tracers, the sediment contained in the plots installed on the River Taw flood plain was tagged with ^{60}Co, whereas that used on the flood plain of the River Culm was tagged with ^{134}Cs. The plots were maintained at each site for a total of 75 days between installation in late autumn 2006 and their removal in early spring 2007. Re-measurement of each plot was undertaken on two separate occasions after overbank flood events. For the River Taw, overbank events occurred on 25 November 2006 and 20 January 2007. Peak discharges for the events recorded at a nearby flow gauging station were 162 $m^3 s^{-1}$ (approximately equivalent to the mean annual flood), for the first event and 77.3 $m^3 s^{-1}$ for the second event. For the River Culm, overbank flood events occurred on 30 December 2006 and 13 February 2007 and the peak discharges, recorded at a nearby flow gauging station, were 21.1 $m^3 s^{-1}$ and 22.3 $m^3 s^{-1}$, respectively.

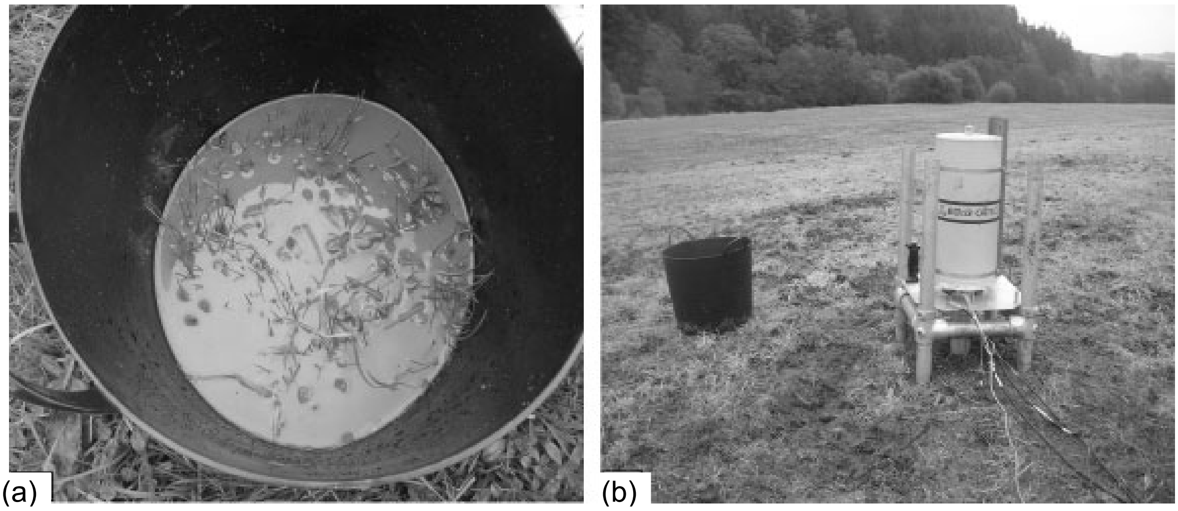

Fig. 1 (a) Simulating deposition during an overbank flood event, and (b) using the *in situ* gamma spectrometer.

THE STUDY SITES

River Taw flood plain

The study site (Fig. 2) is located within the middle reaches of the River Taw catchment (grid reference: SS 658 178), which has an upstream catchment area of approx. 600 km^2. The site extends to 3.9 ha and is under permanent pasture. A railway embankment bounds the site, immediately to the west, forming an effective flood barrier during large inundation events. The northerly part of the flood plain is dominated by a large swale running parallel with the main river, which gradually narrows and deepens with increasing distance northwest. Other topographic features include numerous small hillocks and depressions, as well as a pronounced levee set back from the main river channel

River Culm flood plain

The study site (Fig. 3) is located within the lower reaches of the River Culm catchment (grid reference: SS 984 010), which has an upstream catchment area of approx. 200 km^2. The site extends to 6.3 ha and is under permanent pasture, which is used for livestock grazing between the spring and early autumn. The site is bounded by the embankment of the M5 motorway to the immediate east, and by a ridge to the south and southwest. Both features form an effective flood barrier during large inundation events. Other topographic features include swales, breaches and small hillocks and depressions. A secondary drainage channel, orientated in a northeast to southwest direction, dissects the flood plain.

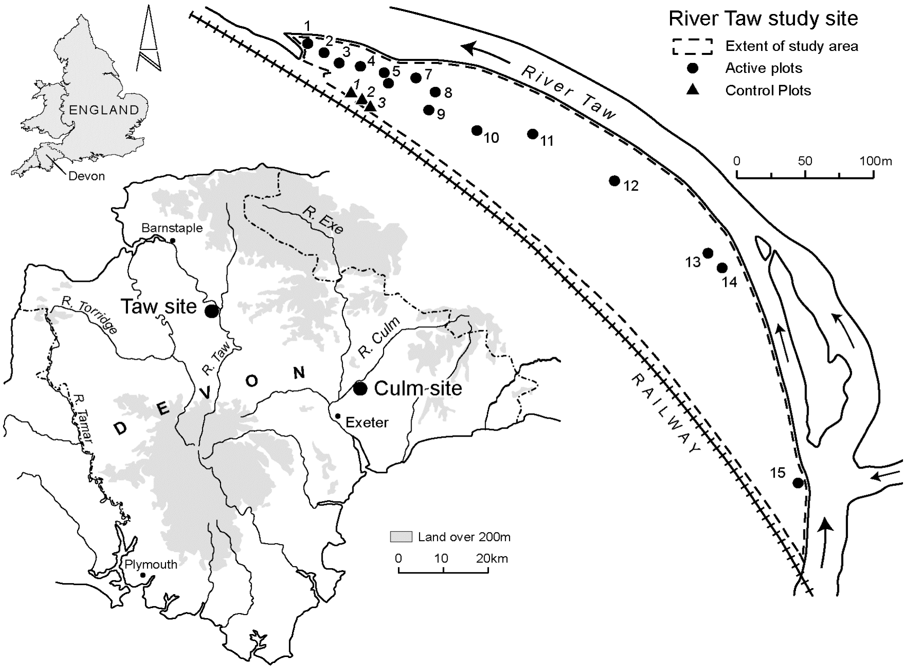

Fig. 2 The locations of the two flood plain sites investigated in this study and a map of the River Taw study site showing the locations of the control and active plots.

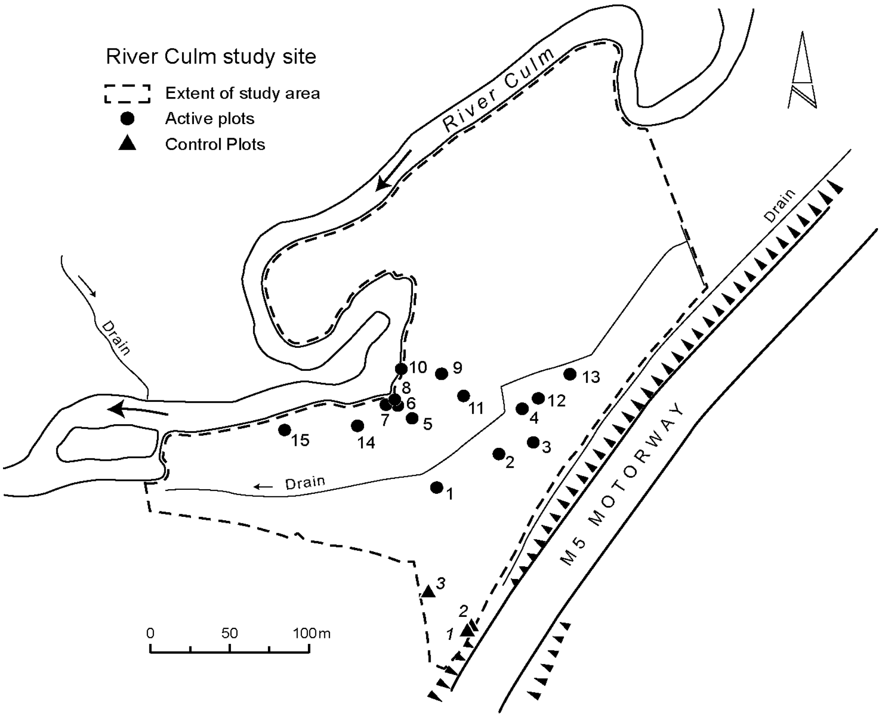

Fig. 3 A map of the River Culm study site, showing the locations of the control and active plots.

RESULTS

Areal activity density values for the individual plots on each flood plain, determined after each inundation event, were decay corrected and adjusted to take account of the changes in AAD values documented for the control plots. The precision of the measurements used to calculate the resulting AAD values was taken into account by expressing the AAD as the likely range of the value at the 90% confidence level. The resulting precision limits indicate the uncertainty associated with each value. Where overlap occurs between repeat measurements, changes in the AAD values were not statistically significant and therefore no remobilisation was deemed to have occurred. Where statistically significant differences existed between the repeat measurements, these were interpreted as reflecting remobilisation of the sediment associated with the plots.

River Taw flood plain

Figures 4 and 5 present a summary of the results of the ^{60}Co AAD measurements undertaken after the two overbank flood events on the River Taw flood plain. Figure 4 relates to the first event and shows that a statistically significant reduction in the AAD values, indicating the occurrence of remobilisation, was documented for 80% of the plots (i.e. 12 plots). Although the three remaining plots also recorded a net reduction in their AAD values, the reduction was not significant when the precision of the measurements was taken into account.

Figure 5 presents equivalent information relating to the measurements undertaken after the second overbank inundation event. It indicates that a significant reduction in the AAD values, relative to those documented after the first event, was found at 73% of the plots (i.e. 11 plots). A small net reduction was recorded by one additional plot and the three remaining plots were characterised by small net increases. None of these latter changes were, however, statistically significant.

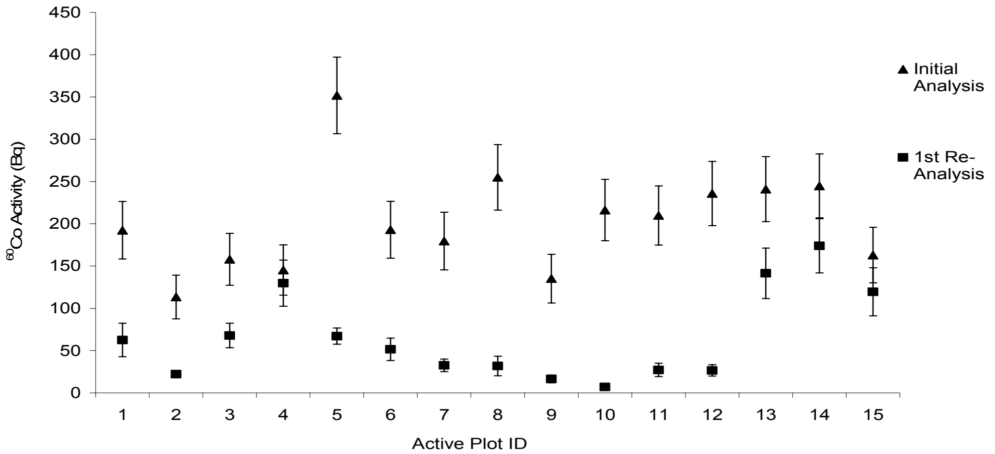

Fig. 4 A comparison of the initial ^{60}Co AAD values for plots on the River Taw flood plain, with those values measured after the first inundation event.

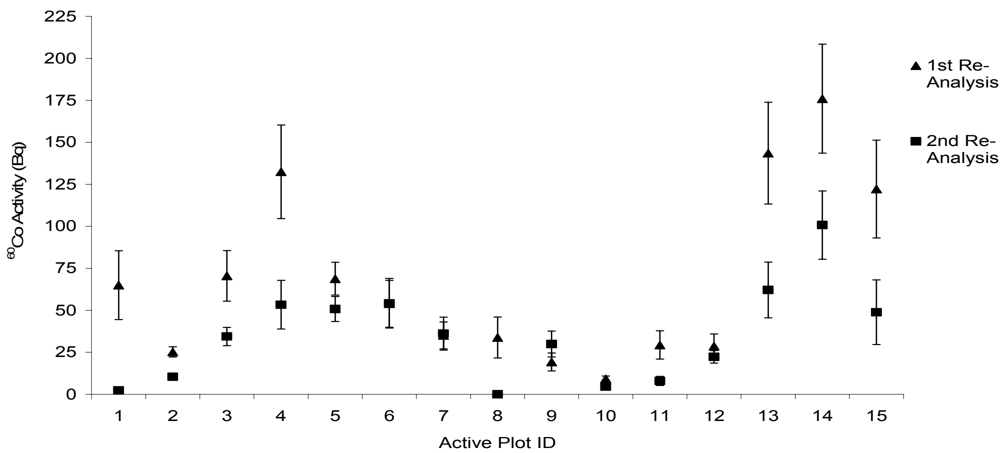

Fig. 5 A comparison of the ^{60}Co AAD values for plots on the River Taw flood plain measured after the second inundation event, with those values measured after the first event.

Figure 6 presents the ^{60}Co AAD values for each plot expressed as percentages, which represent the cumulative magnitude of the reduction of the AAD after each inundation event. It also shows the percentage of the original AAD value for each plot that remained after the second inundation event. Remobilisation removed an average of 66.4% of the initial AAD at the first inundation event, and a further 15.9% at the second inundation event. The average AAD remaining was 17.7%. The reductions of the AAD values indicated above are deemed to be approximately equivalent to the proportion of the sediment originally deposited within each plot that was remobilised.

A preliminary assessment of the key controls on the spatial variability of sediment remobilisation across the study site was undertaken. Table 1 lists the correlation coefficients for the relationships between the relative reduction in ^{60}Co AAD and distance from the river channel, and maximum inundation depths at individual plot locations. These relationships were tested for both the first event and for the cumulative reduction after the two events. A significant positive correlation was found between the reduction in the initial AAD and distance from the river channel after the first inundation event. However, the equivalent relationship for the cumulative reduction after the second event was not statistically significant. There was no significant relationship between the relative reduction in inventory and inundation depth.

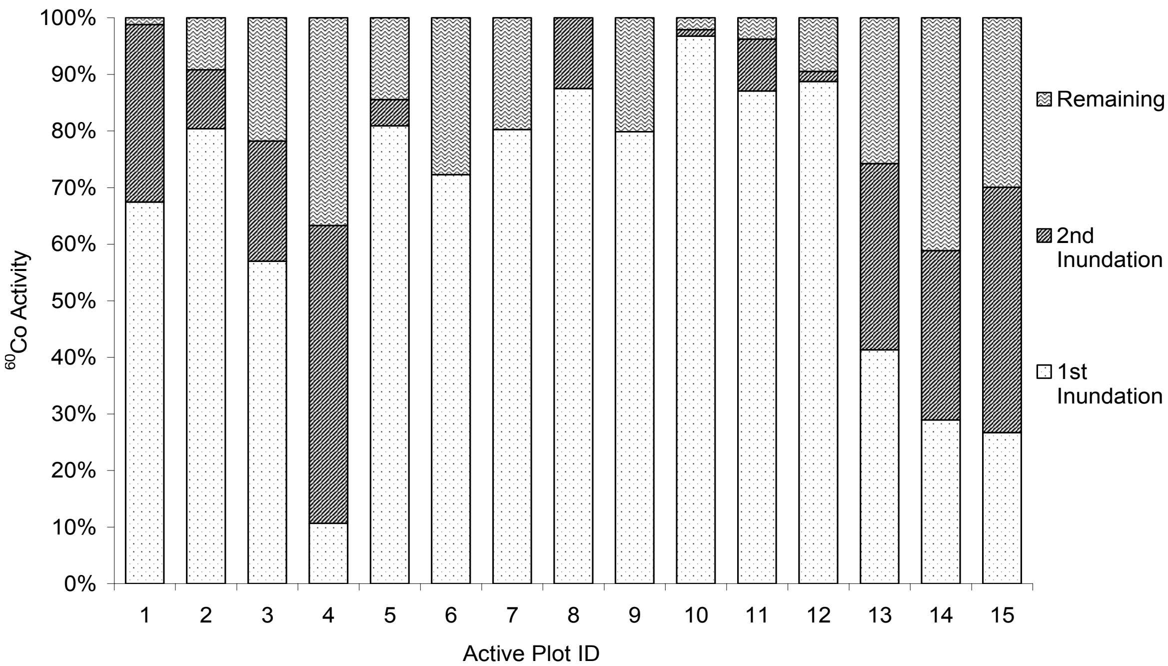

Fig. 6 The relative magnitude of the reduction of the initial ^{60}Co AAD values for the plots on the River Taw flood plain after two inundation events, and the proportion of the original ^{60}Co AAD value remaining after the second inundation event.

Table 1 Correlation coefficients for the relationships between the relative reduction in the ^{60}Co AAD of the plots on the River Taw flood plain and two potential controlling variables.

	Spearman's Rank Correlation Coefficient r_s		
	Distance from river channel	Inundation depth	d.o.f.
% ^{60}Co AAD reduction from 1st inundation event	0.606*	–0.036	15
Cumulative % ^{60}Co AAD reduction after the 1st and 2nd inundation events	0.218	0.326	15

**Sig. (P < 0.01): *Sig. (P < 0.05); d.o.f.: degrees of freedom.

River Culm flood plain

Figure 7 shows the reduction in the initial ^{134}Cs AAD values after the first inundation event and indicates that remobilisation occurred at 87% of the plots (13). The remaining two plots (13%) also recorded a net reduction, but these changes were not significant. Figure 8 presents equivalent data for the measurements taken after the second overbank inundation event. It indicates that a significant further reduction of the initial AAD values occurred at 67% of the plots (i.e. 10 plots). A small net reduction was recorded in the AAD values by three (20%) plots, and the remaining two recorded small increases. However, none of these latter changes were significant.

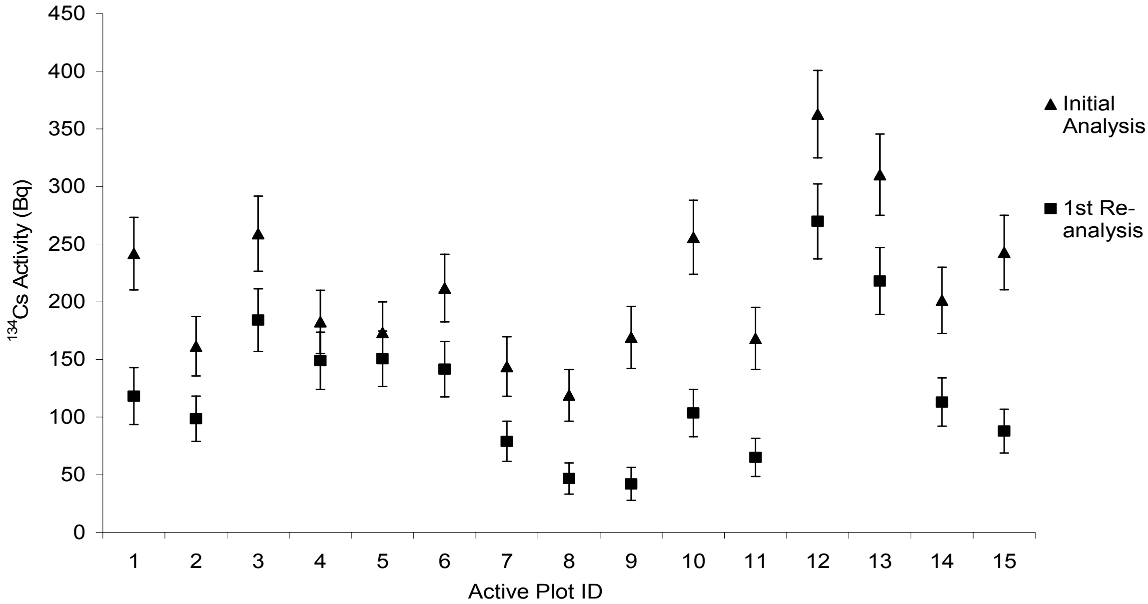

Fig. 7 A comparison of the initial ^{134}Cs AAD values for plots on the River Culm flood plain, with those values measured after the first inundation event.

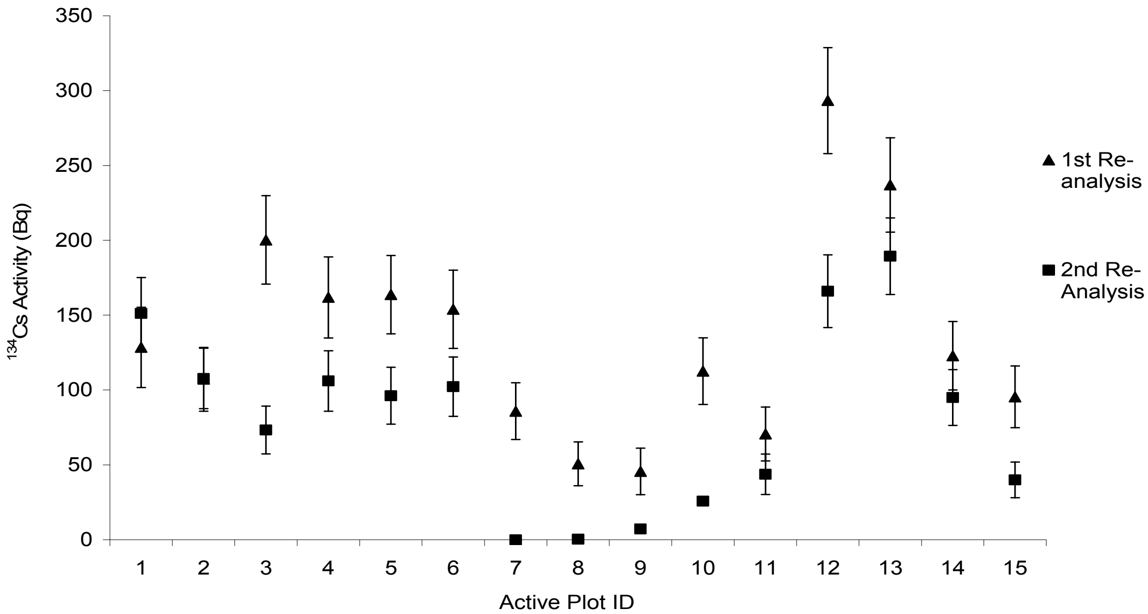

Fig. 8 A comparison of the ^{134}Cs AAD values for plots on the River Culm flood plain measured after the second inundation event, with those values measured after the first event.

Figure 9 presents the ^{134}Cs AAD values for each plot again, expressed as percentages, which represent the magnitude of the reduction of the initial AAD after each inundation event. It also shows the percentage of the initial AAD value for each plot that remained after the second inundation event. Remobilisation removed an average of 38.3% of the initial AAD at the first inundation event, and a further 20.4% during the second event. The average AAD remaining was 41.3%. As for the River Taw site, these reductions of AAD values are also deemed to be approximately equivalent to the proportion of the sediment originally deposited within each plot that was remobilised.

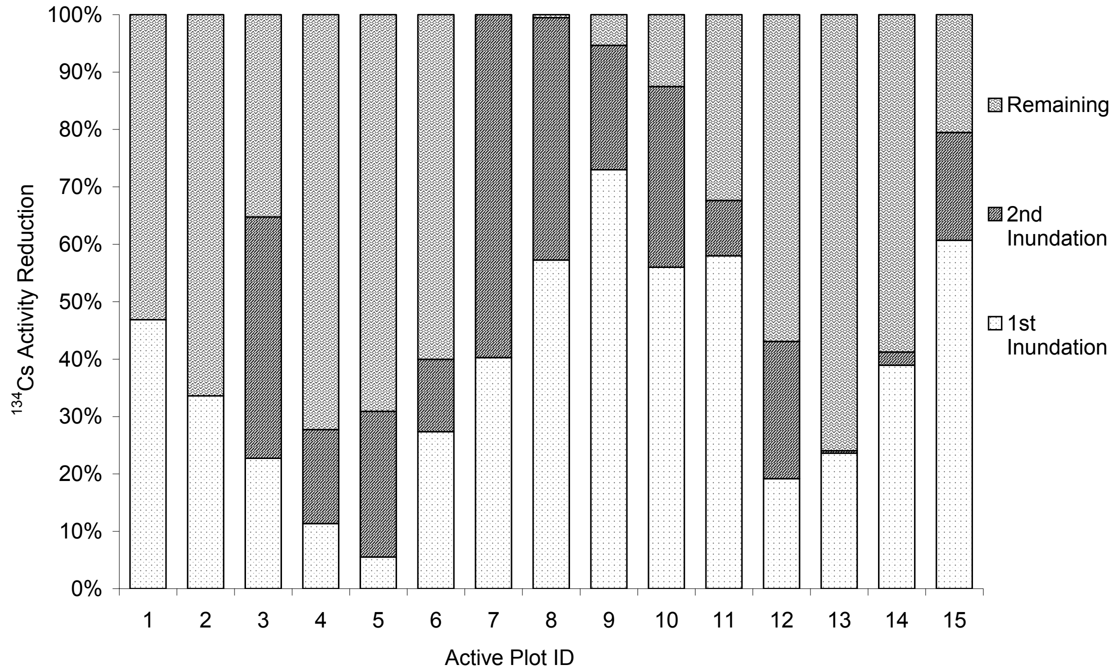

Fig. 9 The relative magnitude of the reduction of the initial ^{134}Cs AAD values for the plots on the River Culm flood plain after two inundation events, and the proportion of the original ^{134}Cs AAD value remaining after the second inundation event.

Table 2 Correlation coefficients for the relationships between the relative reduction in the ^{134}Cs AAD of the plots on the River Culm flood plain, and two potential controlling variables.

	Spearman's Rank Correlation Coefficient r_s		
	Distance from river channel	Inundation depth	d.o.f.
% ^{134}Cs AAD reduction from 1st inundation event	–0.674**	0.275	15
Cumulative % ^{134}Cs AAD reduction after the 1st and 2nd inundation events	–0.702**	0.011	15

** Sig. (P < 0.01); *Sig. (P < 0.05); d.o.f.: degrees of freedom.

Table 2 lists the correlation coefficients for the relationships between the relative reduction in AAD and distance from the river channel and the maximum inundation depth at the plot locations. These relationships were tested for both the first event and for the cumulative reduction after the two events. In this case, significant negative correlations were found between the reduction of the AAD and therefore the amount of sediment remobilised, and distance from the river channel. As with data from the River Taw flood plain, there was no significant correlation with inundation depth.

DISCUSSION

The majority of plots installed on both river flood plains provided clear evidence of appreciable remobilisation of recently deposited sediment during subsequent overbank flood events. Overall, the proportion of the plot sediment remobilised at the River Taw site was substantially greater than for the River Culm site. This contrast can be tentatively related to the lower channel gradient and lower overbank flow velocities associated with the flood events at the River Culm site, and may also reflect differences in the magnitude of the inundation events at the two study sites.

The contrast between the significant negative relationship between the reduction in tracer inventory with distance from the river channel at the River Culm site for both the first inundation event and the cumulative effect of the two events, and the positive relationship demonstrated by the first inundation event at the River Taw site, may reflect differences in hydraulic conditions and the physical characteristics of the two sites, as well as the relatively small number of sampling points. These characteristics could include local micro-topography, surface roughness and the flood plain geometry, and further work is required to explore the effects of these controls using more intensive sampling networks, aimed at explicitly testing their influence, and at a wider range of sites.

Overall, the findings of the study have important implications for interpreting estimates of medium-term sediment deposition rates provided by ^{137}Cs and ^{210}Pb measurements on river flood plains, since these estimates represent the net deposition of sediment over medium timescales. Over shorter timescales, greater amounts of sediment may be deposited at locations across a flood plain, but much of this recently deposited sediment may be remobilised during subsequent overbank flood events. Further work is therefore clearly required in order to establish the proportion of the gross amount of sediment deposited on the flood plain during individual events represented by the estimates of longer-term net deposition rates provided by ^{137}Cs and ^{210}Pb measurements, and to establish the time taken for recently deposited sediment to become fully incorporated into the longer-term sediment column.

CONCLUSIONS

The work described in this paper sought to develop a means of using radionuclide tracers (^{134}Cs and ^{60}Co) to document the extent and magnitude of remobilisation of recently deposited sediment from river flood plains during subsequent overbank flood events. The procedure developed has been applied at flood plain sites on two rivers in Devon, UK, to establish the magnitude of the remobilisation and to undertake a preliminary exploration of the factors controlling the spatial distribution of remobilisation across the study sites. Within the constraints of the experimental procedures employed, and taking account of the uncertainties associated with simulating sediment deposition associated with overbank flood events, the results of the studies suggest that significant remobilisation of recently deposited sediment occurs during subsequent overbank events.

Although the available data obtained from each flood plain site were insufficient to explore fully the factors controlling the spatial variability of sediment remobilisation, the results suggest that remobilisation was not limited to particular areas during overbank flood events, but occurred at a range of sites across both flood plains. Further work is therefore required to undertake more detailed investigations of the spatial variability of sediment remobilisation across river flood plains using denser networks of plots and a more extensive range of river flood plain sites.

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