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Interpretation of caesium-137 profiles in lacustrine and other sediments: the role of catchment-derived inputs

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Abstract

The caesium-137 profiles obtained in many investigations which have attempted to use caesium-137 measurements as a means of assessing the rate of accumulation of recent lake sediments, have not conformed to the classic shape expected from the record of fallout input. Such deviations have been accounted for in terms of post-depositional mobility of the caesium-137 input (e.g. bioturbation) and delayed inputs from the drainage basin. There have, however, been few attempts to determine the likely character of the drainage basin input and to analyse the role of such inputs in influencing the precise form of the caesium-137 profile. This paper presents the results of an attempt to employ existing knowledge concerning the behaviour of caesium-137 in soils and the processes of sediment mobilization to predict the likely form of the record of caesium-137 input to a lake or river floodplain from its drainage basin. The influence of this input on the profile shape will depend on the relative importance of the atmospheric fallout to the lake or floodplain surface and the drainage basin input to the total caesium-137 inventory in the sediment core, and on the land use and sediment sources in the drainage basin. By incorporating the drainage basin input into a simple model of caesium-137 accumulation in lake and floodplain sediments, it was possible to account for the profile shapes measured in four cores investigated by the authors and therefore to verify their utility for assessing rates of sediment accumulation.

Introduction

Information on recent rates of sedimentation in lakes, reservoirs, river floodplains and similar environments is increasingly required, both as a means of deciphering recent trends in environmental pollution and for quantifying the rate of operation of contemporary geomorphological processes. Caesium-137, an artificial radionuclide produced by the atmospheric testing of nuclear weapons in the late 1950's and early 1960's, has proved a valuable tracer for interpreting rates of sedimentation associated with the past 30–40 years (Krishnaswami & Lal, 1978). It has been widely used in both lakes and reservoirs (e.g. Robbins & Edgington, 1975; Ritchie *et al.*, 1973) and has also been applied in floodplain and saltmarsh environments (e.g. Walling & Bradley, 1989; Delaune *et al.*, 1978).

The basis for using caesium-137 in this context is that the first appearance of the radionuclide in the sediment profile can, at most locations, be dated to the early 1950's, and that the vertical distribution of caesium-137 in the sediment profile can be related to the known record of fallout for the subsequent period (Payne, 1985). The peak levels of fallout that occurred in 1963 have thus been used to date deposition occurring at that time. Figure 1a illustrates the typical pattern of fallout that has occurred at sites in the northern hemisphere since the early 1950's, and Fig. 1b shows how this can be matched to the down-profile variations in the caesium-137 content of a lake sediment core. In this lake core taken from Rostherne Mere, UK, and reported by Livingstone & Cambray (1978), the high levels of fallout that occurred in 1959 and 1963 are clearly evident.

The example shown in Fig. 1b must, however, be viewed as an ideal case, since the literature contains many reports from studies where the caesium-137 profile in a lake sediment core does not conform to that expected from the fallout record depicted in Fig. 1a. Explanations involving post-depositional mobility of caesium-137, resulting from molecular diffusion (Davis *et al.*, 1984), bioturbation (Sholkovitz & Mann, 1984), and resuspension and focussing of deposited sediment (Brunskill *et al.*, 1984); and the influence of delayed inputs of caesium-137 from the drainage basin of the lake (Miller & Heit, 1986), have been invoked to account for such situations. It is now clear that lakes such as Rostherne Mere, which yield caesium-137 profiles from their sed-

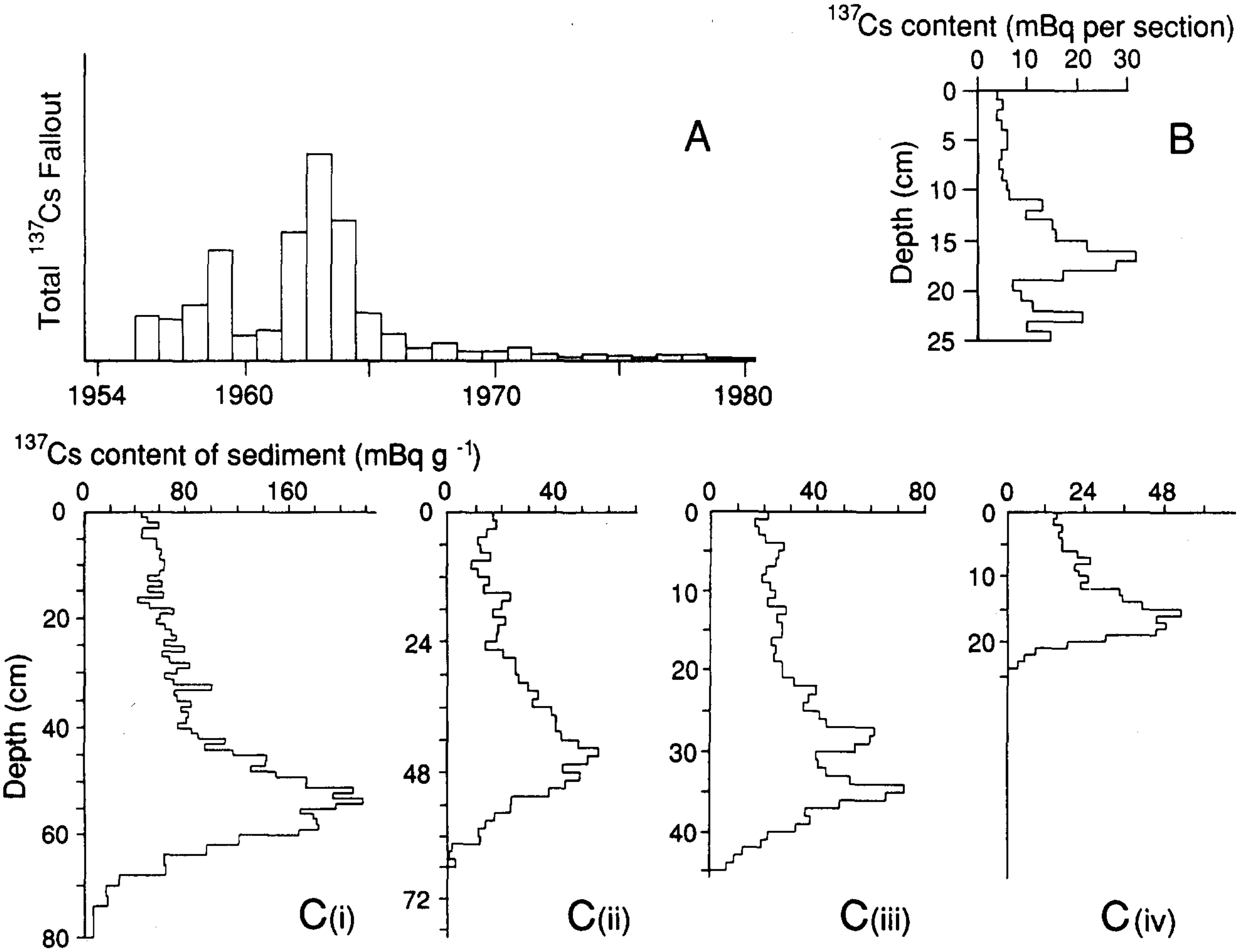

Fig. 1. a. The pattern of total annual caesium-137 fallout in the northern hemisphere (based on Cambray *et al.*, 1982). b. The caesium-137 profile for a sediment core from Rostherne Mere, UK, reported by Livingstone & Cambray (1978). c. Caesium-137 profiles measured by the authors in sediment cores from Chard Lake (Ci), Wadhurst Park Lake (Cii), the River Culm floodplain (Ciii) and the River Axe floodplain (Civ).

iments similar to that shown in Fig. 1b, are somewhat exceptional. Rostherne Mere is indeed rather unusual in that sedimentation rates are relatively rapid (ca. 1 cm yr^{-1}), the deposited sediment is dominated by autochthonous organic sediment associated with the high productivity of the lake (Oldfield, 1981), and the deep water favours anoxic conditions with an associated lack of bioturbation.

The caesium-137 profiles obtained by the authors for two small lakes and two river floodplain sites in the UK, illustrated in Fig. 1c, are more typical of those generally encountered in the literature. These exhibit only a single broad peak, and the rapid decline of caesium-137 concentrations towards the surface in response to the low levels of fallout post 1970 is absent. Bioturbation may provide one possible explanation of the contrast with the profile shape shown in Fig. 1b, but in all four cases the total caesium-137 inventory of the core is considerably in excess of the equivalent estimate of local fallout obtained from measurements of undisturbed soils in the area (Table 1). Additional delayed input of caesium-137 transported from the upstream drainage basin could therefore be expected to exert an important influence on the shape of the caesium profile. In the case of the two lake cores, this additional input would be associated with allochthonous sediment eroded from the upstream drainage basin and transported to the lake, whereas with the two floodplain sites it would be associated with deposition of caesium-bearing sediment during times of floodplain inundation.

Table 1. Caesium-137 inventories for the four sediment cores illustrated in Fig. 1c and their relationship to local fallout inventories.

Core location	Total caesium-137 inventory (mBq cm^{-2})	Local fallout inventory* (mBq cm^{-2})
Chard Lake	1105	285
Wadhurst Park Lake	862	285
River Culm floodplain	1239	270
River Axe floodplain	632	270

* Estimated from soil samples collected from undisturbed non-eroding locations in the vicinity.

Although there are numerous references in the literature to the role of 'watershed integration processes', 'delayed export from the drainage basin', 'watershed wash-in', 'slow erosional transport' and equivalent processes, little information currently exists as to the precise influence of such drainage basin contributions on the final shape of the caesium-137 profile obtained from a lake or floodplain. Such information is, however, essential to ensure correct interpretation of the profile. Furthermore, attempts to quantify the effects of post-depositional mobility and bioturbation on the shape of the caesium-137 profile commonly rely on a comparison of the actual profile shape with an estimate of the shape that would have been generated by the original inputs of caesium-137 to the site (Robbins *et al.*, 1977; Olsen *et al.*, 1981). Again it is important to take account of the role of any delayed input from the drainage basin in establishing the 'original' shape of the profile.

This paper reports an attempt by the authors to obtain an improved understanding of the role of the drainage basin contribution in controlling the precise shape of the caesium-137 profile obtained from a lake or floodplain.

Existing concepts

In discussing the potential effects of the drainage basin contribution on the shape of the caesium-137 profile encountered in a lake core, Wise (1980) emphasised the lag existing between caesium-137 entering the drainage basin as fallout onto the soil and its delivery to the lake. This, he suggested, could cause the caesium-137 content of the upper portion of a lake core to be considerably greater than might be expected from consideration of the pattern of atmospheric fallout to the lake surface alone. However, he did not attempt to formulate a mathematical representation of the processes involved. Subsequent workers have attempted this with varying degrees of success. For example, McCall *et al.* (1984) refer to the watershed 'integrating' the fallout input and assume that the caesium-137 content of sediment eroded from the watershed will be proportional to the cumulative inventory. They define a 'residence time' which represents the period taken for the fallout input to the watershed to be removed. Values cited ranged between 8 and 20 years. Whilst it may be reasonable to assume that the export of caesium-137 from a drainage basin will reflect the cumulative fallout input, the short residence times proposed would seem unrealistic in the light of existing evidence concerning the fate of caesium-137 in soils. Other workers such as Smith & Ellis (1982) and Smith *et al.* (1987) again suggest that caesium-137 export from the watershed will be proportional to the cumulative input, but assume considerably longer and more realistic residence times of the order of hundreds of years. In this case, the radiocaesium content of the drainage basin input would therefore remain essentially constant through time after the main period of buildup prior to 1966. Robbins (1984) follows the suggestion of Menzel (1974) that two components of transfer from the drainage basin are required. These are a direct and an indirect transfer component. The direct transfer component is taken to represent a small fixed proportion of the radionuclide fallout onto the drainage basin during the previous two months. A value of 2.2% was used by Robbins (1984). The indirect transfer component reflects the longer-term transfer of the radionuclide inventory accumulating in the drainage basin through the erosion and transport of sediment particles, and this is represented as a constant proportion of the accumulated input. This proportion was set at 0.007% per year, which is equivalent to a residence time of 1.4×10^4 years. Miller & Heit (1986) employ a different representation which is based on the work of Krey *et al.* (1980) and assumes that the caesium-137 content of the delayed input from the drainage basin will have progressively declined after the period of peak fallout. This is represented as an exponential reduction in the availability of caesium-137 for removal over time. Olsen *et al.* (1981) also proposed that the radionuclide content of the drainage basin contribution would decline through time after the period of peak fallout, but avoided the need to represent the precise form of this decline by assuming that it followed the same trend as the ^{90}Sr content of New York tap-water.

The above representations of the delayed contribution of caesium-137 to a lake from its drainage basin provide significantly different estimates of the form of that input. For example, in some, the radiocaesium content of the input remains essentially constant after increasing through the main period of fallout during the late 1950's and early 1960's, in others it declines, whilst in others there are components reflecting both an input proportional to the cumulative fallout inventory and a fraction of the current fallout. Furthermore, these existing representations are based on gross simplifications of the actual processes involved, since no consideration is given to the manner of caesium-137 storage or to the nature of the removal processes. Recent empirical and experimental work on the behaviour of caesium-137 in soils (Livens & Rimmer, 1988; Bachhuber *et al.*, 1982), on the caesium-137 content of sediment eroded from areas of different land use (Walling & Bradley, 1990) and on the seasonal variation of the caesium-137 content of sediment transported by streams (Dominik *et al.*, 1987) underscores the need for more physically realistic models of the transfer of caesium-137 from a drainage basin into a lake or a floodplain system.

Towards an improved representation of caesium-137 transfer

The caesium-137 content of sediment eroded from a drainage basin and transported to a lake or river floodplain will reflect the dominant source of that sediment. Sediment originating from channel and gully erosion is likely to have only a very low, or even a zero caesium-137, due to the absence of radiocaesium in the source material. Sediment originating from sheet and rill (surface) erosion can be expected to have a much higher caesium-137 content, although the concentrations involved will reflect the land use history of the sediment sources involved. In uncultivated soils, most of the caesium-137 inventory will be concentrated near the surface (e.g. the upper 10 cm) and concentrations will typically decline exponentially with depth. In cultivated soils, however, the caesium-137 will be distributed more uniformly throughout the plough layer (ca. 10–30 cm) and concentrations in eroded soil will generally be less than those in soil eroded from uncultivated areas (Walling & Bradley, 1990). Any attempt to estimate the long-term variation of the caesium-137 content of sediment transported by a stream since the 1950's must, therefore, consider the fate of fallout arriving at the soil surface and the concentrations of radiocaesium in the surface layer. The exact magnitude of the concentrations of caesium-137 in eroded soil will reflect both the caesium-137 content of this surface layer and any enrichment associated with the preferential erosion of fines and organic material (Walling & Moorehead, 1989).

In attempting to model the caesium-137 content of the surface layer of a soil, and therefore the eroded sediment, over the period extending from the 1950's to the present, a fundamental distinction must be made between cultivated and uncultivated soils. In an uncultivated soil, the adsorption of caesium-137 by soil particles can be treated as a first order reversible process. Neglecting any downward movement of radiocaesium with porewater, treating the soil as a semi-infinite media and assuming that radionuclide inputs are initially uniformly distributed at the soil surface, the vertical distribution of caesium-137 concentration with accumulated soil mass per unit area, from the surface downwards, can be characterised by the one-dimensional diffusion equation viz.

$$\frac{\partial C(x,t)}{\partial t} = D_n \frac{\partial^2 C(x,t)}{\partial x^2} - \lambda C(x,t) \tag{1}$$

where: D_n = the effective diffusion coefficient ($g^2\,cm^{-4}\,yr^{-1}$), λ = the decay constant for ^{137}Cs (yr^{-1}), x = the accumulated mass of soil per unit area from the surface downwards ($g\,cm^{-2}$), t = time since the deposition of ^{137}Cs (yr), $C(x, t)$ = the activity of ^{137}Cs at time t and accumulated mass x ($mBq\,g^{-1}$).

Annual inputs must also be considered and an initial exponential depth distribution of the caesium-137 concentration $C(x, t')$ ($mBq\,g^{-1}\,yr^{-1}$) with a relaxation accumulated mass H ($g\,cm^{-2}$) for an instantaneous input $I(t')$ ($mBq\,cm^{-2}\,yr^{-1}$) at time t' (yr) can be assumed:

$$C(x,t') = \frac{I(t')}{H}\, e^{-\frac{x}{H}} \tag{2}$$

Solution of Eqn. 1 $C(x, t, t')$ ($mBq\,g^{-1}\,yr^{-1}$) for any accumulated mass x and time t under the initial condition represented by Eqn. 2 yields (Crank, 1975):

$$C(x,t,t') = \frac{e^{-\lambda(t-t')}}{\sqrt{4\pi D_n(t-t')}} \times \left[\int_{-x}^{\infty} C(x+y,t')\, e^{-\frac{y^2}{4D_n(t-t')}}\, dy + \int_{x}^{\infty} C(x-y,t')\, e^{-\frac{y^2}{4D_n(t-t')}}\, dy \right] \tag{3}$$

Where y is the integration variable. For a continuous input $I(t')$, the caesium-137 concentration $C(x, t)$ ($mBq\,g^{-1}$) within the soil can be represented as:

$$C(x,t) = \int_0^t C(x,t,t')\, dt' \tag{4}$$

In the case of sheet erosion, involving the removal of a layer of uniform depth from the surface, with an annual erosion rate r_n ($g\,cm^{-2}\,yr^{-1}$) $\ll H + \sqrt{2D_n t}$, the annual removal of caesium-137 from a unit area of uncultivated soil $A_n(t)$ ($mBq\,cm^{-2}\,yr^{-1}$) is approximately:

$$A_n(t) \approx r_n C(0,t) = r_n C_n(t) \tag{5}$$

where $C_n(t)$ ($mBq\,g^{-1}$) is the caesium-137 concentration in eroded sediment.

In the case of cultivated soil, the dominant control on the distribution of the accumulated caesium-137 within the profile will be the mixing associated with regular cultivation. Downward diffusion can be neglected and a uniform distribution of accumulated caesium-137 within the plough depth can be assumed. However, the initial distribution of the caesium-137 fallout input to the surface in the months prior to incorporation by cultivation must also be considered. Assuming that the accumulated caesium-137 inventory within the plough depth is uniformly distributed within an accumulated mass D_e (g cm^{-2}), and taking account of inputs since the soil was last cultivated, removal of caesium-137 by sheet erosion from a unit area of cultivated soil $A_c(t)$ (mBq cm^{-2} yr^{-1}) can be represented as:

$$A_c(t) = \alpha I(t) + \frac{r_c}{D_e}\int_0^{t-1}(1-\alpha)I(t') \times e^{-\left(\frac{r_c}{D_e}+\lambda\right)(t-t')}\,dt' = r_c C_c(t) \quad (6)$$

where: $r_c =$ the erosion rate for cultivated soils (g cm^{-2} yr^{-1}), $\alpha = C(O, t, t-1)\, r_c/I(t-1)$, is the fraction of the recent caesium-137 fallout input removed, $C_c(t) =$ caesium-137 concentration in eroded sediment (mBq g^{-1}).

The above equations have been used to estimate the trend in the caesium-137 content of suspended sediment transported by a stream over the period 1954 to present, assuming that all the sediment has been eroded from the soil surface and that selective enrichment does not occur. The results depicted in Fig. 2 relate to a hypothetical drainage basin under permanent pasture and therefore with no cultivation (Fig. 2a, $H = 0.750$, $D_n = 0.500$ and $r_n = 0.002$) and to a cultivated basin (Fig. 2b, $D_e = 25.00$, $r_c = 0.02$ and $\alpha = 0.003$). Annual fallout inputs of caesium-137 typical of Devon, UK, have been assumed. Clear contrasts exist between the results for the two basins. The caesium-137 content of sediment eroded from the non-cultivated basin is considerable greater than that from the cultivated basin, reflecting the higher concentrations of caesium-137 at the surface of uncultivated soils uninfluenced by the mixing associated with cultivation. More importantly, in terms of the implications of these results for the caesium profile in deposited sediment, the overall trend differs substantially between the two examples. In the case of the uncultivated basin (Fig. 2a), concentrations remain high throughout the period following the occurrence of peak values in the mid 1960's, whereas concentrations decline much more rapidly in the case of the cultivated basin (Fig. 2b). The simple models used to derive Fig. 2 take no account of the possible enrichment of the caesium-137 content of eroded sediment relative to that of the soil, but such mechanisms can be seen as influencing the absolute concentrations rather than the overall trend through the period concerned. Furthermore, no explicit account is taken of sediment derived from channel erosion. However, if it is assumed that sediment derived from channel sources has a zero or negligible caesium-137 content, it will dilute the content of caesium-137 in the transported sediment, whilst the overall trend will again be maintained.

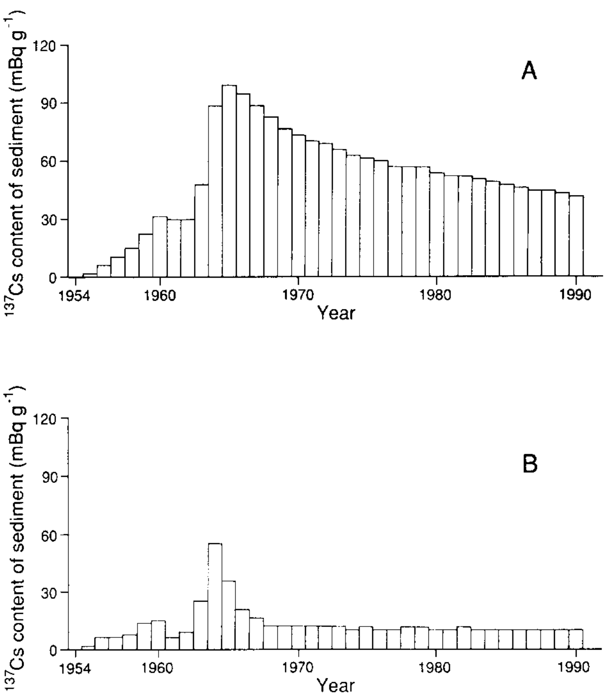

Fig. 2. Estimates of the caesium-137 content of sediment transported to a lake or river floodplain from its drainage basin during the period 1954–1990. (a) represents a drainage basin with uncultivated soils and (b) represents a drainage basin with cultivated soils.

Implications for caesium-137 profiles

In the absence of post-depositional mobility (e.g. bioturbation), the form of the caesium-137 profile exhibited by sediment deposited in a lake or a river floodplain will reflect the relative importance of the contributions to the total inventory provided by fallout to the lake surface and sediment input from the surrounding drainage basin. In a lake where the atmospheric fallout component is dominant, the profile will closely reflect the pattern exhibited by the fallout record (Fig. 1a). Where sediment inwash from the surrounding drainage basin is important, the shape of the profile may more closely resemble the trends shown by Figs. 2a,b, and will in turn reflect the relative importance of cultivated and uncultivated soils as sediment sources. In most cases, erosion rates associated with cultivated soils will be much greater than those associated with uncultivated areas and the former source will therefore commonly exert the greatest influence on catchment-derived inputs of radiocaesium.

Figure 3 attempts to demonstrate the influence on the form of the caesium-137 profile obtained from a lake sediment core of both the relative contribution of atmospheric fallout and sediment inwash to the overall caesium-137 inventory of a lake core and the relative importance of cultivated and uncultivated soils as sediment sources. The total annual caesium-137 input to the water column $I_w(t)$ (mBq yr^{-1}) has been calculated as the sum of that derived from the drainage basin and from direct atmospheric input:

$$I_w(t) = S_n A_n(t) + S_c A_c(t) + S_l I(t) \tag{7}$$

Where S_n, S_c and S_l are the areas (cm^2) of non-cultivated land, cultivated land and lake surface respectively. The annual caesium-137 input per unit area $I_{in}(t)$ (mBq cm^{-2} yr^{-1}) to a specific site on a lake bottom may be calculated as:

$$I_{in}(t) = a[C_n(t) + r_a C_c(t)] + bI(t) \tag{8}$$

Where: $r_a = S_c r_c / S_n r_n$, a, b = site specific scaling parameters which reflect the absolute magnitude of the radiocaesium input attributable to drainage basin (a (g cm^{-2} yr^{-1})) and atmospheric fallout (b) inputs in relation to the values of radiocaesium concentration in eroded soil and the atmospheric fallout per unit area of lake surface. These parameters will reflect the influence of lake trap efficiency, short-term sediment focussing and the influence of particle size sorting during erosion and deposition. In the case of floodplain sites the value of b will be 1.0.

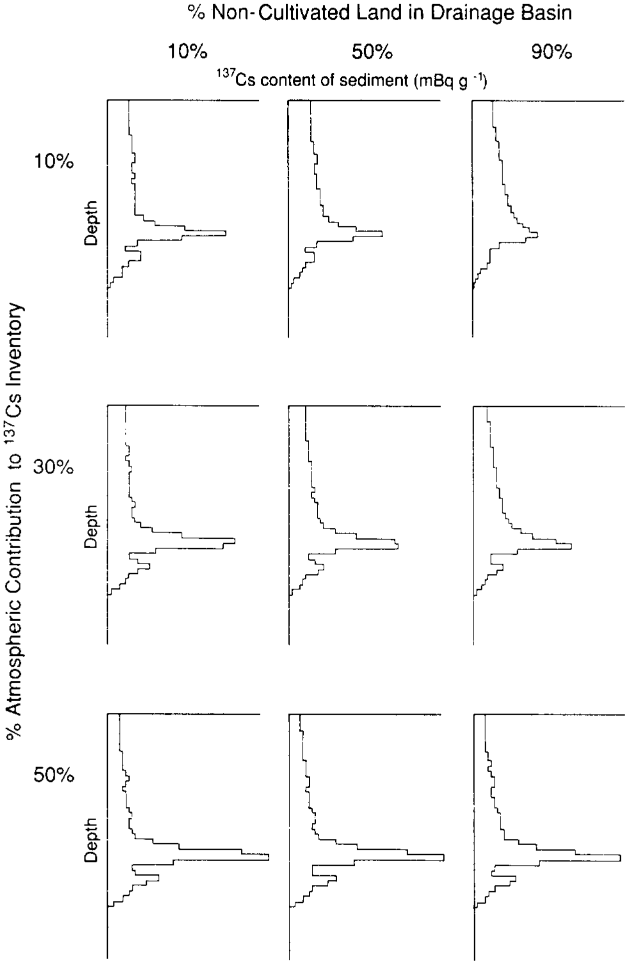

Fig. 3. A schematic representation of the influence of catchment land use and the relative importance of atmospheric fallout to the lake surface and sediment inwash from the surrounding drainage basin, on the shape of the caesium-137 profile of sediment deposited in a lake. All profiles have the same depth scale but the concentration scales are different since the areas contained within the profile shapes have been normalised to a uniform value.

The concentration of caesium-137 $C_0(t)$ (mBq g^{-1}) in the sediment will be proportional to $I_{in}(t)$:

$$C_0(t) \propto I_{in}(t) = a'[C_n(t) + r_a C_c(t)] + b'I(t) \qquad (9)$$

Where a' and b' are constants. Let t_0 be the time when the sediment core is taken, the caesium-137 concentration then is:

$$C_0(t_0, t) = C_0(t)\,e^{-\lambda(t_0 - t)} \qquad (10)$$

To see the influence of the catchment-derived caesium-137 on the shape of the caesium-137 profile of a lake sediment core with a constant sediment accumulation rate and without post-depositional disturbance, we divide $C_0(t_0, t)$ by the total caesium-137 input to give the relative caesium-137 concentration $C_0'(t_0, t)$:

$$C_0'(t_0, t) = \frac{C_0(t_0, t)}{\int_0^{t_0} C_0(t)\,dt} = \left\{ \gamma \frac{C_n(t) + r_a C_c(t)}{\int_0^{t_0} [C_n(t) + r_a C_c(t)]\,dt} + (1 - \gamma) \frac{I(t)}{\int_0^{t_0} I(t)\,dt} \right\} e^{-\lambda(t_0 - t)} \qquad (11)$$

Where γ represents the catchment contribution and is given as:

$$\gamma = \frac{\int_0^{t_0} a'[C_n(t) + r_a C_c(t)]\,dt}{\int_0^{t_0} \{a'[C_n(t) + r_a C_c(t)] + b'I(t)\}\,dt} \qquad (12)$$

Three levels of percentage atmospheric fallout contribution (10%; 30% and 50%, determined by γ) and three levels of percentage non-cultivated land (10%, 50% and 90%, determined by r_a) are represented. Erosion rates of 0.2 and 2 t ha^{-1} yr^{-1} have been assumed for uncultivated and cultivated soils respectively, and Eqns. 5 & 6 have been used to estimate the drainage basin contribution from sediment inwash. Typical values of D_n (0.50) for uncultivated soils in the UK and of the plough depth D_e (25.0), and H (0.75) have been employed. The absolute magnitude of the erosion rates employed makes little difference to the form of the simulated profiles, although their relative magnitude will clearly influence the relative amounts of sediment derived from the two sources. In this analysis, a value of 50% cultivated land results in 90% of the total sediment load being derived from cultivated fields and 10% from uncultivated fields. The simulation assumes that all caesium-137 inputs to the water column from both atmospheric fallout to the lake surface and sediment inputs from the drainage basin are deposited without significant delay and that post-depositional mobility (e.g. bioturbation) does not occur.

Predicting caesium-137 profiles

Figure 3 provides an estimate of the form of the caesium-137 profile in a lake sediment core and its relationship to the drainage basin contribution in the absence of post-depositional mobility of the caesium-137 input. It is well-known that such mobility will occur in most lake sediments and it is frequently invoked to account for the occurrence of only a broad single peak in the lower portion of the profile, as distinct from the well-defined double peak evident in most of the profiles depicted on Fig. 3. Furthermore, in considering the likely form of caesium-137 profiles associated with floodplain deposits, it is clear that the profile must incorporate elements of the exponential form normally associated with the distribution of caesium-137 in soils receiving atmospheric fallout at the surface and resulting from downward transmission of the radiocaesium input by chemical and physical processes

(Eqn. 1). In order to predict the actual form of the caesium-137 profile to be expected in a lake or floodplain sediment receiving sediment inwash from the drainage basin, a preliminary attempt has been made to incorporate the effects of post depositional mobility of caesium-137 by representing this as a simple diffusion process. Therefore, Eqn. 1, used to describe the post-depositional mobility of caesium-137 in an uncultivated soil profile, may also be used to represent the movement of caesium-137 within the lake sediment core, if the constant D_n is replaced by D_l (g cm^{-4} yr^{-1}), the diffusion coefficient for caesium-137 in lake sediment. Assuming that caesium-137 can only diffuse within the sediment, that the *in-situ* sediment accumulation rate for a specific site is R (g cm^{-2} yr^{-1}) and that the caesium-137 input $I_{in}(t')$ is initially uniformly distributed within R, the initial distribution of the caesium-137 concentration in the sediment $C'(x, t')$ (mBq g^{-1}) may be given as:

$$C_l'(x,t') = \begin{cases} \dfrac{I_{in}(t')}{R} & x \leq R \\ C_l(x,t') & x > R \end{cases} \tag{13}$$

Where: x = accumulated mass of sediment per unit area, from the surface downwards (g cm^{-2}), and $C_l(x, t)$ = caesium-137 concentration in the sediment at time t (mBq g^{-1}). Taking Eqn. 13, the solution of Eqn. 1 with a rising upper boundary (rate R) can be written as:

$$\begin{aligned} C_l(x,t) = \frac{1}{\sqrt{4\pi D_l}} \Biggl\{ & \int_{x-R}^{x+R} \frac{I_{in}(t-1)}{R} \\ & \times \mathrm{e}^{-\left(\frac{y^2}{4D_l}+\lambda\right)} \mathrm{d}y \\ & + \int_{x+R}^{\infty} C_l(y,t-1)\, \mathrm{e}^{-\left(\frac{y^2}{4D_l}+\lambda\right)} \mathrm{d}y \\ & + \int_{R-x}^{\infty} C_l(y,t-1)\, \mathrm{e}^{-\left(\frac{y^2}{4D_l}+\lambda\right)} \mathrm{d}y \Biggr\} \end{aligned} \tag{14}$$

with $C_l(x, 0) = 0$.

When considering the distribution of caesium-137 in floodplain sediment, the initial distribution of caesium-137 concentration differs from that for lake sediment and may be expressed as:

$$C_f'(x,t') = \begin{cases} \dfrac{a[C_n(t') + r_a C_c(t')]}{R} & x \leq R \\ C_f(x,t') + \dfrac{I(t')}{H}\, \mathrm{e}^{-\frac{(x-R)}{H}} & x > R \end{cases} \tag{15}$$

Where $C_f(x, t)$ is the caesium-137 concentration in floodplain sediment (mBq g^{-1}) and x, t have the same meanings as before. The solution of Eqn. 1 with an initial distribution given by Eqn. 15 and a rising boundary is the same as that for lake sediment, but the drainage basin term is:

$$I_{in}(t) = a[C_n(t) + r_a C_c(t)] \tag{16}$$

Case studies

The equations representing the distribution of caesium-137 in lake sediment (Eqns. 8, 13 & 14) and in floodplain sediments (Eqns. 14, 15 & 16) have been fitted to the four caesium-137 profiles presented in Fig. 1c. The five parameters involved are listed in Table 2. One (r_a) can be estimated from the land use characteristics of the basin and a knowledge of likely erosion rates, whereas the remaining four must be estimated by optimising the correspondence between the measured and predicted caesium-137 profile. In this case, two of the parameters (a and b) were obtained using a least squares fitting procedure and the remaining two (D_l, and R) were estimated on a trial and error basis. The results are presented in Fig. 4, and the close correspondence between the measured and predicted caesium-137 profiles suggests that the factors and mechanisms discussed above could provide an acceptable explanation of the observed caesium-137 profiles at these four sites. It is beyond the scope of this paper to discuss the physical interpretation of the parameter values listed in Table 2, but initial analysis suggests that

Table 2. Parameters of the caesium-137 deposition models fitted to the four core profiles presented in Fig. 4.

Parameter	Core			
	Chard Lake	Wadhurst Lake	Culm Floodplain	Axe Floodplain
a (g cm^{-2} yr^{-1})	0.353	0.252	0.348	0.162
b	1.636	1.145	1.000*	1.000*
D_l (g^2 cm^{-2} yr^{-1})	0.012	0.125	0.040	0.020
R (g cm^{-2} yr^{-1})	0.315	0.810	1.100	0.640
r_a	1.000	0.625	5.000	5.000
r' **	1.959	1.570	1.308	0.621

* Parameter b is set to 1.0 in floodplain locations;

** r' is the annual sediment accumulation rate calculated as R/ρ (sediment density).

the apparent differences between the sites can be accounted for by contrasts in their physical characteristics. The equations fitted to the profiles assume a uniform annual rate of sedimentation and, provided this in realistic, it is possible to use them to date any depth within the profile (Fig. 4).

The input of caesium-137 mobilised from the drainage basin by erosion clearly exerts an important influence on the form of the caesium-137 profiles, and in Fig. 5 the patterns of variation of the concentration of caesium-137 in this eroded sediment estimated by the fitting procedures are presented for the four sites. These patterns are consistent with the current levels of caesium-137 in the suspended sediment transported by the four rivers involved. The drainage basins of both Chard Lake and Wadhurst Park Lake are occupied largely by uncultivated pasture and the lower caesium-137 concentrations associated with the sediment entering Wadhurst lake can be explained by the greater importance of channel erosion in that basin, related to the more deeply incised channel network. Channel erosion generates sediment with a low caesium-137 content which will dilute the overall concentration of caesium-137 in the suspended sediment transported by the river. The drainage basins of the River Culm and the River Axe exhibit many similarities in terms of land use and other physiographic characteristics and these similarities are clearly reflected in the very similar forms exhibited by their predicted drainage basin contributions.

Perspective

The concepts and relationships outlined in this paper provide a means of establishing the likely

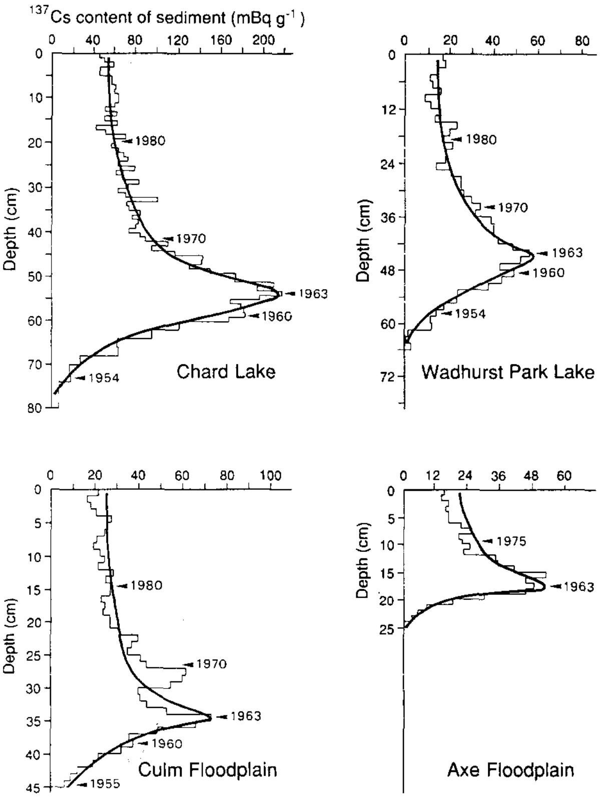

Fig. 4. The results of fitting the caesium-137 deposition models to the four cores depicted in Figure 1c.

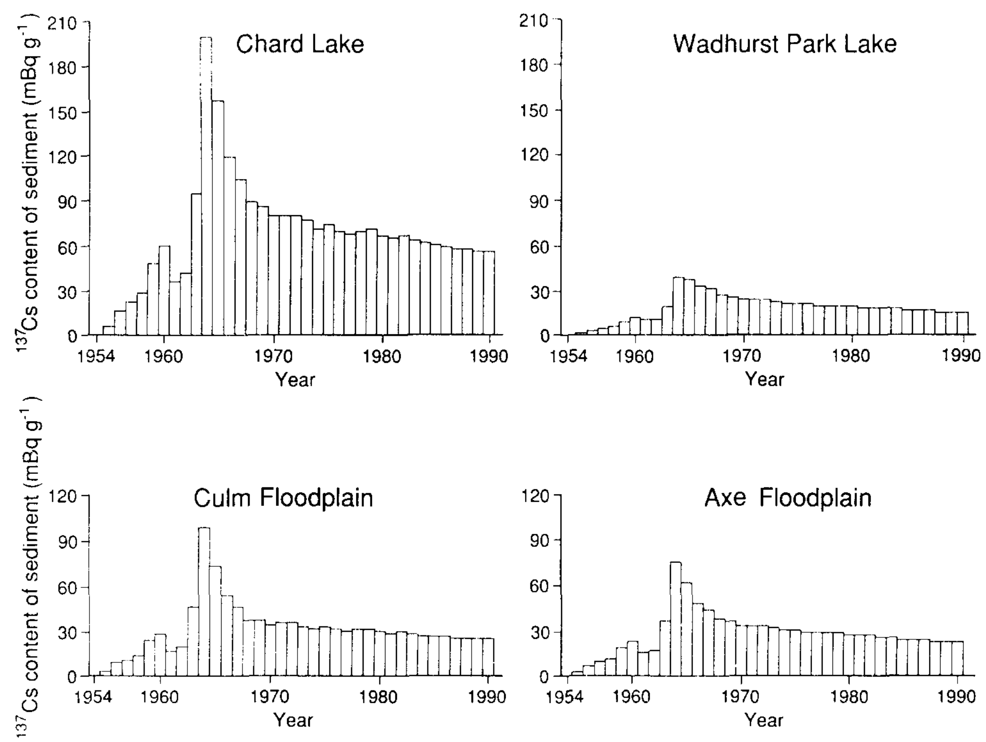

Fig. 5. The caesium-137 content of sediment providing the drainage basin contribution to the caesium-137 inventory of the four cores illustrated in Fig. 4, estimated using the caesium-137 deposition models.

nature of the drainage basin contribution to the caesium-137 profile recorded in lake or floodplain sediments and of evaluating the influence of this contribution on the shape of the profile. This influence will depend upon the relative importance of the atmospheric fallout to the lake or floodplain surface and of the drainage basin input to the total caesium-137 inventory of the sediment core and on the relative importance of cultivated and non-cultivated soils as sediment sources within the drainage basin. They also provide a means of establishing whether the shape exhibited by the caesium-137 profile for a particular site can be accounted for in terms of the factors which are generally accepted as controlling the incorporation of caesium-137 into sediment deposits, and therefore of confirming the utility of the profile for dating purposes.

More work is undoubtedly required to improve the representation of the processes responsible for controlling both the precise form of the drainage basin input and post-depositional mobility of caesium-137 and to include inputs of autochthonous sediment. In particular, the effects of bioturbation on the final form of the caesium-137 profile must be addressed. Nevertheless, it is hoped that this paper has underscored and clarified the importance of the drainage basin contribution in influencing the form of the caesium-137 profile in lake and floodplain deposits and that it has thereby demonstrated the need for increased interchange between catchment hydrologists, limnologists and sedimentologists if the full potential of such sediment records is to be realised.

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