USE OF CESIUM-137 AS A TRACER IN THE STUDY
OF RATES AND PATTERNS OF FLOODPLAIN
SEDIMENTATION

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ABSTRACT Rates and patterns of contemporary floodplain sedimentation have proved difficult to document using conventional monitoring techniques due to both operational and spatial sampling constraints. The use of fallout radionuclide tracers, particularly \(^{137}\)Cs, offers an alternative approach to investigating floodplain sedimentation. The \(^{137}\)Cs content of floodplain sediments reflects two primary sources; firstly atmospheric fallout to the floodplain surface and, secondly, the deposition of sediment-associated \(^{137}\)Cs during flood events. By analyzing either the depth distribution of \(^{137}\)Cs or the total \(^{137}\)Cs inventory of sediment cores, it is possible to derive estimates of average deposition rates over the past 35 years. Spatial variation of the grain size composition of deposited sediment must, however, also be considered when interpreting inventory data. This paper describes a procedure for deriving estimates of sedimentation rates for individual points on the floodplain based on measurements of the total \(^{137}\)Cs inventory and the \(^{137}\)Cs content of surface sediment. The resultant data can be used to study the spatial pattern of sedimentation within a floodplain reach. A case study of a short reach of the floodplain of the River Culm in Devon, UK, is used to demonstrate the approach. Average sedimentation rates in the range 0.06-0.60 g cm\(^{-2}\) year\(^{-1}\) have been documented.

INTRODUCTION

Information concerning rates and patterns of contemporary floodplain sedimentation is extremely difficult to obtain using conventional monitoring procedures, due to a variety of operational problems and both spatial and temporal sampling constraints. Recent work has, however, demonstrated that fallout radionuclide tracers, and more particularly cesium-137 (\(^{137}\)Cs), can provide a valuable means of assembling detailed information on average rates and patterns of floodplain sedimentation over the past 35 years (cf. Walling & Bradley, 1989a, b; Walling et al., 1992). In essence, the basis for using \(^{137}\)Cs for this purpose is that radiocesium is rapidly and strongly adsorbed by the fine fractions of soils and sediments and accumulates in floodplain sediments as a result of inputs from two primary sources. These sources represent direct atmospheric fallout to the floodplain surface and the deposition of sediment-associated \(^{137}\)Cs during the process of sediment accretion. This sediment-associated \(^{137}\)Cs represents radiocesium originating as fallout over the upstream basin which has been adsorbed by soil and sediment particles and subsequently mobilized by erosion and transported downstream as an integral part of the suspended sediment load of the river. Both the vertical distribution and the total inventory of \(^{137}\)Cs in floodplain sediments will therefore commonly differ from those in the soils of surrounding areas above the level of floodplain inundation, since the latter areas will have received \(^{137}\)Cs only from atmospheric fallout.
Fig. 1B illustrates a typical $^{137}$Cs profile from the floodplain of the River Culm in Devon, UK, and Fig. 1A shows a typical profile from undisturbed pasture in the immediate vicinity, but above the level of inundating floodwaters. In this area of the UK, levels of Chernobyl fallout were negligible and fallout associated with the atmospheric testing of nuclear weapons, primarily in the late 1950s and the early 1960s, represents the sole source of radiocesium. In the case of the undisturbed pasture (Fig. 1A), fallout reaching the soil surface has been adsorbed and subsequently redistributed within the upper soil horizons by diffusion, translocation and mixing associated with biological activity. The profile exhibits the classic pattern of exponential decline in radiocesium activity with depth and retention of the majority of the $^{137}$Cs in the upper 10 cm, which has been widely documented (cf. Walling & Quine, 1992). The form of the radiocesium profile from the floodplain differs markedly from that for the undisturbed pasture. First, the total inventory associated with the floodplain profile is significantly greater than that for the pasture and, secondly, the shape of the $^{137}$Cs profile is different. In this case, the gradual accretion of the floodplain surface has caused the fallout input to be incorporated within a greater depth of sediment and this fallout input has been supplemented by the input of sediment-associated radiocesium contained in the deposited sediment. The shape of the profile therefore partially
reflects the temporal pattern of atmospheric fallout during the period 1955 to the present (cf. Pennington et al., 1973; Walling & He, 1992) and the level represented by the subsurface peak can be tentatively dated to 1963, the year of maximum fallout.

Walling & Bradley (1989) have described two approaches to using information on the $^{137}\text{Cs}$ content of floodplain cores to estimate rates of sedimentation over the past 30-40 years. In the first, the shape of the depth profile is used. If this is compared with that from an adjacent undisturbed reference site (cf. Fig. 1A & B), the degree of 'stretching' can be estimated and this in turn can be used to estimate the depth of sedimentation. Alternatively, the position of the level with peak activity can be used to estimate the depth of the 1963 surface, or more complex models can be employed to ascribe dates to several depths in the profile (cf. Walling & He, 1992). In the second approach, the total inventory of a floodplain core is compared with a reference value representing local fallout and the value of 'excess' inventory is used in combination with an estimate of the mean $^{137}\text{Cs}$ content of suspended sediment during the period since 1955 to estimate the amount and thus the depth of sediment accretion (cf. Walling et al., 1992).

However, both the approaches outlined above have important limitations. Use of information relating to the shape of the $^{137}\text{Cs}$ depth profile necessitates analysis of a large number of samples from sectioned cores. In view of the long counting times commonly required by gamma spectrometry measurements, it will therefore generally be impractical to analyze more than a few cores, particularly where deposits of accretion are substantial. This approach is therefore of limited value in the study of detailed spatial patterns of floodplain sedimentation where large numbers of cores would be required. The 'excess' inventory approach has the major advantage that only a single $^{137}\text{Cs}$ measurement is required on each core in order to assay the total inventory, and a greater number of cores can therefore be used. Nevertheless, there are uncertainties associated with deriving estimates of sedimentation depth from values of 'excess' inventory. More particularly, it is necessary to assume that the mean $^{137}\text{Cs}$ concentration of deposited sediment is effectively constant within the area studied. In reality, some variation in this concentration is likely to occur across an area, in response to variations in the grain size composition of deposited sediment. Because $^{137}\text{Cs}$ is likely to be preferentially associated with the finer fractions of the deposited sediment (cf. Walling & Woodward, 1992), use of a mean value of $^{137}\text{Cs}$ content could lead to overestimation of deposition rates for points where the deposited sediment contains an increased proportion of fines and underestimation for points where coarser sediment predominates. Temporal shifts in the calibre of deposited sediment would also introduce further uncertainties into the estimation of deposition rates.

Despite these limitations and uncertainties, the use of whole core measurements of total inventories undoubtedly offers considerably greater potential for investigating spatial patterns of floodplain sedimentation than interpretation of the shape of $^{137}\text{Cs}$ profiles, by virtue of the much greater number of sampling points that can be studied. Typically, it may be necessary to assay 25 samples from a sectioned core, in order to define the profile shape and estimate the rate of deposition for that single sampling point. With whole core measurements, an equivalent number of analyses could generate estimates of deposition rates for 25 individual sampling points. There is, however, a need to refine the procedures used to estimate rates of deposition from whole core $^{137}\text{Cs}$ measurements, particularly to take account of the potential influence of spatial variation in the grain size of deposited sediment. This paper reports an attempt by the authors to refine the whole core approach when applied to a study of rates and patterns of floodplain sedimentation within a small reach of the floodplain of the River Culm in Devon, UK (Fig. 1C).
DATA COLLECTION

In this study, attention focussed on documenting the detailed pattern of sedimentation rates in an area of floodplain adjacent to a meander bend (Fig. 1C). In total, 53 whole cores were collected from the study area using a motorized percussion corer equipped with 6.9 cm diameter core tube. The sampling points were located on a 7m x 7m survey grid and the cores were collected to depths of up to 70 cm to ensure that the total depth of $^{137}$Cs-bearing sediment was sampled. Samples of surface sediment (0-1 cm) were also collected immediately adjacent to each coring point. Several additional cores were collected from representative sites using a 12.0 cm diameter corer in order to provide larger diameter cores for sectioning into depth increments. These depth incremental samples were used to provide additional data to support the development of the calculation procedures reported.

After collection, all cores and samples were air dried and disaggregated prior to gamma assay using a high purity germanium detector linked to a multi-channel analyzer. Counting times were typically c. 30 000 s, providing an analytical precision of c. ± 6% (2 s.d.). Measurements of grain size composition were also undertaken on the surface samples and a selection of other samples using laser diffraction (Malvern MasterSizer). All samples used for determination of grain size composition were treated to remove organic matter and chemically dispersed prior to analysis.

A REFINED APPROACH FOR ESTIMATING RATES OF DEPOSITION

The basic data

The basic data assembled for this study are presented in Fig. 2 which depicts the topography of the study area relative to an arbitrary datum (Fig. 2A), the spatial distribution of total $^{137}$Cs inventories across the area (Fig. 2B), and the $^{137}$Cs activity (mBq g$^{-1}$) and grain size composition (% < 0.063 mm) of the surface samples (Fig. 2C & D). Fig. 2D indicates that significant variations in the grain size composition of the surface samples occur across the study area and these are closely related to both the variations in the $^{137}$Cs content of the surface sediments mapped in Fig. 2C and the local microtopography (Fig. 2A). Areas with an increased proportion of sediment < 0.063 mm are in general marked by higher levels of $^{137}$Cs activity. The data presented in Fig. 2C & D suggest that any attempt to derive estimates of rates of sedimentation based on values of excess inventory and an estimate of the mean $^{137}$Cs content of deposited sediment during the period since 1955 is likely to involve significant errors, with, for example, underestimation in areas close to the channel and over-estimation in areas nearer the centre of the meander core.

Down-profile variation in the grain size composition of the floodplain sediments as measured in one of the sectioned cores is shown in Fig. 3A. The grain size composition of the sediment remains essentially constant with depth, indicating that the spatial pattern of grain size composition depicted in Fig. 2D is likely to be representative of the pattern operating in the medium-term past. This in turn means that the spatial pattern exhibited by the $^{137}$Cs activity of the surface samples is also likely to be representative of the medium-term situation. The current spatial pattern of $^{137}$Cs activity in the surface samples reflects the $^{137}$Cs content of the deposited sediment, since fallout inputs to the surface are currently negligible, and thus in turn primarily reflects spatial variation in the grain size composition of that sediment.
FIG. 2 Information on the topography (A), total $^{137}$Cs inventories (B), $^{137}$Cs activity of surface sediments (C) and grain size composition of surface sediments (D) assembled for the study area.
Modelling $^{137}$Cs accumulation in floodplain sediments

The total $^{137}$Cs inventory (mBq cm$^{-2}$) of a sediment core collected from a floodplain will, as noted above, reflect contributions from both direct atmospheric fallout to the floodplain surface and radiocesium associated with deposited sediment which has been mobilized from the upstream drainage basin. Walling & He (1992) have proposed a model which enables the form of the $^{137}$Cs profile to be modelled based on information relating to these two contributions and a simple representation of post-depositional mobility. Following their model, the annual input of $^{137}$Cs to a specific point on the floodplain $I_{in}(t)$ (mBq cm$^{-2}$ year$^{-1}$) can be expressed as:

$$I_{in}(t) = I_a(t) + I_{ca}(t)$$ (1)

where $I_a(t)$ is the direct atmospheric input and $I_{ca}(t)$ is the catchment-derived input (both expressed in mBq cm$^{-2}$ year$^{-1}$). The catchment-derived input $I_{ca}(t)$ can be seen as reflecting contributions from soil erosion on both cultivated land and permanent pasture and may be expressed as:

$$I_{ca}(t) = a[I_u(t) + r_a I_c(t)]$$ (2)

where:

$I_u(t)$ = the $^{137}$Cs activity in surface soils of undisturbed pasture (mBq g$^{-1}$);
$I_c(t)$ = the $^{137}$Cs activity in surface soils from cultivated land (mBq g$^{-1}$);
$r_a$ = the ratio of the sediment contribution from cultivated land to that from undisturbed pasture;
$a$ = a site specific constant (g cm$^{-2}$ year$^{-1}$) reflecting the selectivity of both the erosion and the deposition processes.

Sediment eroded from river banks and other deep sources is likely to contain negligible levels of $^{137}$Cs activity. After deposition, some mobility of the $^{137}$Cs inputs will occur in response to mixing and diffusion processes. If it is assumed that the sediment at a specific site is homogeneous and can be treated as a semi-infinite medium, that the sediment accumulation rate ($R$) is effectively constant, and that the post-depositional mixing of $^{137}$Cs can be represented by a simple diffusion coefficient $D$ (g$^2$ cm$^{-4}$ year$^{-1}$), then the variation of $^{137}$Cs activity $A(x, t)$ (mBq g$^{-1}$) with depth can be described by the following eqn:

$$\frac{\partial A(x, t)}{\partial t} = \frac{\partial}{\partial x} \left[ D \frac{\partial A(x, t)}{\partial x} \right] - R' \frac{\partial A(x, t)}{\partial x} - \lambda A(x, t)$$ (3)

where:

$\lambda$ = the annual decay constant for $^{137}$Cs;
$t$ = time since $^{137}$Cs was first introduced (years);
$x$ = cumulative mass per unit area from the surface downwards (g cm$^{-2}$) and $R'$ is:

$$R' = R + R_m$$ (4)

where $R_m$ is the downward migration rate of $^{137}$Cs in the sediment which is needed to take account of the evidence of slow downward migration of $^{137}$Cs in undisturbed soils (cf. Fig. 1A) which will also occur in floodplain sediments.

Mass conversion of $^{137}$Cs requires the following boundary conditions to be met:
Rates and Patterns of Floodplain Sedimentation

\[-D \frac{\partial A(x, t)}{\partial x} \bigg|_{x=0} + \frac{R' A(x, t)}{1} \bigg|_{c=0} = 0 \quad (5)\]

\[\lim_{x \to \infty} \frac{\partial A(x, t)}{\partial x} = 0 \quad (6)\]

For an instantaneous input \( I_{in}(x, t') \) (mBq g\(^{-1}\) year\(^{-1}\)) at time \( t' \), solution \( A(x, t, t') \) (mBq g\(^{-1}\) year\(^{-1}\)) of Eqn (3) under boundary conditions (5) and (6) is:

\[
(x, t, t') = e^{-\lambda(t-t')} \int_{0}^{\infty} I_{in}(y, t') \left\{ \exp\left( \frac{x^2}{2D} - \frac{y^2}{4D} \right) \left[ \exp\left( -\frac{(x+y)^2}{4D(t-t')} \right) + \exp\left( -\frac{(x-y)^2}{4D(t-t')} \right) \right] \right\} dy
\]

where \( \text{erfc}(u) \) is the error-function complement defined as:

\[
\text{erfc}(u) = \frac{2}{\sqrt{\pi}} \int_{u}^{\infty} e^{-z^2} dz
\]

For a continuous input, the \(^{137}\)Cs activity distribution with depth \( A(x, t) \) can be expressed as:

\[
A(x, t) = \int_{0}^{t} A(x, t, t') \, dt'
\]

In the case of floodplain sediments it is reasonable to assume that the catchment-derived \(^{137}\)Cs input will be uniformly distributed within the deposited sediment. For the atmospheric input, experimental evidence suggests that instantaneously deposited \(^{137}\)Cs will be approximately exponentially distributed within the surface layer of sediment with a relaxation depth \( H \) expressed in cumulative mass per unit area (g cm\(^{-2}\)). The initial \(^{137}\)Cs distribution in the sediments for Eqn (3) can therefore be represented as:

\[
I_{in}(x, t') = \begin{cases} \frac{a}{R} \left[ I_u(t') + r_d I_c(t') \right] & x \leq R \\ \left( I_u(t) \left[ \frac{x-R}{H} e^{-\frac{x}{H}} \right] \right) & x > R \end{cases}
\]

Fig. 3B shows the result of fitting the above model to the \(^{137}\)Cs profile illustrated in Fig. 1B. Information on the temporal distribution of fallout inputs during the period 1954 to 1990 was derived using the measured fallout data for Milford Haven, UK, reported by Cambrey et al. (1982) adjusted to represent the local fallout inventory. The profile shape is closely reproduced, suggesting that the model provides an acceptable representation of radioesium accumulation in this floodplain environment. The \(^{137}\)Cs concentrations in deposited sediment (the catchment-derived input) predicted by the model are presented in Fig. 3C. The close agreement between the \(^{137}\)Cs concentrations predicted by the model for recent years and those measured in sediment samples provides further confirmation of the validity of the model.

Estimating sediment accumulation rates

The above model can be used to estimate the sediment accumulation rate (g cm\(^{-2}\) year\(^{-1}\)) at a specific point on the floodplain over the period since the initiation of \(^{137}\)Cs fallout, from
the total $^{137}$Cs inventory measured at the point (cf. Fig. 3B) and the concentration of $^{137}$Cs measured in the surface sediments (cf. Fig. 3C), by assuming that the sedimentation rate has been essentially constant over the period.

Following the arguments outlined above, The $^{137}$Cs inventory $A_{inv}$ (mBq cm$^{-2}$) for a specific point on the floodplain can be expressed as:

$$A_{inv} = \int_{0}^{t} l_{a} (t') e^{-\lambda (t-t')} dt' + \int_{0}^{t} l_{ca} (t') e^{-\lambda (t-t')} dt'$$

and from Eqn (11) the excess $^{137}$Cs inventory $A_{ex}$ (mBq cm$^{-2}$) can be defined as:
\[ A_{\text{ex}} = A_{\text{inv}} - \int_0^t a(t') e^{-\lambda(t-t')} \, dt' \]  

which is equivalent to the catchment-derived $^{137}\text{Cs}$ input corrected for decay to the present:

\[ A_{\text{ex}} = \int_0^t a \left[ I_u(t') + r_{ac} I_c(t') \right] e^{-\lambda(t-t')} \, dt' \]  

If it is assumed that the surface sediment collected from each site is representative of recently deposited sediment and that no mixing with deeper sediment has occurred, the radiocesium activity of this sediment can be viewed as representative of recent catchment-derived inputs, because atmospheric inputs of $^{137}\text{Cs}$ are currently negligible. From Eqns (2) and (10), we therefore obtain:

\[ A_s(t) = \frac{I_{ca}(t)}{R} = \frac{a}{R} \left[ I_u(t) + r_{ac} I_c(t) \right] \]  

where $A_s(t)$ (mBq g$^{-1}$) is the radiocesium activity in surface sediment. From Eqn (14) we have:

\[ a = \frac{R A_s(t)}{I_u(t) + r_{ac} I_c(t)} \]  

and by substituting Eqn (15) into Eqn (13) the sediment accumulation rate $R$ (g cm$^{-2}$ year$^{-1}$) for a particular point on the floodplain can be estimated as:

\[ R = \frac{A_{\text{ex}} \left[ I_u(t) + r_{ac} I_c(t) \right]}{A_s(t) \int_0^t \left[ I_u(t') + r_{ac} I_c(t') \right] e^{-\lambda(t-t')} \, dt'} \]  

RESULTS

The results of applying this procedure for estimating sedimentation rates during the period 1954-1991 to the information on total radiocesium inventories and concentrations of radiocesium in surface sediments within the study area presented in Fig. 3 are shown in Fig. 4. The values of sediment accumulation rate depicted evidence variation from 0.06 g cm$^{-2}$ year$^{-1}$ to 0.60 g cm$^{-2}$ year$^{-1}$ and the resultant pattern clearly demonstrates that sedimentation rates may display complex local patterns in response to local topographic conditions and proximity to the river channel. In this area, maximum sedimentation rates occur close to the channel and relatively low rates are found in the depressions within the meander core. Such data could provide a valuable basis for testing floodplain sedimentation models.

PERSPECTIVE

The results presented above clearly emphasize the potential for using $^{137}\text{Cs}$ as a sediment tracer in floodplain environments. The information on rates and patterns of floodplain sedimentation assembled inevitably possesses limitations in terms of its temporal resolution, since the sedimentation rates represented mean values for a period of c. 35 years, but the ability to document medium-term rates could equally be seen as a significant advantage. Furthermore, information with an equivalent degree of spatial resolution would be difficult to obtain using any other monitoring technique. Previous attempts using $^{137}\text{Cs}$ inventories of floodplain cores to document rates and patterns of floodplain sedimentation have suffered from inaccuracies associated with the difficulty in accounting for spatial variations in the grain size composition of deposited sediment, but the approach advocated in this paper essentially overcomes that limitation. Using this approach, medium-term rates and patterns of floodplain sedimentation can be documented during a short visit to a study site,
which will be needed to collect sediment cores and samples of surface sediment.

FIG. 4 The pattern of sedimentation rates within the study area estimated using the approach described in the paper.

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