Some applications of caesium-137 measurements in the study of erosion, transport and deposition

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Abstract Caesium-137, a radionuclide originating as fallout generated by the atmospheric testing of nuclear weapons, can provide the geomorphologist with a valuable tracer for investigating the movement of sediment through the fluvial system. Three examples of possible applications drawn from the work of the authors in Devon, UK, are presented. These involve the use of ^{137}Cs for, firstly, fingerprinting suspended sediment sources, secondly, investigating patterns of soil erosion and sediment delivery on cultivated hillslopes, and thirdly, elucidating rates and patterns of flood plain deposition.

INTRODUCTION

Caesium-137 is a major component of the fallout associated with the atmospheric testing of nuclear weapons and this radionuclide is currently present in the global environment in significant quantities as a result of weapons testing during the 1950s and early 1960s. Significant fallout of ^{137}Cs was first detected in 1954 and records from a global network of measuring stations (Cambray, *et al.*, 1980; US Health and Safety Laboratory, 1977) indicate that fallout rates peaked in 1963–1964 and subsequently declined markedly as a result of the 1963 Nuclear Test Ban Treaty. Small perturbations in more recent years can be related to Chinese and French tests continuing until the late 1970s. Figure 1 provides an example of the pattern of annual fallout during the period 1950–1985 for Milford Haven, UK, based on data collected by the UK Atomic Energy Research Establishment (Cambray, personal communication). Local increases in ^{137}Cs fallout occurred in many areas of Europe and in neighbouring regions as a result of the 1986 Chernobyl accident. In some areas close to the site of the accident these inputs exceeded the accumulated fallout from weapons testing (cf. Dorr & Munnich, 1987), but in general they represented only a relatively minor contribution to the total ^{137}Cs inventory (cf. Cambray *et al.*, 1987). The total amount of weapons-testing fallout received at the land surface varies globally in response to both the magnitude of annual rainfall and the pattern of atmospheric circulation responsible for dispersing the fallout. For example, the total receipt of weapons-testing ^{137}Cs reported for sites in New South Wales, Australia by Campbell *et al.* (1986) is about 40% of that recorded for sites with similar annual rainfall in the UK.

Existing evidence indicates that in most situations, ^{137}Cs reaching the soil surface as fallout is rapidly and strongly adsorbed by clay minerals in the
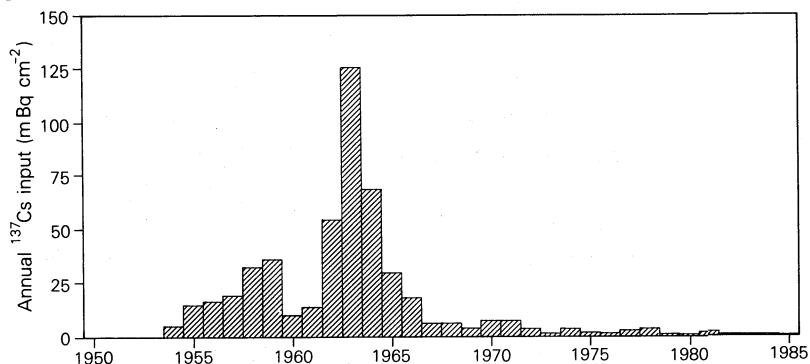
Fig. 1 *Annual fallout of ^{137}Cs recorded at Milford Haven, UK, during the period 1950–1985 (data provided by Dr R. Cambray, UK Atomic Energy Authority, Harwell).*

upper soil horizons and that further downward translocation by physico-chemical processes is limited (cf. Tamura, 1964; Gale *et al.,* 1963; Frissel & Pennders, 1983). Subsequent movement of the radioisotope is therefore generally associated with the erosion, transport and deposition of sediment particles (e.g. Rogowski & Tamura, 1970a, b; Campbell *et al.,* 1982). Because of both this behaviour and its relatively long half-life (30.1 years), which means that approximately 60% of the total input since 1954 could still remain within the system, ^{137}Cs possesses very considerable potential for use as a "natural" tracer of sediment movement. Several potential applications have been highlighted by Campbell (1983) and a recent review by Ritchie (1987) further emphasizes the range of possibilities available. Geomorphologists could profitably increase their efforts to exploit this potential and this contribution provides three examples of applications developed by the authors in Devon, UK. These involve its use for, firstly, fingerprinting suspended sediment sources, secondly, investigating patterns of soil erosion and sediment delivery on cultivated hillslopes and, thirdly, elucidating rates and patterns of flood plain deposition.

MEASUREMENT CONSIDERATIONS

Caesium-137 concentrations in soils and sediments can be measured relatively easily by gamma spectrometry. Germanium (Ge) detectors are commonly used for this purpose and the detector is generally housed in a lead shield in order to minimize background interference. The main problem with such measure-ments relates to the low levels of ^{137}Cs generally encountered in environ-mental samples. These necessitate long counting times. Counting times of the order of 36 000 s (10 hours) will frequently be required in order to obtain an acceptable precision and this in turn means that the number of samples that can be processed may be an important constraint in many studies. Minimum sample size may also prove a constraint, because the levels of activity commonly associated with environmental samples require a mass of at least

20 g to register a sufficient number of disintegrations.

FINGERPRINTING SUSPENDED SEDIMENT SOURCE

The context

Over the past few decades, recognition of the important role of suspended sediment in the fluvial transport of nutrients and contaminants and in non-point pollution from land use activities has focussed increasing attention on the sources involved and the pathways associated with the conveyance of sediment from its source to the basin outlet (e.g. Glymph, 1975; Wolman, 1977). In addition to an assessment of the magnitude of suspended sediment loads, information concerning the nature, relative importance and spatial distribution of sediment sources is therefore increasingly required. Similar requirements have also been promoted by recent interest in the establishment of sediment budgets for drainage basins (e.g. Swanson *et al.,* 1982), by advances in phsyically-based distributed modelling of sediment yield (e.g. Beasley *et al.,* 1982) and by a desire for more meaningful geomorphological interpretation of sediment yield data in terms of landscape evolution (e.g. Finlayson, 1978).

The development of the "fingerprinting" technique as a means of assessing sediment sources within a drainage basin has, therefore, attracted considerable interest, in that it offers a relatively simple means of establishing the relative importance of major sediment sources (e.g. Wall & Wilding, 1976; Wood, 1978; Oldfield *et al.,* 1979). In essence this method involves firstly, the selection of a physical or chemical property which clearly differentiates potential source materials, and, secondly, a comparison of measurements of this property obtained from suspended sediment with those for the potential sources. Additional considerations relating to the choice of appropriate sediment properties and procedures for establishing the relative importance of individual source materials are discussed by Peart & Walling (1986).

The viability of this approach to determining the relative importance of the major sediment sources within a drainage basin depends heavily upon the availability of a sediment property capable of clearly distinguishing sediment derived from different sources such as cultivated fields and channel banks. Work undertaken by the authors suggests that the ^{137}Cs concentration of source material and suspended sediment affords an excellent fingerprint. Different source materials are characterized by different concentrations of ^{137}Cs which will in turn reflect the amount of fallout received and its degree of incorporation within the soil profile. Channel banks, which are in most cases essentially vertical, will receive relatively little fallout as compared to field areas and will therefore be characterized by very low concentrations, or even an absence, of ^{137}Cs. Caesium-137 reaching the soil surface will be strongly adsorbed by the fine fraction and will therefore be preferentially concentrated near the surface. Where cultivation occurs, however, this surface concentration will be mixed throughout the depth of cultivation (ca. 10–30 cm) and ^{137}Cs concentrations in surface topsoil will be appreciably lower than

those encountered in uncultivated soil. A typical example of the distribution of ^{137}Cs in the upper soil horizons of permanent pasture and of arable fields in the vicinity of Exeter, UK, is provided in Fig. 2. Here, sediment eroded
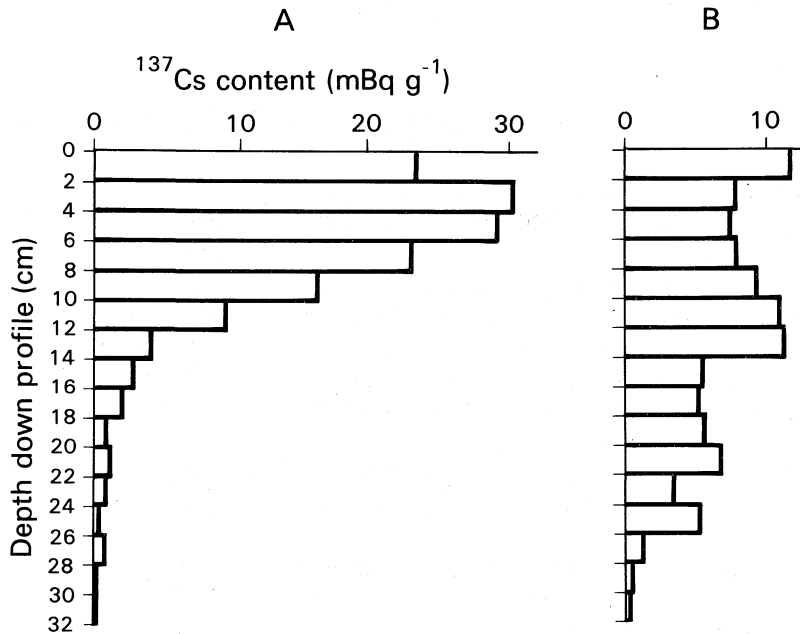

Fig. 2 *The vertical distribution of ^{137}Cs in soil profiles representative of (A) undisturbed pasture and (B) arable fields within the Jackmoor Brook basin.*

from cultivated fields could be expected to be characterized by ^{137}Cs concentrations that are only about 40% of those associated with sediment derived from uncultivated areas. Both sources would, however, provide sediment with ^{137}Cs concentrations about an order of magnitude greater than those encountered in sediment derived from channel bank sources. By virtue of its dependence on atmospheric fallout, which can be viewed as essentially uniform over small areas, the ^{137}Cs concentration of sediment and source material provides a fingerprint which is largely independent of soil and regolith properties which may exhibit marked spatial heterogeneity.

An example

The potential offered by ^{137}Cs as a means of fingerprinting sediment source can be further demonstrated by considering the results obtained from a study undertaken by Peart & Walling (1986) in the Jackmoor Brook basin, near Exeter, UK. This small drainage basin (Fig. 3) has a drainage area of 9.3 km^2 and its altitude ranges from 21.5 m at the basin outlet to 235 m on the
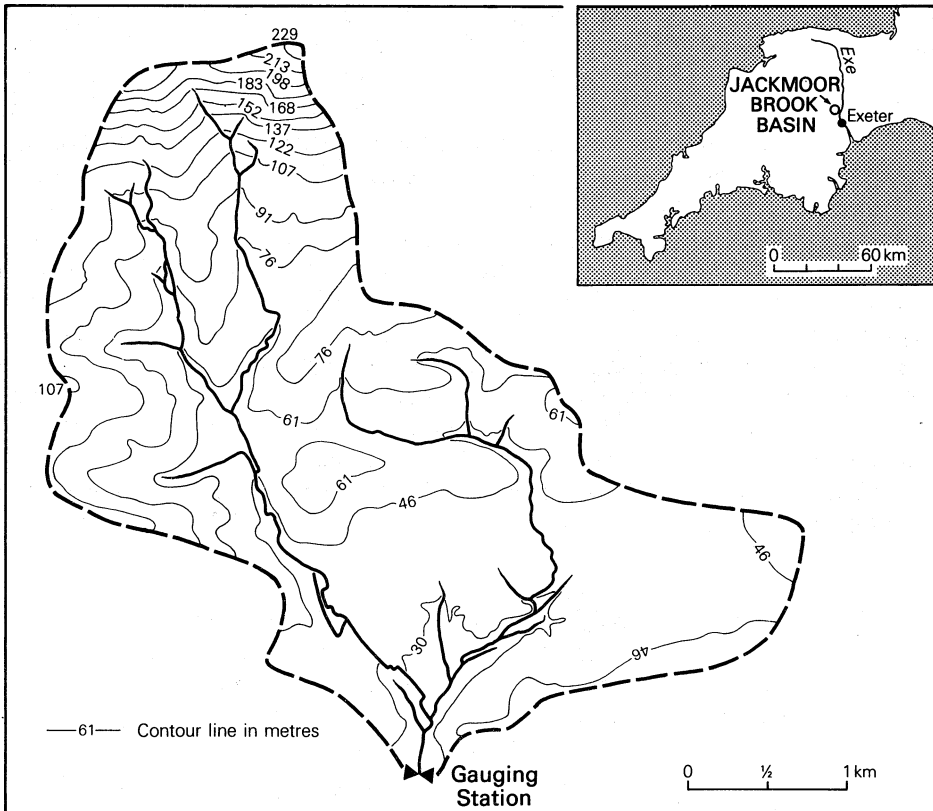
Fig. 3 *The Jackmoor Brook study basin.*

northern divide. Slopes are predominantly gentle (<4°), although steeper ground occurs towards the northwestern margin (8°). The basin is underlain by Permian sandstones, breccias and conglomerates. Land use is predominantly mixed arable farming, with cattle and sheep rearing and a rotation of cereals, root crops and grass. The majority of the grassland is in leys. Mean annual precipitation and runoff are estimated at 825 mm and 350 mm respectively. Within the local area, this drainage basin is noteworthy for the relatively high suspended sediment concentrations of up to 3500 mg l^{-1} which may occur during storm events. Based on available records the mean annual suspended sediment yield is estimated to be c. 60 t km^{-2} year^{-1}. The stream network is only moderately incised into the valley bottoms, and bank heights are commonly less than 1 m although deeper incision of 2–3 m occurs in places. Flood plain development is limited and active channel incision reaches bedrock in most locations. Neither the channel network nor the agricultural land with its pattern of hedge bank boundaries provide obvious evidence of major sediment sources and for this reason the fingerprinting technique appeared to offer a useful means of identifying the dominant sediment sources.

Three potential sediment sources were distinguished within the basin,

namely, channel banks, arable fields and permanent pasture, and representative source material was collected from over 100 sites within the basin. These sites were selected to embrace the major components of variability within the three source types. Analysis of these samples was restricted to the <63 μm fraction, in order to minimize differences in particle size composition between source material and suspended sediment. Available evidence indicated that the >63 μm fraction of the suspended sediment load transported by the Jackmoor Brook rarely exceeded 5%. In the knowledge that suspended sediment properties would be likely to vary according to season and in response to variations in discharge and suspended sediment concentration (e.g. Walling & Kane, 1982), suspended sediment sampling was undertaken over a range of conditions. Bulk samples of river water (c. 100 l) were collected during storm events using a pump sampler and the suspended sediment was recovered using a continuous flow centrifuge. The suspended sediment samples were freeze dried prior to analysis.

Mean values of ^{137}Cs content for the three potential source materials and for suspended sediment are listed in Table 1 (A). The high values of

Table 1 *Comparison of the ^{137}Cs content of suspended sediment transported by the Jackmoor Brook with that of potential source material associated with arable fields, permanent pasture and bank material*

Caesium-137 content (mBq g^{-1})	Bank material	Arable topsoil	Pasture topsoil	Suspended sediment
A	1.5	9.0	23.0	17.0
B	2.25	13.5	34.5	17.0

A = Raw data
B = Data corrected for particle size enrichment

^{137}Cs content associated with suspended sediment indicate that channel banks are unlikely to be a significant sediment source in this basin and suggest that cultivated fields and pasture provide the dominant source. A direct comparison of the ^{137}Cs levels associated with suspended sediment and potential source materials is, however, likely to yield misleading results, because of the enrichment of suspended sediment in clay-sized particles relative to the source material. In view of the preferential association of ^{137}Cs with the clay fraction, suspended sediment derived from a particular source will inevitably contain higher concentrations of the radionuclide than the source material. Measurements of the grain size composition of suspended sediment and of the three potential source materials indicated that the former typically exhibited an enrichment factor for fines of the order of 1.5. The values of ^{137}Cs concentration listed for the source materials in Table 1 have therefore been increased by applying this enrichment factor of 1.5, in order to make them directly comparable with that for suspended sediment. The

amended values listed in Table 1 (B) suggest that arable fields are likely to provide the dominant source of the suspended sediment transported by the Jackmoor Brook, since the fingerprint values associated with topsoil from areas of permanent pasture are about double those characterizing suspended sediment. Furthermore, permanent pasture accounts for only a small proportion of the basin area.

Although the fingerprint evidence provided in Table 1 (B) points strongly to arable fields as providing the dominant sediment source in this basin, the possibility that the values of ^{137}Cs associated with suspended sediment could result from a mixture of sediment derived from areas of permanent pasture and from channel banks cannot be ruled out. Further confirmation can, however, be obtained by considering evidence from other fingerprinting properties. Peart & Walling (1986) used a number of property ratios to distinguish sediment derived from surficial and channel sources and Table 2 provides examples of the data provided by the property ratios which were judged by those authors to be the most reliable fingerprints. All four property ratios point to the dominance of surface soil as the sediment source and Table 3 lists the estimates of the relative importance of the two sources obtained by Peart & Walling

Table 2   Comparison of mean values of selected property ratios for suspended sediment and potential source materials from the Jackmoor Brook

Property ratio	Bank material	Surface soil	Suspended sediment
Carbon/nitrogen	7.31	9.83	9.82
SIRM*/magnetic susceptibility	47.74	15.58	17.87
Dithionite iron/magnetic susceptibility	41.50	7.40	7.92
Manganese/dithionite iron	0.058	0.116	0.110

SIRM = Saturation isothermal remanent magnetization

Table 3   The relative contribution of bank material and surface soil sources to the total suspended load of the Jackmoor Brook estimated using a simple mixing model applied to the data in Table 2

Property ratio	Relative contribution (%) Surface soils	Bank material
Carbon/nitrogen	99.6	0.4
SIRM/magnetic susceptibility	93.0	7.0
Dithionite iron/magnetic susceptibility	98.5	1.5
Manganese/dithionite iron	89.0	11.0
Mean	95.0	5.0

(1986) using a simple mixing model of the form:

$$C_s = \frac{P_r - P_b}{P_s - P_b} \times 100$$

where: C_s = % contribution from surficial sources;
 P_r = property ratio value characteristic of suspended sediment;
 P_s = property ratio value characteristic of surficial soil; and
 P_b = property ratio value characteristic of bank material.

The property ratios listed in Table 2 are based on intrinsic soil properties and are unable to distinguish topsoil from arable fields and permanent pasture. However, ^{137}Cs concentrations provide a means of evaluating the relative contributions of these two potential surface sources. A mixing model similar to that outlined above has been used in conjunction with the data listed in Table 1 (B) to apportion the 95% of the total sediment yield attributed to surficial sources in Table 3 between arable fields and permanent pasture. The results are presented in Table 4. These suggest that arable fields represent the dominant sediment source in this basin and account for approximately 75% of the sediment derived from surficial sources.

Table 4   *The relative contribution of topsoil from arable fields and permanent pasture and bank material to the total suspended sediment load of the Jackmoor Brook estimated using a mixing model applied to the ^{137}Cs concentration data listed in Table 1*

Source	Relative Contribution (%)
Channel banks	5
Permanent pasture top soil	19
Arable topsoil	76

In the above example of the use of ^{137}Cs to fingerprint sediment source, attention has focussed on the average values associated with suspended sediment, and therefore the relative importance of the various sources to the long term sediment yield. More detailed work could, however, investigate both seasonal and inter- and intra-storm event variations in the relative importance of individual sources. Table 5, for example, compares the average values of ^{137}Cs content associated with suspended sediment collected during the winter (October–March) and summer (April–September) periods of 1986–1987 from three sites within the Jackmoor Brook catchment, with a view to identifying any seasonal variation in the relative importance of the various sources. At all three sites, the ^{137}Cs concentration associated with suspended sediment is higher during the winter than during the summer season. This points to an increased importance of surface sources during the winter period, which is consistent with the local cultivation practice.

Table 5   *Average values of ^{137}Cs content associated with suspended sediment collected during the winter and summer periods of 1986–1987 from three sites within the Jackmoor Brook basin*

Site	Mean ^{137}Cs concentration (mBq g^{-1})	
	Winter	*Summer*
Basin outlet	*17.8*	*11.2*
Yendacott	*17.6*	*12.8*
Shute	*19.5*	*13.4*

Autumn-sown cereals are the dominant crop in this area and the surface of many of the cultivated fields is therefore unprotected by vegetation during the winter period. These fields are cultivated and sown in the autumn and an appreciable crop cover does not appear until late March.

Caesium-137 concentration can provide the geomorphologist with a valuable means of fingerprinting sediment sources and evaluating the relative importance of those sources. In many instances, however, its use will be best supported by other fingerprinting properties, in order to check the consistency of the results obtained and to permit more detailed apportionment between individual sources.

INVESTIGATING PATTERNS OF SOIL EROSION AND SEDIMENT DELIVERY ON HILLSLOPES

Background

Because the ^{137}Cs reaching the soil surface in a drainage basin is under most circumstances rapidly and strongly adsorbed within the upper soil horizons and its subsequent movement associated with the erosion, transport and deposition of sediment particles, an investigation of levels of total ^{137}Cs activity within the profile (mBq cm^{-2}) at different sites could provide valuable information on the spatial distribution of erosion and deposition. If the measured values are compared with an estimate of the original input, depletion would indicate erosion, whereas areas of deposition would be marked by enhanced levels of ^{137}Cs. Estimates of the total or baseline input are commonly obtained by measuring the total activity at undisturbed sites located on an interfluve, which are unlikely to have experienced either erosion or deposition. These have been termed input sites by Campbell *et al.* (1982) and control sites by De Jong *et al.* (1983). This approach has, for example, been used by McHenry & Ritchie (1977) and McHenry *et al.* (1978) to study patterns of erosion and deposition along slope transects within the White Clay Lake basin in Wisconsin, USA; by Longmore *et al.* (1983) to map the major areas of soil erosion and deposition within an upland drainage basin on the Darling Downs, Australia, and by Loughran *et al.* (1982) to study sediment movement within a small drainage basin in the Hunter Valley,

New South Wales, Australia. The potential application of this approach can be further demonstrated by considering the results of a study undertaken by the authors in a drainage basin near Exeter, UK.

An example

Caesium-137 profiles for four sites within the Jackmoor Brook drainage basin, which was described in the previous section (cf. Fig. 3), are illustrated in Fig. 4. The samples were collected from an area of 800 cm^2 at depth increments of 2 cm using the scraper plate technique advocated by Campbell & Loughran (personal communication). Profile A was obtained from an area of permanent pasture that was considered to provide a representative input or control site for the basin. It evidences the typical down-profile distribution of ^{137}Cs described by other workers for undisturbed sites, with the majority of the radionuclide being contained in the top 10 cm and an exponential decrease occurring below. The total activity of 254 mBq cm^{-2} recorded for this site is close to the mean value of 250 mBq cm^{-2} for five input sites located in the basin which has been used as a reference or control. This mean value was in close agreement with the findings of Cambray *et al.* (1982) who suggested that the magnitude of ^{137}Cs input over the UK was closely controlled by mean annual precipitation. The remaining three profiles illustrated in Fig. 3 exhibit a contrasting down-profile distribution of ^{137}Cs which is characteristic of cultivated soils. The mixing associated with ploughing and other cultivation incorporates the ^{137}Cs more uniformly within the profile and produces a near constant down-profile distribution. The value of total activity for profile B is less than the input or control value of 250 mBq cm^{-2} and is indicative of an eroded site. The down-profile distribution suggests a maximum cultivation depth of c. 28 cm which is consistent with the agricultural machinery used in this area. In contrast to profile B, profiles C and D evidence total ^{137}Cs activities well in excess of the reference or control value of 250 mBq cm^{-2}. These high values are indicative of depositional sites where soil eroded from upslope has been deposited and subsequently incorporated within the profile by cultivation. Profile C has a ^{137}Cs "excess" of 61%, and this value is increased to 64% for profile D. The evidence for deposition provided by the excess ^{137}Cs activity in these two profiles is further substantiated by the down-profile distribution which extends well below the depth of cultivation. A simple comparison of the ^{137}Cs distributions for these two profiles with the 28 cm cultivation depth inferred above suggests that approximately 15–20 cm of sediment has been deposited at these two sites during the past 30 years. This is consistent with the location of these sites near the foot of a slope.

The assembly of ^{137}Cs profile data is extremely time consuming both in terms of the depth-incremental field sampling involved and the substantial number of samples from each site requiring analysis for ^{137}Cs content. Its potential for studying spatial patterns of erosion and deposition is consequently limited. An alternative involves the collection of single whole-core samples from each site and measurement of the total ^{137}Cs activity (mBq cm^{-2}) of the bulk sample. Comparison of these values with the

reference or control value will indicate the existence of areas of erosion and deposition and provide some indication of the relative magnitude of the rates involved. In view of the simpler sampling procedure involved and the need to analyse only a single sample from each site, it is possible to establish a relatively dense network of measuring sites.
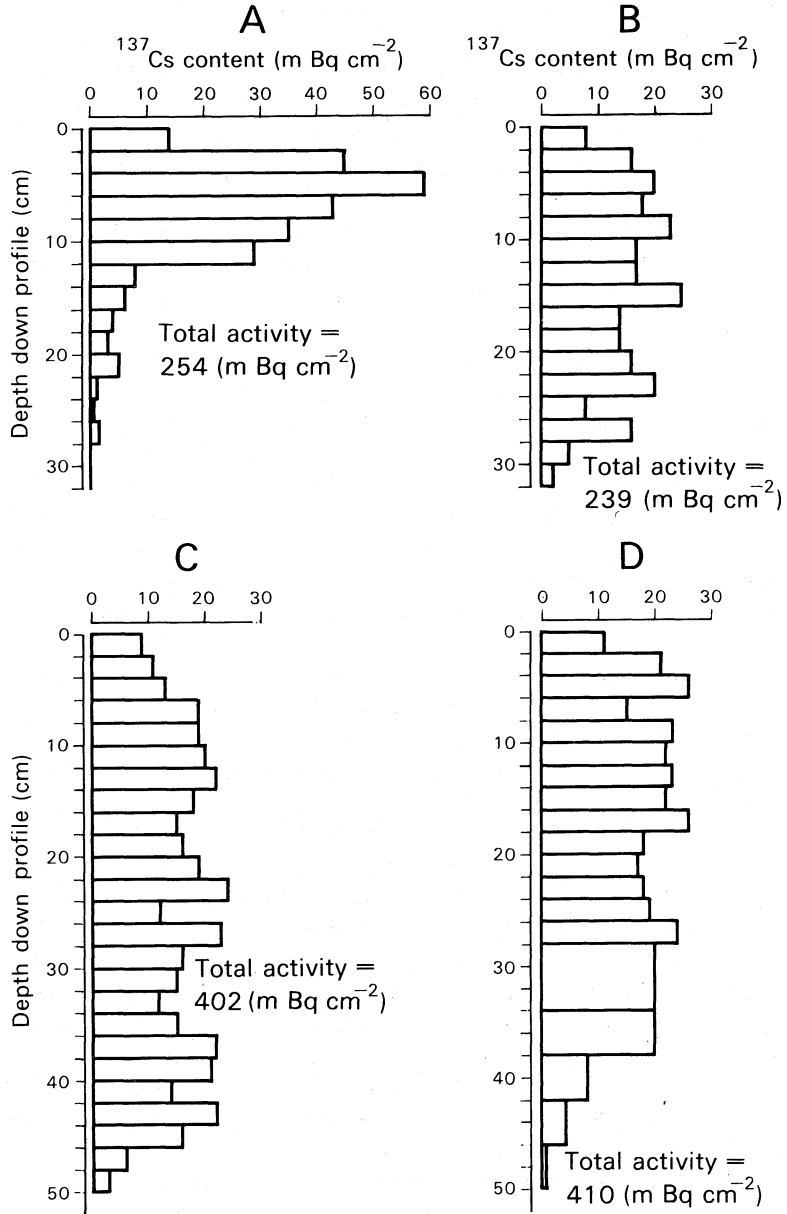

Fig. 4 Caesium-137 profiles representative of undisturbed pasture (A) and eroded (B) and depositional sites (C & D) within cultivated fields in the Jackmoor Brook basin.

This whole-core sampling approach has been used by the authors to investigate patterns of erosion and deposition on three cultivated fields, two located within, and one immediately adjacent to, the Jackmoor Brook drainage basin described above. The three fields shown in Figs 5, 6 & 7 were selected to represent contrasting slope angles. These range from an average slope of approximately 12° in the case of field 1, through 6° for field 2, to 3° for field 3. All three fields have been used for arable cultivation during a large proportion of the preceding 25 years. The sampling programme employed involved the collection of samples along downslope transects located so as to afford a near-uniform distribution of sample sites within each field. Additional sampling sites were located in the vicinity of downslope hedge boundaries where depositional areas might be expected. The whole-core samples (42 cm^2) were collected to a depth of approximately 60 cm using a steel tube percussion corer specially developed for this purpose. The basal 2.5 cm of each core was analysed separately for ^{137}Cs content, a zero concentration indicating that the core had penetrated to the bottom of the ^{137}Cs profile.

The data assembled for the fields have been plotted on Figs 5, 6 & 7. In intepreting these data it is important to recognize that the results obtained from the gamma spectrometry analysis involve an analytical precision of the order of ±5%. The total activity recorded for an individual site must therefore differ from the input or control value by more than 5% if it is to afford definitive evidence of erosional loss or depositional gain. In the case of field 1 (Fig. 5), all sample sites, with the exception of those at the base of the slope, provide evidence of erosion. This erosion has clearly been relatively severe, since the ^{137}Cs levels indicate that >50% of the input has been lost from an appreciable proportion of the sites and that the loss is greater than 60% at several sites. Similarly, it is apparent that substantial deposition has taken place at the base of the slope, since samples from these sites evidence ^{137}Cs levels up to 88% greater than the control value. An attempt has been made to generalize the pattern demonstrated by the individual sites by interpolating isopleths through the data points. Such isopleths have been referred to as isocaes by Longmore *et al.* (1983). More sample sites would be required to generate a definitive map, but if it assumed that the magnitude of the erosional loss is approximately proportional to the percentage ^{137}Cs loss, the resultant pattern of erosion indicates that most erosion has occurred on the steepest part of the field and that this has been preferentially concentrated down a spur. Field evidence suggests that this spur area, and also the other two zones evidencing high rates of erosion are characterized by the thinnest soils within the field. The pattern of erosion may thus reflect the increased incidence of surface runoff from these areas. The continuation of the zone of maximum erosion associated with the spur from the top to the bottom of the field suggests that little or no deposition occurs down the slope. This conclusion is substantiated by the absence of areas of enhanced ^{137}Cs concentrations from all areas of the field except the base of the slope.

An approximate ^{137}Cs budget can be derived for the field by estimating the fraction of the overall ^{137}Cs input that has been mobilized by erosion,
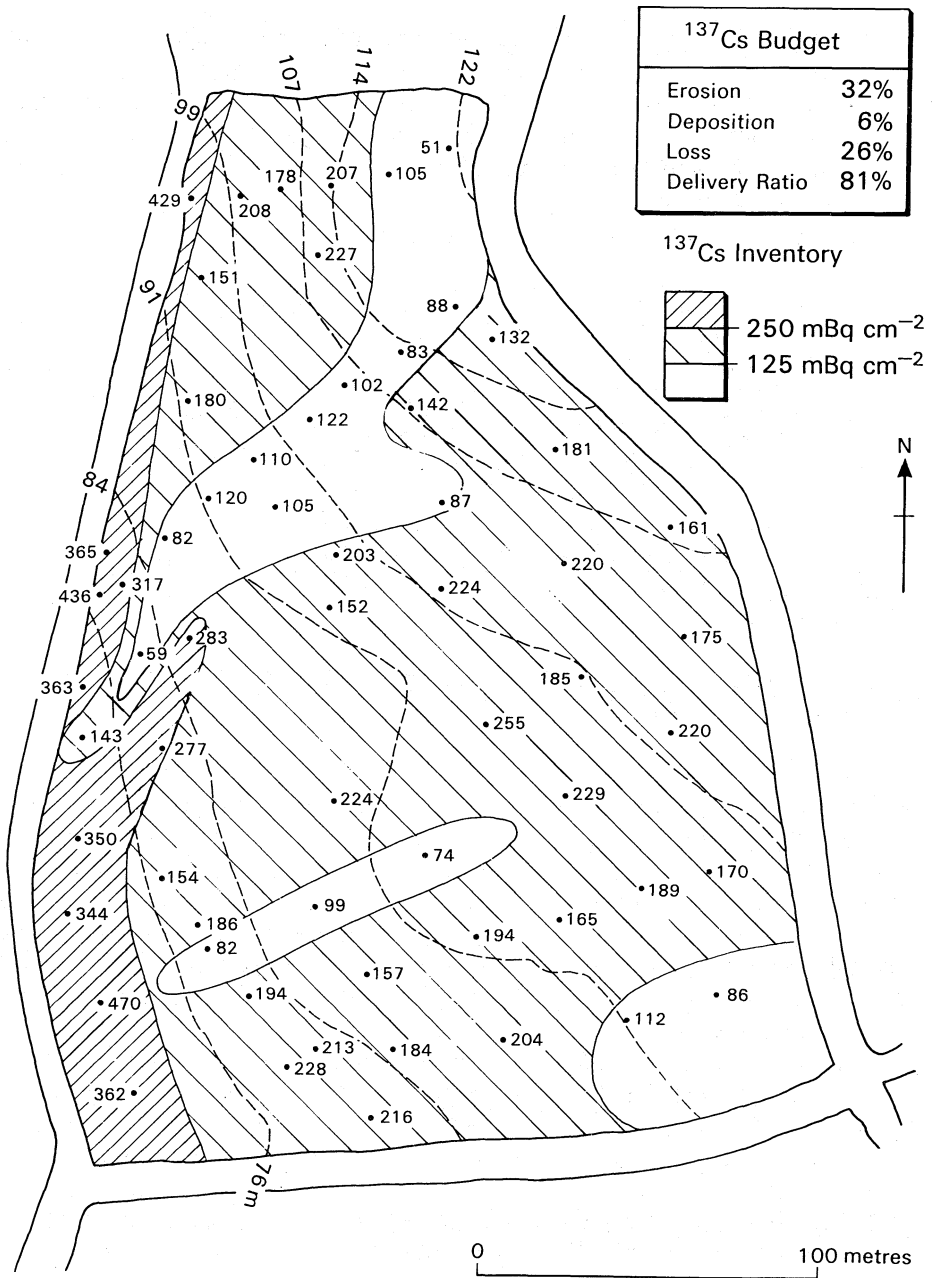
Fig. 5 The distribution of ^{137}Cs within field 1 and the associated ^{137}Cs budget.

and the relative proportions of this fraction that have been redeposited at the base of the slope or transported beyond the field. In this case, approximately 32% of the input of ^{137}Cs has been mobilized, with 7% having been redeposited at the bottom of the slope and the remaining 26% transported

beyond the field. Although these proportions relate specifically to the input of ^{137}Cs, it is possible to argue that they are at least indicative of the relative proportions of the eroded soil that have been redeposited or transported beyond the field and therefore of the sediment delivery ratio (cf. Walling *et al.,* 1986a). Following these assumptions, the sediment delivery ratio for field 1 can be estimated at 81%.

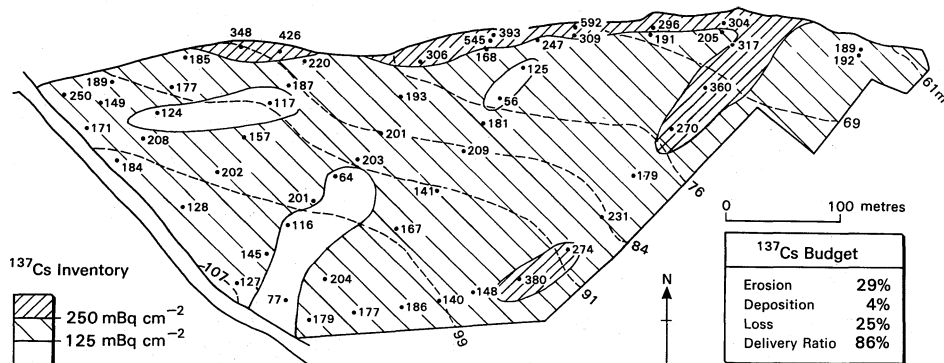Equivalent results for field 2 are presented in Fig. 6. The pattern is

Fig. 6 *The distribution of* ^{137}*Cs within field 2 and the associated* ^{137}*Cs budget.*

similar to that for field 1 in that there is evidence of significant erosion over the majority of the field and the areas of most severe erosion are primarily associated with the contour convexities or spurs. Deposition again occurs above the boundary hedge at the base of the slope. In this case, however, there is evidence of deposition extending upslope into a minor contour concavity which appears to be linked to another small area of deposition towards the top of the field. In addition, the main zone of maximum erosion is not continuous over the full length of the slope. The ^{137}Cs budget for the field again indicates that 29% of the total input has been mobilized, although in this case only 4% has been redeposited within the field and 25% has been transported beyond the field. The sediment delivery ratio of 86% is higher than that for field 1 and this can perhaps be explained by the fact that the downslope hedge boundary is oblique rather than normal to the slope and that there is therefore a greater likelihood that sediment could be transported laterally across the base of the slope towards the lowest point of the field.

The data collected from field 3 and mapped in Fig. 7 evidence a very different pattern to that shown by the previous two examples. Firstly, there are only very small areas of the field where the ^{137}Cs levels are less than 50% of the input or control value and there appears in general to have been less mobilization of the ^{137}Cs input. The areas of maximum ^{137}Cs loss are, however, still associated with areas of contour convexity. Secondly, there are substantial areas of deposition *within* the field as well as along the downslope boundary. Most of the depositional areas within the field are associated with small depressions marked by contour concavities, and it is apparent that a
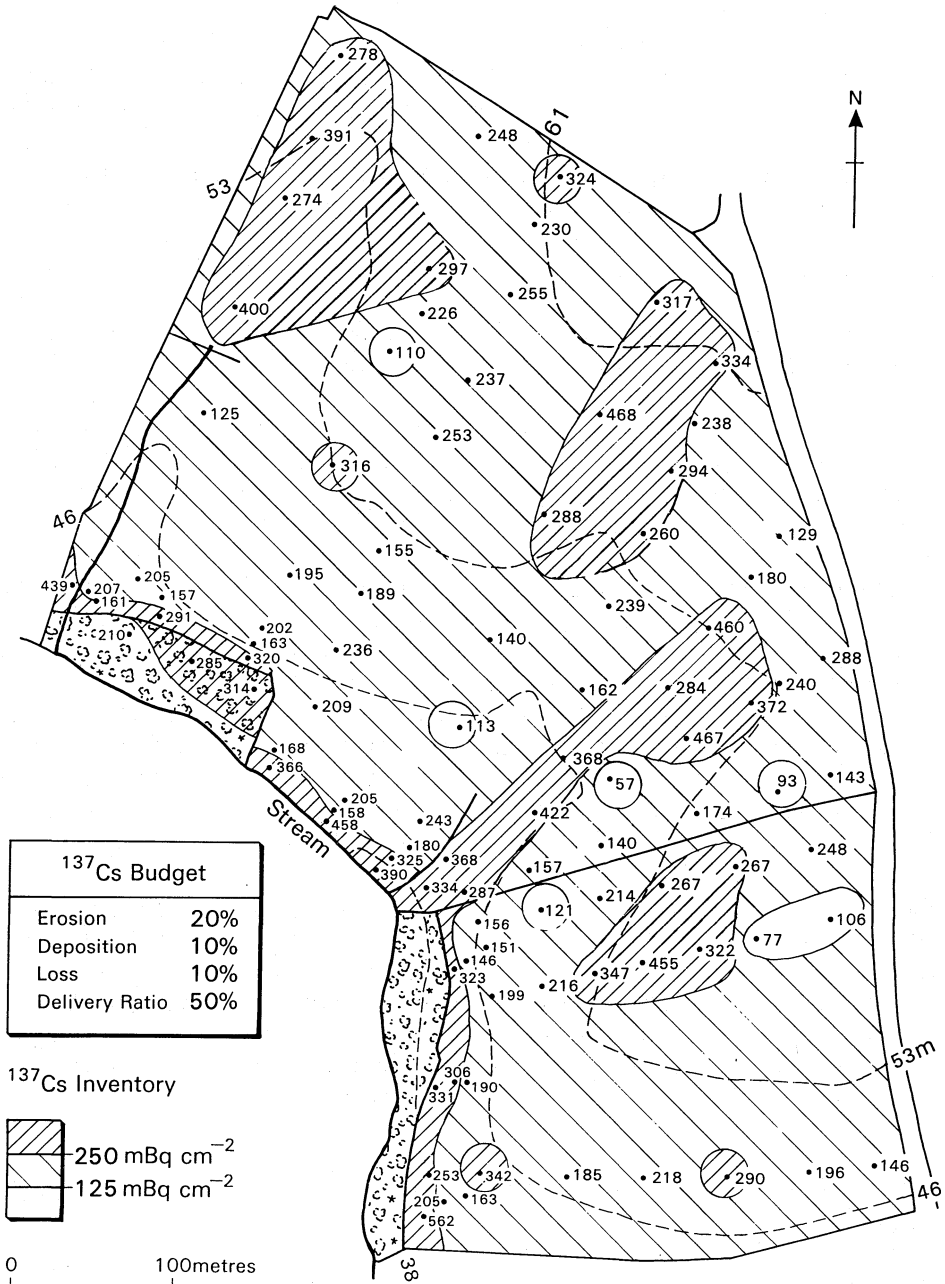
Fig. 7   The distribution of ^{137}Cs within field 3 and the associated ^{137}Cs budget.

substantial proportion of the sediment eroded from the slopes is deposited in these depressions before reaching the downslope field boundary. Thirdly, the overall ^{137}Cs budget for the field differs markedly from those of the other two fields. Only 20% of the total input of ^{137}Cs has been mobilized, and of

this 10% has been redeposited within the field and only 10% has been transported beyond the field. The delivery ratio of approximately 50% stands in marked contrast to the values of 81% and 86% associated with the other fields. These contrasts undoubtedly reflect the influence of slope steepness, since the slopes in field 3 are considerably gentler than those in fields 1 and 2. In view of the close similarities between the patterns of erosion and deposition and the sediment delivery ratios associated with fields 1 and 2, it is suggested that similar fields in this locality with slopes of the order of 6° or more are associated with relatively high rates of erosion and efficient sediment delivery systems, whereas fields with slopes of about 3° or less are characterized by much lower erosion rates and reduced sediment delivery ratios.

The results obtained from this study of three cultivated fields demonstrate the potential offered by ^{137}Cs measurements for elucidating the pattern of erosion and deposition within a field and the overall sediment delivery ratio. Although the approach necessarily possess limitations in terms of the representativeness of the sampling sites, the precision of the analytical measurements and the interpolation procedures involved, it has the great advantage of providing an integrated assessment of the impact of the erosion processes operating within the field over the past 25 years. Any alternative means of assembling such data would probably involve a laborious programme of long term monitoring with all its attendant problems. Extension of such ^{137}Cs measurements to embrace the whole of a small drainage basin could provide a means of establishing a sediment budget for the entire drainage basin and estimating the overall sediment delivery ratio (cf. Walling *et al.,* 1986a). More detailed work would be required to generate estimates of the actual rates of erosion and deposition within th fields, but the studies of Kachanoski & de Jong (1984), Campbell *et al.* (1986) and Kachanoski (1987) indicate that it is possible to establish a relationship between the long term erosion rate and the percentage of the total input of ^{137}Cs lost from the soil profile. Both theoretical models and empirical evidence of the variation of the ^{137}Cs content of eroded soil through time obtained from cores taken from depositional areas are being used by the authors to develop a series of relationships of this type applicable to the study area.

INVESTIGATING RATES AND PATTERNS OF FLOOD PLAIN DEPOSITION

The background

Caesium-137 has been used in numerous studies as a means of dating lake sediment cores (cf. Ritchie *et al.,* 1973; Pennington *et al.,* 1973; Robbins & Edginton, 1975). In this application, dates are ascribed to specific levels in the core by identifying the first appearance of significant amounts of ^{137}Cs (1955–1956) and by relating the precise form of the ^{137}Cs concentration profile to the pattern of annual deposition. The 1963–1964 level has, for example, been identified by the existence of a pronounced peak in the

concentration values corresponding to the peak fallout at that time (cf. Fig. 1). It must, however, be recognized that a close correspondence between the ^{137}Cs profile and the pattern of annual fallout can only be expected in water bodies where autochthonous sedimentation is dominant, since allochthonous sediment eroded from the watershed will be characterized by ^{137}Cs concentrations reflecting the cumulative pattern of fallout receipt at its source (cf. Walling *et al.,* 1986a). Furthermore, several studies have demonstrated that diffusion and mixing processes and sediment focussing may complicate the ^{137}Cs profiles exhibited by lake sediment cores (cf. Robbins & Edgington, 1975; Davis *et al.,* 1984; Anderson *et al.,* 1987). Detailed investigations of the total ^{137}Cs content (mBq cm^{-2}) of a network of sediment cores from a lake or reservoir could also provide a basis for investigating the spatial pattern of deposition within a water body and the incidence of sediment focussing (e.g. Plato & Jacobson, 1976).

Caesium-137 has also been used to estimate rates of sedimentation in other depositional environments, including salt marshes (Delaune *et al.,* 1978) and river backwater zones (Ritchie & McHenry, 1985). Furthermore, work undertaken by the authors indicates that this radionuclide can provide a basis for documenting rates and patterns of flood plain accretion by overbank deposition of fine sediment. In the case of flood plains, however, it is necessary to take account of both the accumulation and vertical redistribution of ^{137}Cs fallout in the flood plain soils and the addition ^{137}Cs associated with deposited sediment, in interpreting the evidence provided by this radionuclide. Fig. 8 compares two ^{137}Cs profiles (B & C), obtained from permanent pasture located on the flood plain of the River Culm in Devon, UK, with a characteristic profile (A) from permanent pasture in the vicinity of the
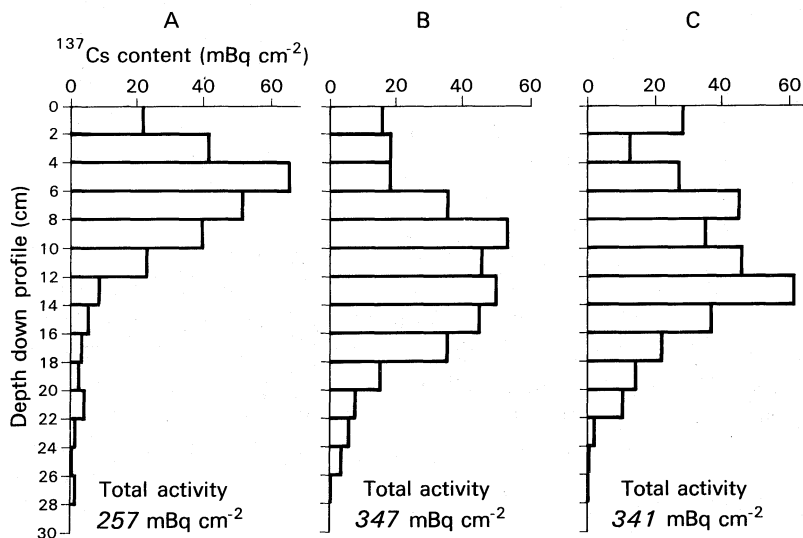

Fig. 8   *Caesium-137 profiles representative of an undisturbed input or control site adjacent to the flood plain of the River Culm (A), and of two sites on the flood plain evidencing deposition (B & C).*

flood plain, but above the level of flood water inundation. In all cases the profiles represent undisturbed conditions with no cultivation. Profile A may be viewed as a reference or control site. It exhibits the typical exponential depth distribution associated with such sites and the total ^{137}Cs content is consistent with the input values encountered in the neighbouring Jackmoor Brook catchment discussed previously. Profiles B & C from the two flood plain sites are characterized by higher total ^{137}Cs contents and by different depth distributions. Both features are consistent with a situation where sediment deposited during overbank flooding has provided an additional input of ^{137}Cs and has caused an upward "stretching" of the profile. Estimates of deposition rates could be based either on the amount of excess ^{137}Cs or the degree of "stretching" (cf. Walling *et al.,* 1986b).

A case study

Further discussion of the potential for using ^{137}Cs as a means of investigating rates and patterns of flood plain deposition is best undertaken by more detailed reference to work undertaken on the flood plain of the River Culm. Figure 9 depicts a 13 km reach of the lower course of the River Culm, Devon, UK, which has a drainage area of 276 km^2. Along most of this reach, the river flows in a gravel bed channel which is approximately 12 m wide. The banks are up to 1 m high and are largely formed of fine alluvial material. Overbank flooding is relatively frequent during the winter months and substantial inundation of this area of flood plain generally occurs on about seven occasions each year. Depths of inundation vary with the local topography of the flood plain, but in the middle reaches flood water depths are typically about 40 cm for the mean annual flood and 70 cm for a 50 year flood. Caesium-137 profiles have been measured at 8 sites along this reach and these are presented in Fig. 9. In all cases, the total ^{137}Cs content of the flood plain sediments at the profile sites exceeds the input or control value of 260 mBq cm^{-2} and therefore suggests that deposition has occurred. Similarly, all profiles show some evidence of "stretching" when compared with the characteristic input profile illustrated in Fig. 8(A).

One means of estimating the amount or rate of deposition at each site is to examine the "excess" ^{137}Cs contents of the profiles. These range from 81 to 377 mBq cm^{-2}. If, following the arguments advanced by Walling *et al.* (1986b), it is assumed that the average ^{137}Cs content of suspended sediment transported by the river over the past 30 years adjusted for decay to the present, is approximately 12.5 mBq g^{-1} and that this value is also representative of the sediment deposited on the flood plain during this period, these excess values provide tentative estimates of sediment deposition of the order of 6–30 g cm^{-2}. Since the bulk density of the flood plain deposits is typically about 1 g cm^{-3}, these are equivalent to sedimentation depths of 6 to 30 cm and of sedimentation rates of 2 to 10 mm year^{-1} over the past 30 years during which appreciable levels of ^{137}Cs would have been present in suspended sediment.

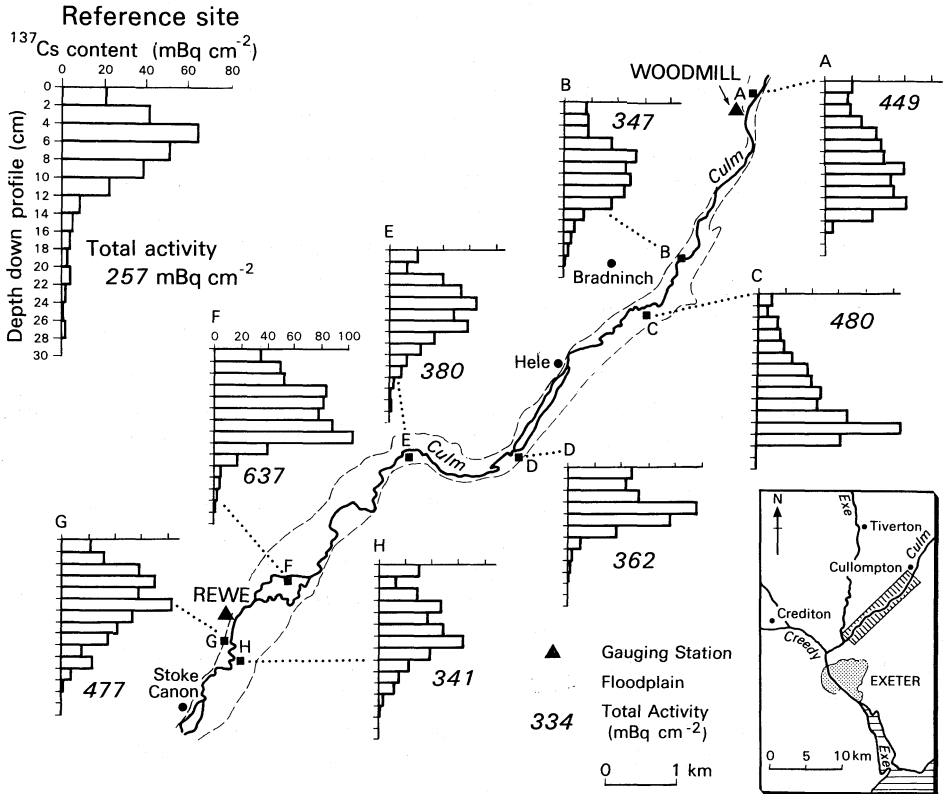Comparison of the ^{137}Cs profiles illustrated in Fig. 9 with the input

Fig. 9   Caesium-137 profiles associated with eight sites representative of depositional environments along the flood plain of the River Culm.

profile depicted in Fig. 8(A), and also included on Fig. 9, provides a basis for estimating the degree of "stretching" of the profile, which in turn provides an alternative estimate of the depth of sedimentation and the associated sedimentation rate. Matching of the lower portions of the profiles in Fig. 9 with that shown in Fig. 8(A) suggests that the former exhibit "stretching" by of the order of 6 to 20 cm, which is equivalent to sedimentation rates of 2 to 6.7 mm year^{-1}. These values are in reasonably close agreement with those obtained above and the profiles exhibiting high degrees of "stretching" are commonly those with high values of ^{137}Cs "excess". There are some minor discrepancies between the two sets of data, but these are not unexpected in view of the various assumptions involved and the fact that sedimentation may not have been continuous over the period and that the particle size composition and therefore the ^{137}Cs content of the deposited sediment could be expected to vary from site to site. Both approaches to the use of ^{137}Cs measurements to estimate depths and rates of flood plain deposition provide estimates which are consistent with other evidence available for this reach of the River Culm from measurements of the reduction in suspended sediment loads through the reach and from sedimentation traps (cf. Walling *et al.,* 1986b; Lambert & Walling, 1987). Further work is in progress to refine these

approaches to estimating depths and rates of flood plain deposition.

As with the use of ^{137}Cs measurements to investigate patterns of erosion and deposition in agricultural fields discussed previously, the number of samples requiring analysis precludes the investigation of a large number of site profiles, in order to study spatial patterns of flood plain deposition. However, single whole-core samples can again be used for this purpose, since the values of total ^{137}Cs content (mBq cm^{-2}) associated with each core may be compared with the input or control value to assess the depth and rate of deposition at that site. Figure 10 provides a map of the study reach onto which the values of total ^{137}Cs content obtained for more than 120 whole-core samples taken from the reach have been superimposed. In this case about 30% of the values are less than the reference value of 260 mBq cm^{-2} and these are thought to represent sites where scour has occurred or where flood plain development has occurred only recently as a result of channel migration. Removal of part of the profile by erosion will result in reduced values of total ^{137}Cs content, and, if deposition has been restricted to only part of the past 30 years, reduced values of total ^{137}Cs content will again occur. No simple relationship between depth of scour and the proportion of the ^{137}Cs that has been lost will, however, exist since the value recorded for a site could reflect a combination of both scour and subsequent deposition. It is not possible to distinguish those sites where scour has occurred from those indicative of recent channel migration, but it seems reasonable to suggest that scour has occurred at a number of sites and that the reach is not characterized solely by deposition.

The values of ^{137}Cs "excess" associated with those sites where the core value exceeds the reference level, and where net deposition has therefore occurred, range up to 773 mBq cm^{-2}. Values of the order of 40–125 mBq cm^{-2} are, however, typical of most of the reach. Based on the assumptions outlined above, these are indicative of depositional depths and rates between approximately 3 and 10 cm and 1 and 3 mm year^{-1} respectively. Looking at the overall distribution of values within the reach there would also appear to be a tendency for the value of ^{137}Cs excess, and therefore the depths and rates of deposition, to increase downstream in response to the increasing width and decreasing gradient of the flood plain. In the downstream portion of the reach in the vicinity of the villages of Rewe and Stoke Canon, several values of ^{137}Cs excess greater than 400 mBq cm^{-2} are evident. These are indicative of depositional depths and rates in excess of about 30 cm and 10 mm year^{-1} respectively.

The whole-core approach can also be used to investigate local patterns of sedimentation within smaller areas of flood plain. Two examples of such studies undertaken within the study reach of the River Culm are provided in Fig. 11. In this case the objective was to investigate the influence of the microtopography of the flood plain on depths and rates of sedimentation. At the first location (Fig. 11(A)), attention focussed on the influence of a small, essentially closed, depression about 50 m from the river channel. The values of total ^{137}Cs content for the individual cores plotted on the map indicate that relatively high rates of deposition occurred immediately adjacent to the channel and also in the bottom of the depression. Depths and rates of
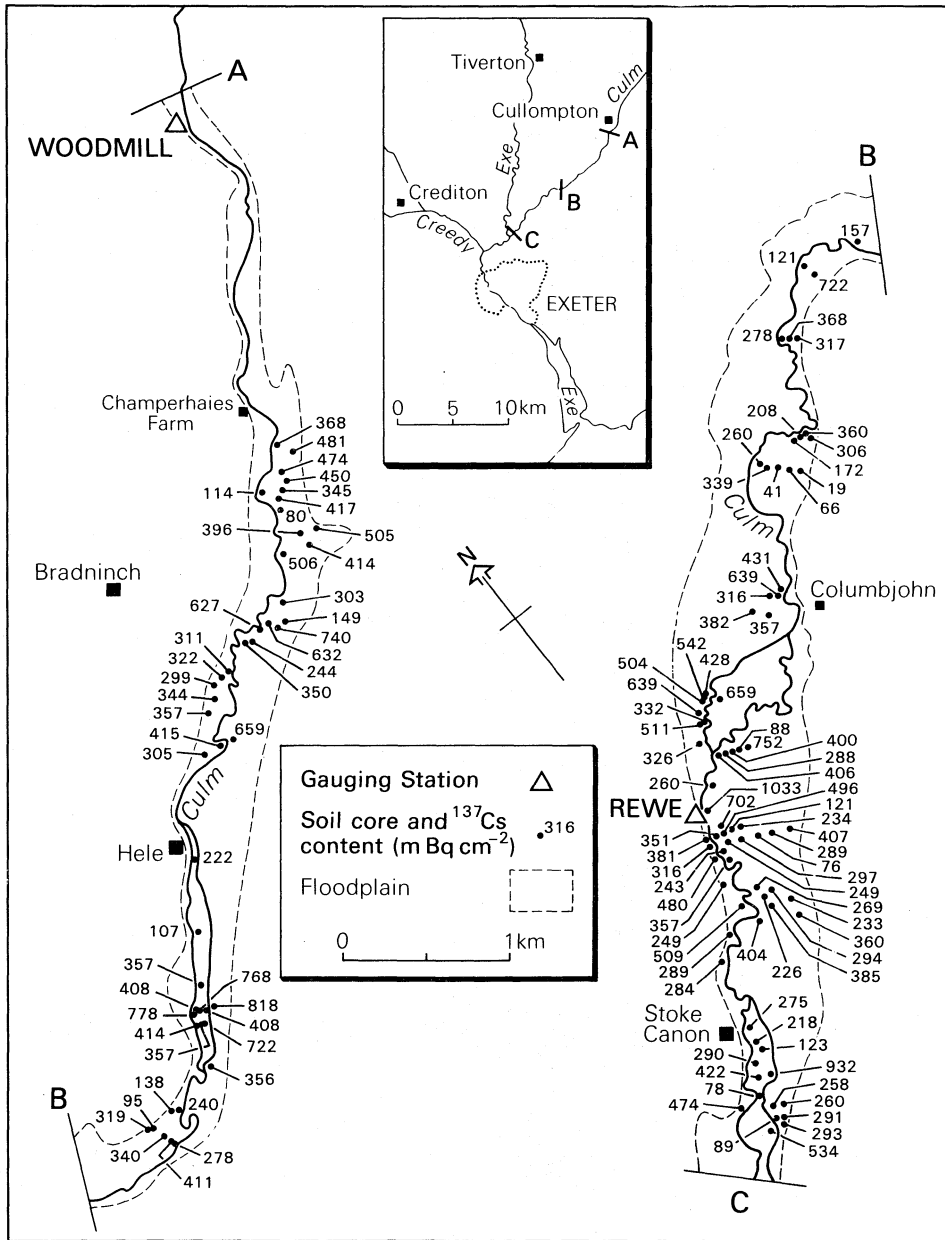
Fig. 10 *Values of* ^{137}Cs *content associated with whole-core samples collected from a variety of locations along the flood plain of the River Culm.*

deposition in the former location can be estimated to be of the order of 10–40 cm or 3–13 mm year^{-1}. In the centre of the depression the corresponding values are 36 cm and 12 mm year^{-1}. The existence of several points where ^{137}Cs totals are less than the reference value of 260 mBq cm^{-2}

points to the local occurrence of scour which would appear in this case to be associated with the small chutes entering the depression to the north and west.

At the second study site (Fig. 11(B)), interest focussed on the influence of a linear depression trending essentially parallel to the channel. In this case there is no evidence of relatively high rates of deposition adjacent to the channel, and most of the area within and surrounding the depression evidences scour or only relatively low values of ^{137}Cs "excess". The depression apparently acts as a secondary conveyance channel during overbank flows and the relatively high flow velocities occurring at such times cause scour, or at
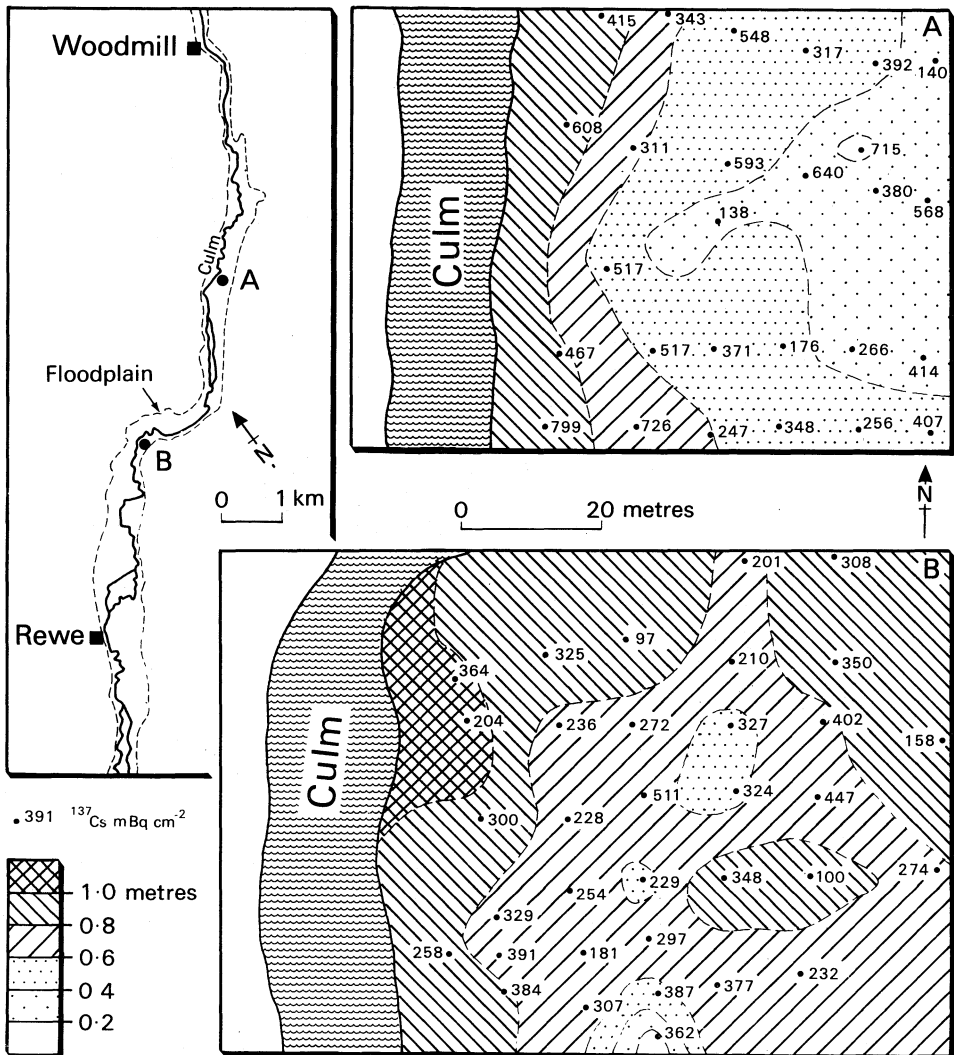

Fig. 11 Local patterns of ^{137}Cs content exhibited by whole-core samples collected from two small areas of the flood plain of the River Culm adjacent to the river channel.

least severely limit rates of deposition. There is some evidence of increased deposition in the more pronounced part of the depression to the south and this may be ascribed to the isolation of this area as a small closed depression during the latter stages of flood water drainage from the flood plain. The considerable spatial variability in deposition rates evident within these two small study areas emphasizes the complexity of flood plain aggradation and suggests that scope exists to use even more intensive sampling networks to unravel the patterns involved and their controls.

THE PROSPECT

The three examples of the use of ^{137}Cs measurements in the study of fluvial erosion, transport and deposition described in this paper undoubtedly represent only a few of the wide range of potential applications. More work is required to investigate other applications and to exploit this potential fully. With its half-life of 30.1 years, ^{137}Cs originating from the bomb tests undertaken in the late 1950s and the 1960s will provide the geomorphologist with a valuable tracer for several decades to come and the opportunities that it offers should be grasped. In those areas where significant amounts of fallout occurred as a result of the Chernobyl accident, interpretation may prove more difficult, but additional opportunities could exist to trace the movement of this essentially instantaneous input of ^{137}Cs through the fluvial system (cf. Walling and Bradley, 1988).

REFERENCES

Anderson, R. F., Schiff, S. L. & Hesslein, R. H. (1897)   Determining sediment accumulation and mixing rates using ^{210}Pb, ^{137}Cs, and other tracers: problems due to postdepositional mobility or coring artifacts. *Can. J Fish. Aquat. Sci.* **44**, 231-250.
Beasley, D. B., Huggins, L. F. & Monke, E. H. (1982)   Modelling sediment yields from agricultural watersheds. *J. Soil Wat. Conserv.* **37**, 114-117.
Cambray, R. S., Fisher, E. M. R., Playford, K., Eakins, J. D. & Peirson, D. H. (1980)   Radioactive fallout in air and rain: results to end of 1979. UK Atomic Energy Authority Rep. AERE-R- 9672.
Cambray, R. S., Playford, K. & Lewis, G. N. J. (1982)   Radioactive fallout in air and rain: results to end of 1981. UK Atomic Energy Authority Rep. AERE-R-10845.
Cambray, R. S., Cawse, P. A., Garland, J. A., Gibson, J. A. B., Johnson, P., Lewis, G. N. J., Newton, D., Salmon, L. & Wade, B. O. (1987)   Observations on radioactivity from the

Chernobyl accident. *Nuclear Energy* **26**, 77-101.

Campbell, B. L., Loughran, R. J. & Elliott, G. L. (1982) Caesium-137 as an indicator of geomorphic processes in a drainage basin system. *J. Aust. Geogr. Studies* **20**, 49-64.

Campbell, B. L. (1983) Application of environmental caesium-137 for the determination of sedimentation rates in reservoirs and lakes and related catchment studies in developing countries. In: *Radioisotopes in Sediment Studies* IAEA-TECDOC-298, 7-29.

Campbell, B. L., Loughran, R. J., Elliott, G. L. & Shelly, D. J. (1986) Mapping drainage basin sediment sources using caesium-137. In: *Drainage Basin Sediment Delivery* (Proc. Albuquerque Symp. Aug. 1986), 437-446 IAHS Publ. no. 159.

Davis, M. B., Moeller, R. E. & Ford, J. (1984) Sediment focusing and pollen influx. In: *Lake Sediments and Environmental History* (ed. E. Y. Haworth & J. W. Lund), Leicester Univ., UK, 261-293.

De Jong, E., Begg, C. B. M. & Kachanoski, R. G. (1983) Estimates of soil erosion and deposition for some Saskatchewan soils. *Can. J. Soil Sci.* **63**, 607-617.

Delaune, R. D., Patrick, W. H. & Buresh, R. J. (1978) Sedimentation rates determined by ^{137}Cs dating in a rapidly accreting salt marsh. *Nature* **275**, 532-533.

Dorr, H. & Munnich, K. O. (1987) Spatial distribution of soil-^{137}Cs and ^{134}Cs in West Germany after Chernobyl. *Naturwissenschaften* **74**, 249-251.

Finlayson, B. L. (1978) Suspended solid transport in a small experimental catchment. *Z. Geomorphol.* **NF22**, 192-210.

Frissel, M. J. & Pennders, R. (1983) Models for the accumulation and migration of ^{90}Sr, ^{137}Cs, ^{239,240}Pu and ^{241}Am in the upper layer of soils. In: *Ecological Aspects of Radionuclide Release* (ed. P. J. Coughtrey), 63-72, Special Publ. Brit. Ecol. Soc. No. 3.

Gale, H. J., Humphreys, D. L. O. & Fisher, D. M. R. (1963) The weathering of caesium-137 in soil. UK Atomic Energy Authority Rep. AERE-R-4241.

Glymph, L. M. (1975) Evolving emphases in sediment yield predictions. In: *Present and Prospective Technology of Predicting Sediment Yields and Sources* USDA ARS-S-40, 1-4.

Kachanoski, R. G. (1987) Comparison of measured soil 137-cesium losses and erosion rates. *Can. J. Soil Sci.* **67**, 199-203.

Kachanoski, R. G. & De Jong, E. (1984) Predicting the temporal relationship between soil cesium-137 and erosion rate. *J. Environ. Qual.* **13**, 301-304.

Lambert, C. P. & Walling, D. E. (1987) Floodplain sedimentation. A preliminary investigation of contemporary deposition within the lower reaches of the River Culm, Devon, UK. *Geograf. Ann.* **69A**, 47-59.

Longmore, M. E., O'Leary, B. M., Rose, C. W. & Chandica, A. L. (1983) Mapping soil erosion and accumulation with the fallout isotope caesium-137. *Aust J. Soil Res.* **21**, 373-385.

Loughran, R. J., Campbell, B. L. & Elliott, G. L. (1982) The identification and quantification of sediment sources using ^{137}Cs. In: *Recent developments in the Explanation and Prediction of Erosion and Sediment Yield* (Proc. Exeter Symp. July 1982), 361-369. IAHS Publ. no. 137.

McHenry, J. R. & Ritchie, J. C. (1977) Estimating field erosion losses from fallout caesium-137 measurements. In: *Erosion and Solid Matter Transport in Inland Waters* (Proc. Paris Symp. July 1977), 26-33, IAHS Publ. no. 122.

McHenry, J. R., Ritchie, J. C. & Bubenzer, G. D. (1978) Redistribution of caesium-137 due to erosional processes in a Wisconsin watershed. In: *Environmental Chemistry and Cycling Processes* (Proc. Augusta Conf., May 1976), 495-503, ERDA Symp. Series.

Oldfield, F., Rummery, T. A., Thompson, R. & Walling, D. E. (1970) Identification of suspended sediment sources by means of magnetic measurements. *Wat. Resour. Res.* **15**, 211-218.

Peart, M. R. & Walling, D. E. (1986) Fingerprinting sediment sources: The example of a drainage basin in Devon, UK. In: *Drainage Basin Sediment Delivery* (Proc. Albuqerque Symp. Aug. 1986), 41-55, IAHS Publ. no. 159.

Pennington, W., Cambray, R. S. & Fisher, E. M. (1973) Observations on lake sediment using fallout ^{137}Cs as a tracer. *Nature* **242**, 324-326.

Plato, P. & Jacobson, A. P. (1976) Cesium-137 in Lake Michigan sediments: areal distribution and correlation with other man-made materials. *Environ. Pollut.* **10**, 19-33.

Ritchie, J. C. (1987) Literature relevant to the use of radioactive fallout cesium-137 to measure soil erosion and sediment deposition. USDA ARS Hydrology Laboratory Tech. Rep. HL-9.

Ritchie, J. C., McHenry, J. R. & Gill, A. C. (1973) Dating recent reservoir sediments. *Limnol. Oceanogr.* **18**, 254-263.

Ritchie, J. C. & McHenry, J. R. (1985) A comparison of three methods of measuring recent rates of sediment accumulation. *Wat. Resour. Res.* **21**, 91-103.

Robbins, J. A. & Edgington, D. N. (1975) Determination of recent sedimentation rates in Lake Michigan using Pb-210 and Cs-137. *Geochim. Cosmochim. Acta* **39**, 285-304.

Rogowski, A. S. & Tamura, T. (1970a) Environmental mobility of cesium-137. *Radiation Botany* **10**, 35-45.

Rogowski, A. S. & Tamura, T. (1970b) Erosional behaviour of cesium-137. *Health Phys.* **18**,

467-477.

Swanson, F. J., Janda, R. J., Dunne, T. & Swanston, D. N. (1982)   Sediment budgets and routing in forested drainage basins. USDA Forest Service General Tech. Rep. PNW-141.

Tamura, T. (1964)   Selective sorption reaction of caesium with mineral soils. *Nuclear Safety* **5**, 262-268.

US Health and Safety Laboratory (1977)   Environmental Quarterly, July 1, ERDA Rep. HASL-321

Wall, G. J. & Wilding, L. P. (1976)   Mineralogy and related parameters of fluvial suspended sediments in Northwestern Ohio. *J. Environ. Qual.* **5**, 168-173, 35. 1.

Walling, D. E. & Bradley, S. B. (1988)   Transport and redistribution of Chernobyl fallout radionuclides by fluvial processes: some preliminary evidence. *Environ. Geochem. Health* **10**, 35-39.

Walling, D. E., Bradley, S. B. & Wilkinson, C. J. (1986a)   A caesium-137 budget approach to the investigation of sediment delivery from a small agricultral drainage basin in Devon, UK. In: *Drainage Basin Sediment Delivery,* (Proc. Albuquerque Symp., Aug. 1986), 423-435. IAHS Publ. no. 159.

Walling, D. E., Bradley. S. B. & Lambert, C. P. (1986b)   Conveyance losses of suspended sediment within a floodplain system. In: *Drainage Basin Sediment Delivery* (Proc. Albuquerque Symp., Aug. 1986), 119-131, IAHS Publ. no. 159.

Walling, D. E. & Kane, P. (1982)   Temporal variations of suspended sediment properties. In: *Recent Developments in the Explanation and Prediction of Erosion and Sediment Yield.* (Proc. Exeter Symp. July 1982) 409-419, IAHS Publ. no. 137.

Wolman, M. G. (1977)   Changing needs and opportunities in the sediment field. *Wat. Resour. Res.* **13**, 50-54.

Wood, P. A. (1978)   Fine-sediment mineralogy source rocks and suspended sediment, Rother Catchment, West Sussex. *Earth Surf. Processes* **3**, 255-263.