Conveyance losses of suspended sediment within a flood plain system

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ABSTRACT Depositional losses of suspended sediment within a 13 km reach of the lower course of the River Culm, Devon, UK (drainage area 276 km^2) have been investigated. This stretch of the river evidences a well developed flood plain which is frequently inundated by floodwater and detailed records of suspended sediment load obtained from upstream and downstream gauging stations indicate that approximately 28 percent of the upstream load may be deposited within the reach. The magnitude of the conveyance loss for individual events varies according to their characteristics. Rates of deposition have been estimated from the conveyance loss and these have been compared with data obtained from sedimentation traps and from analysis of the ^{137}Cs content of flood plain soils. Average rates of approximately 500 gm^{-2} year (0.5 mm $year^{-1}$) are indicated, although the ^{137}Cs data suggest that considerable spatial variation may occur. An investigation of the characteristics of the suspended sediment transported through the reach shows that conveyance losses are associated with a preferential loss of the coarser fractions, although appreciable deposition of the clay fraction also occurs.

INTRODUCTION

Although studies of sediment delivery from drainage basins and the linkages between on-site erosion and downstream sediment yield have traditionally focussed on the depositional losses occurring on slopes and in headwater channels (e.g. Piest et al., 1975) considerable conveyance losses may also occur at downstream locations within the main channel system (cf. Frickel et al., 1975; Trimble, 1981; Walling, 1983). Well-developed flood plains may, in particular, provide an important sink for suspended sediment during periods of inundation, but relative little information currently exists regarding the magnitude of the depositional losses that may occur. In the UK, for example, the fine alluvial deposits that are widespread along the flood plains of major lowland rivers (cf. Lewin, 1981) are seen as evidence of long-term overbank deposition (e.g. Brown, 1983), but little is known about contemporary rates of deposition or the contemporary significance of the flood plains within the overall sediment budgets of the rivers involved. Further information concerning the magnitude of conveyance losses associated with flood plain systems is required, to provide an improved understanding of both sediment delivery dynamics and the role of the flood plain as a potential sink for sediment-associated contaminants which could accumulate within its surface deposits.

In common with other aspects of sediment delivery, investigation of conveyance losses within a flood plain system poses many practical difficulties. There are no generally-accepted or proven measurement procedures, and any attempt to document deposition rates which are likely to be both of low magnitude and highly variable spatially will inevitably face problems. This paper discusses several of the methods currently being employed by the authors in a study of conveyance losses along a

13 km stretch of the flood plain of the River Culm in Devon, UK, and some of the results obtained.

THE STUDY AREA

The River Culm, an eastern tributary of the River Exe which joins the main river about 3 km north of Exeter (Fig. 1), has a total catchment area of 276 km^2. Its lower reaches between Cullompton and Stoke Canon (Fig. 1) meander across a well-developed flood plain which averages about 450 m in width. 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 typically occurs on about seven occasions each year. During a major flood approximately 5.5 km^2 of flood plain between Cullompton and Stoke Canon is inundated. 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. Land use on the flood plain is almost exclusively permanent pasture which is used for cattle grazing and hay and silage production. Grazing is restricted to the summer months, in view of the dangers of flooding and waterlogged conditions which characterize the winter.

The study has focussed on the 11 km stretch of the Culm Valley between the flow gauging stations at Woodmill (upstream) and Rewe (downstream) (Fig. 1). These gauging stations provide records of flood events moving through the reach and of suspended sediment concentrations which are continuously monitored at both sites using optical turbidity meters (cf. Walling, 1978). Suspended sediment loads calculated for both sites provide information on the magnitude of the sediment loads transported into and out of the study reach. Sediment concentrations rarely exceed 1000 mgl^{-1} and the load is dominated by clay- and silt-sized material. the < 63 µm and < 2 µm fractions typically account for 97 percent and 75 percent of the total load respectively.

Four approaches to the study of conveyance losses within the study reach have been employed. These are discussed in turn.

I COMPARISON OF UPSTREAM AND DOWNSTREAM LOADS

Only one significant tributary, the River Weaver, enters the study reach between the gauging stations at Woodmill and Rewe. With a drainage area of 16.8 km^2 the sediment loads transported by the River Weaver are small in comparison to those transported by the main river and comparison of the loads passing the upstream and downstream gauging stations provides a means of assessing the magnitude of conveyance losses within the study reach. A detailed analysis of the sediment load records from the two gauging stations has been undertaken for the period November 1982 to May 1984 and the results (Table 1) indicate that the load recorded at the downstream gauging site for this period was only 72 percent of that recorded at the upstream site, suggesting a conveyance loss of 28 percent. Subdivision of the record of sediment load into periods of storm runoff and periods of stable flow (Table 1) shows that the majority of this loss was associated with storm events and that only minimal losses (four percent) were associated with sediment transport during periods of stable flow. This contrast can be readily accounted for in terms of the importance of flood plain inundation to the depositional process. The storm-period sediment load measured at Rewe was only 70 percent of that recorded at the upstream site of Woodmill.

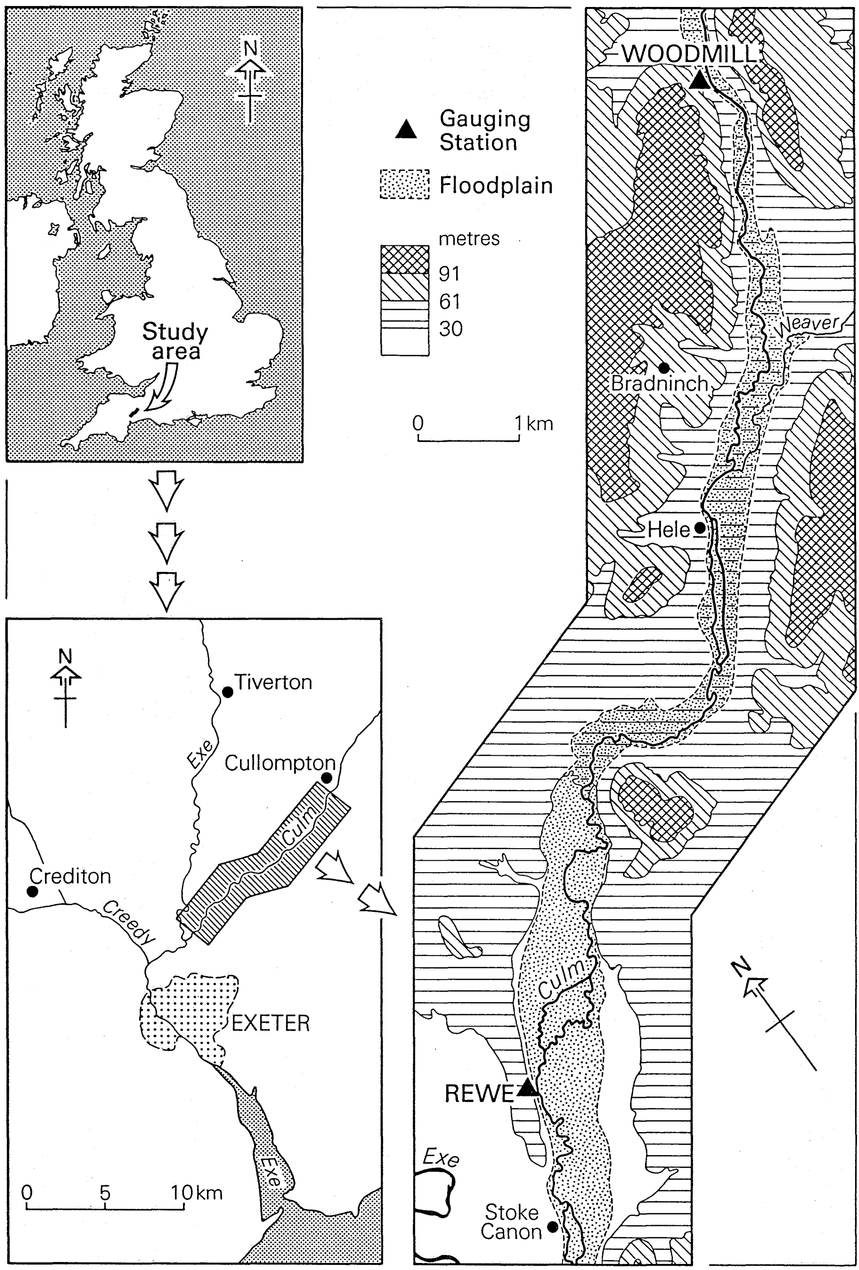

Figure 1.

Table 1 shows that conveyance losses of suspended sediment within the study reach during the period November 1982 to May 1984 amounted to 3345 tonnes or 28 percent of the total upstream load. These figures depend heavily on the accuracy of the sediment load data for the two sites, but a detailed evaluation of the measurement and calculation errors involved

Table 1 Conveyance losses of suspended sediment between the gauging stations at Woodmill and Rewe, November 1982 - May 1984

Sediment Load	Woodmill (Upstream)	Rewe (Downstream)	Percentage Loss
Storm-period suspended sediment load (t)	10847	7542	30
Stable flow suspended sediment load (t)	1012	972	4
Total suspended sediment load (t)	11859	8514	28

suggested that in combination these were unlikely to exceed ± 10 percent and that the apparent reduction in load at the downstream site could not be accounted for by such errors. Furthermore, the values of conveyance loss presented in Table 1 are likely to be underestimates, since they take no account of tributary inputs of suspended sediment within the study reach associated with the River Weaver or with bank erosion which must represent a significant sediment source. The data presented in Table 1 may therefore be viewed as minimum estimates of conveyance losses.

In addition to an assessment of the overall conveyance loss occurring within the study reach, the sediment load data available for the upstream and downstream gauging sites also permitted an analysis of the magnitude of the losses associated with individual flood events. Figure 2 provides a typical example of the flood hydrographs and associated sediment concentration records from the two sites. The event which occurred on 12 November 1982 was approaching the magnitude of the mean annual flood and was associated with considerable flood plain inundation. The effects of overbank spillage in reducing the downstream flood peak and attenuating the hydrograph are clearly apparent and this is coupled with a downstream reduction in suspended sediment concentration. The suspended sediment load for this event calculated for the upstream measuring station was 385 t whilst that for the downstream station was 350 t, providing a conveyance loss of 35 t or nine percent.

Analysis of upstream and downstream suspended sediment loads for 25 individual storm runoff events which occurred during the period November 1982 - May 1984 evidenced 21 events during which significant conveyance losses occurred and four where the downstream loads were greater than the upstream values. However, all the 15 events which produced overbank flooding were associated with conveyance losses and these ranged from 8 - 53 percent. No simple pattern emerged to account for the precise magnitude of the loss associated with a particular event, but flood magnitude and duration and the magnitude of the upstream sediment load appeared to be important factors. Maximum conveyance losses were commonly associated with events with high peak discharges and substantial loads (Fig. 3).

II RATES OF DEPOSITION

The results presented above indicate that during the period November 1982 to May 1984 3345 t of sediment were deposited within the flood plain system of the River Culm between the gauging stations at Woodmill and

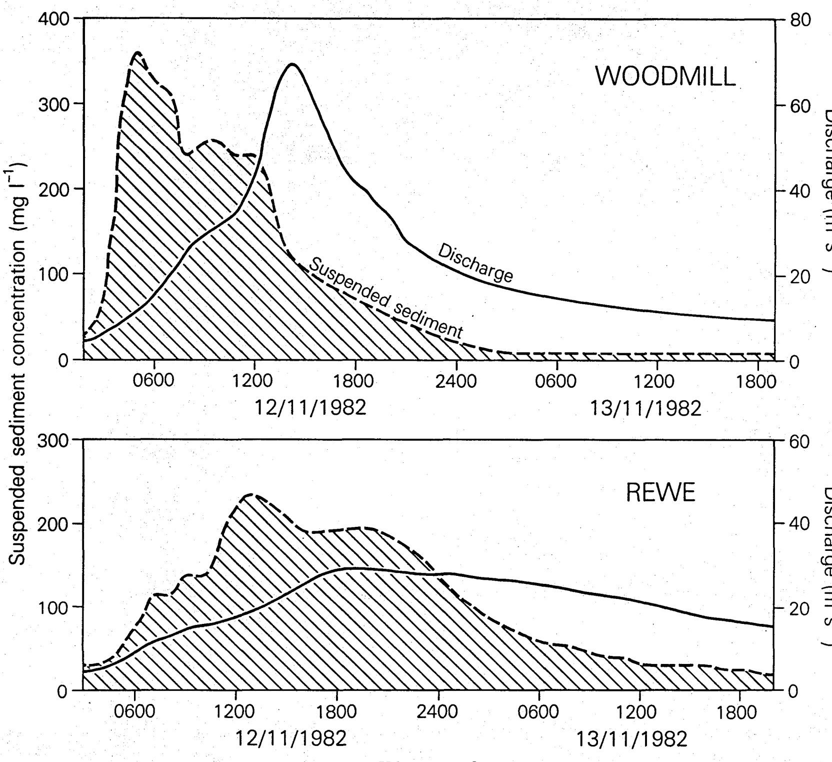

Figure 2.

Rewe. Since this period includes the winter flood seasons of 1982/3 and 1983/4, which account for the majority of the sediment transport by this river, the data point to an annual conveyance loss of approximately 1750 t $year^{-1}$. However, this value takes no account of inputs of suspended sediment to the study reach from bank erosion and from the River Weaver and other small streams. No reliable estimates of the former exist, but Hooke (1977) reports bank recession rates of up to 0.2 m $year^{-1}$ within this reach. The annual input from this source has therefore been tentatively estimated at 150 t $year^{-1}$. Assuming an annual suspended sediment yield of 40 t km^{-2} $year^{-1}$, which is typical of the area involved, for the River Weaver and other small streams entering the study reach, the tributary input can be estimated at 600 t $year^{-1}$. Taking account of these two inputs, the estimate of the annual conveyance loss within the study reach may be increased to 2500 t $year^{-1}$.

There is little evidence of accumulation of fine sediment within the gravel-bed channel of the River Culm and field evidence suggests that the majority of this conveyance loss is associated with overbank deposition on the flood plain. The area of flood plain inundated by flood events varies according to the magnitude of the event and rates of deposition will clearly exhibit marked spatial variation in response to variations in the frequency of inundation and to the interactions of the floodwater with the local topography of the flood plain. However, assuming an average area of inundation of 5 km^2, the annual conveyance loss of 2500 t $year^{-1}$ is equivalent to an average rate of deposition within the flood plain of 500 gm^{-2}.

In order to provide some independent verification of this value, field measurements of flood plain deposition rates have been made using

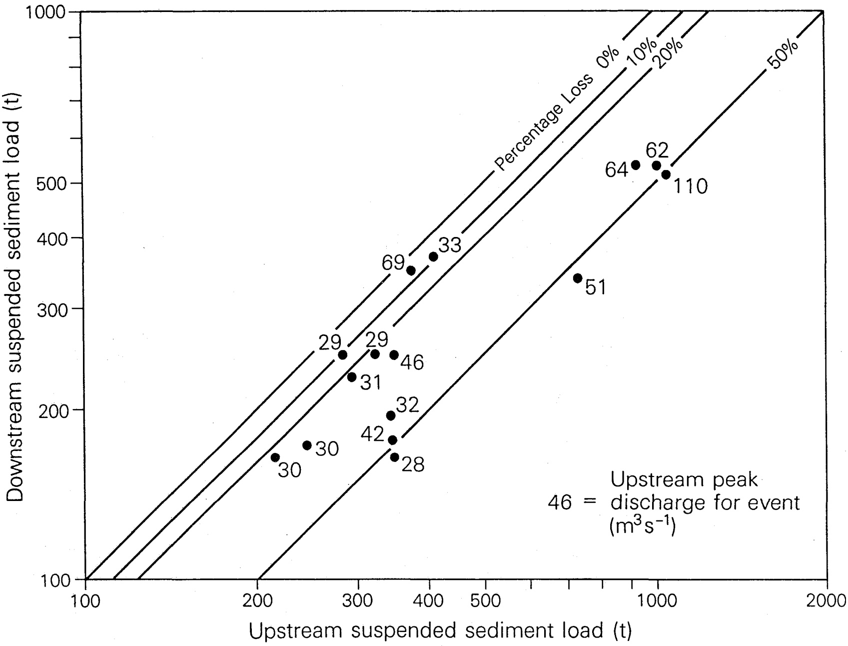

Figure 3.

sedimentation traps. The traps employed consisted of small pieces of plastic of "artificial grass" mat (2870 cm^2) fixed to the flood plain surface with steel pins. With 3 cm plastic tufts fixed to a pliable plastic base, the mats provide close replication of the natural flood plain surface, although it was necessary to install them on a small plastic sheet to avoid soil particles being splashed from the flood plain surface onto the mats. These sedimentation traps were recovered at the end of individual flood events and returned to the laboratory where the deposited sediment was removed by washing, before being dried and weighed.

Any attempt to use such sedimentation traps to provide representative data on rates of flood plain deposition inevitably faces problems associated with the marked spatial heterogeneity of the flood plain environment. A very large number of traps located at many different sites would be required. This was beyond the scope of this investigation which aimed to use the traps to provide a general confirmation of the likely rates of deposition. Measurements were restricted to one site in the central area of the study reach near Silverton Mill. Substantial overbank inundation occurred at this site, with water depths of up to 1.2 m. The results obtained from measurements for three flood events are summarized in Table 2. Considerable variability is apparent between the values obtained from individual traps for a specific event, but the mean values are consistent with the average rate of deposition of 500 gm^{-2} $year^{-1}$ proposed above. Furthermore, when the mean values for individual events are compared with estimates of the average rates of deposition associated with those events (calculated from the measured conveyance loss through the study reach divided by the area of inundation) there is close agreement both in terms of the relative ranking of the events and of the absolute magnitude of the deposition rates. However, these calculations take no account of the need to correct the measured

Table 2 Measured rates of deposition obtained for individual events using sedimentation traps and estimates of the average rate of deposition within the study reach during these events based on the reduction in sediment load between the upstream and downstream gauging stations

Event	Measured Sedimentation Rate (gm^{-2}) $\bar{x}$	s	n	Sediment loss Woodmill-Rewe (t)	Estimated average sedimentation rate for reach (gm^{-2})
14.1.84) 17.1.84)	51	32	9	244	49
24.1.84	8	2	4	36	7.2
27.1.84	102	26	9	536	107

conveyance losses for additional inputs from bank erosion and from minor tributaries and a considerably greater number of measurements are required to place statistical reliance on the absolute magnitude of the results obtained.

III SPATIAL VARIABILITY OF FLOOD PLAIN DEPOSITION

Calculations based on measured conveyance losses corrected for additional sediment inputs to the study reach provide an estimate of the average deposition rate within the flood plain of 500 gm^{-2} $year^{-1}$ and this is in reasonable agreement with the limited number of direct measurements of deposition undertaken using sedimentation traps. However, it is clear that marked spatial variation in rates of deposition, at both the macro and micro scales, must inevitably occur within the flood plain environment, in response to downstream changes in its character and to local variations in micro-topography and flow conditions. In view of the labor intensive nature of sedimentation trap measurements and the event-based nature of the data provided, an alternative approach, capable of providing a longer-term view of the spatial pattern of deposition was sought.

Studies undertaken by the authors indicate that measurements of the ^{137}Cs activity of flood plain soils possess considerable potential for investigating spatial patterns of deposition within the flood plain domain. Caesium-137 is present in the environment only as a product of the atmospheric testing of nuclear devices during the late 1950s and early 1960s and fallout of this environmental radioisotope was first detected in 1954. Rates of fallout reached a maximum in 1964 and declined rapidly after the nuclear test ban treaty (cf. Pennington et al., 1976). Existing evidence indicates that on reaching the soil surface as fallout, ^{137}Cs is rapidly and strongly sorbed within the upper soil horizons and that further downward translocation is limited (cf. Tamura, 1964). Subsequent movement of ^{137}Cs within the landscape is therefore associated with the erosion, transport and deposition of sediment particles (e.g. Campbell et al., 1982). Caesium-137 has a half-life of 30.1 years and approximately 60 percent of the total input of this radioisotope since fallout began in 1954 remains at undisturbed sites.

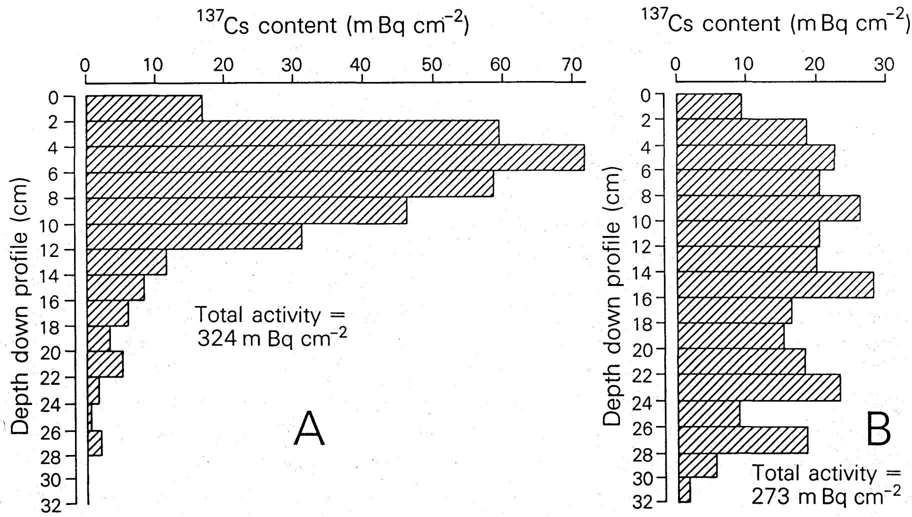

Figure 4.

Measurements of the distribution of ^{137}Cs within the soils and sediments of a flood plain system provide a means of documenting both the magnitude and the spatial pattern of deposition over the past 30 years. If the baseline input of ^{137}Cs from atmospheric fallout to the flood plain surface can be established, comparison of the ^{137}Cs content of the soil profile with this baseline affords a means of detecting areas of deposition. Enhanced levels of ^{137}Cs activity will be associated with deposition of suspended sediment eroded from elsewhere in the drianage basin. Reduced levels will similarly be associated with areas of scour, where sediment has been eroded from the flood plain surface. The methods employed for field sampling and laboratory analysis of ^{137}Cs activity used in this study are described elsewhere (Walling et al., 1986).

Measurements of the ^{137}Cs content of soils from several sites in the vicinity of the study reach which were characterized by hilltop locations, minimal slopes and permanent pasture undisturbed by cultivation or erosion provided an estimate of the baseline activity of 340 $mBqcm^{-2}$. In most cases, values of ^{137}Cs activity obtained for soil profiles from the flood plain exceeded this baseline level, providing evidence of sediment deposition.

Figure 4 provides typical examples of both the vertical distribution of ^{137}Cs and the total activity of soil profiles from a baseline input site (A) and the flood plain surface (B and C). In the case of the two flood plain sites, which are located on Fig. 5, the excess ^{137}Cs activity associated with deposition amounts to approximately 65 $mBqcm^{-2}$. It is not possible to obtain a direct measure of the depth, and therefore the rate, of deposition at these two sites from the ^{137}Cs data, but there are several possible approaches to obtaining estimates of these values. Firstly, comparison of the shapes of the three profiles, indicates that whereas the input site (A) exhibits a typical exponential decrease of ^{137}Cs activity with depth, the flood plain sites exhibit "stretching" of the upper portion of the profile and peak levels of ^{137}Cs occur lower in the profile. This is consistent with a situation of progressive surface accumulation and where maximum levels of ^{137}Cs fallout occurred about 20 years ago. Matching of the lower portions of the three profiles suggests that the upper parts of profiles B and C have been "stretched" by 4-6 cm

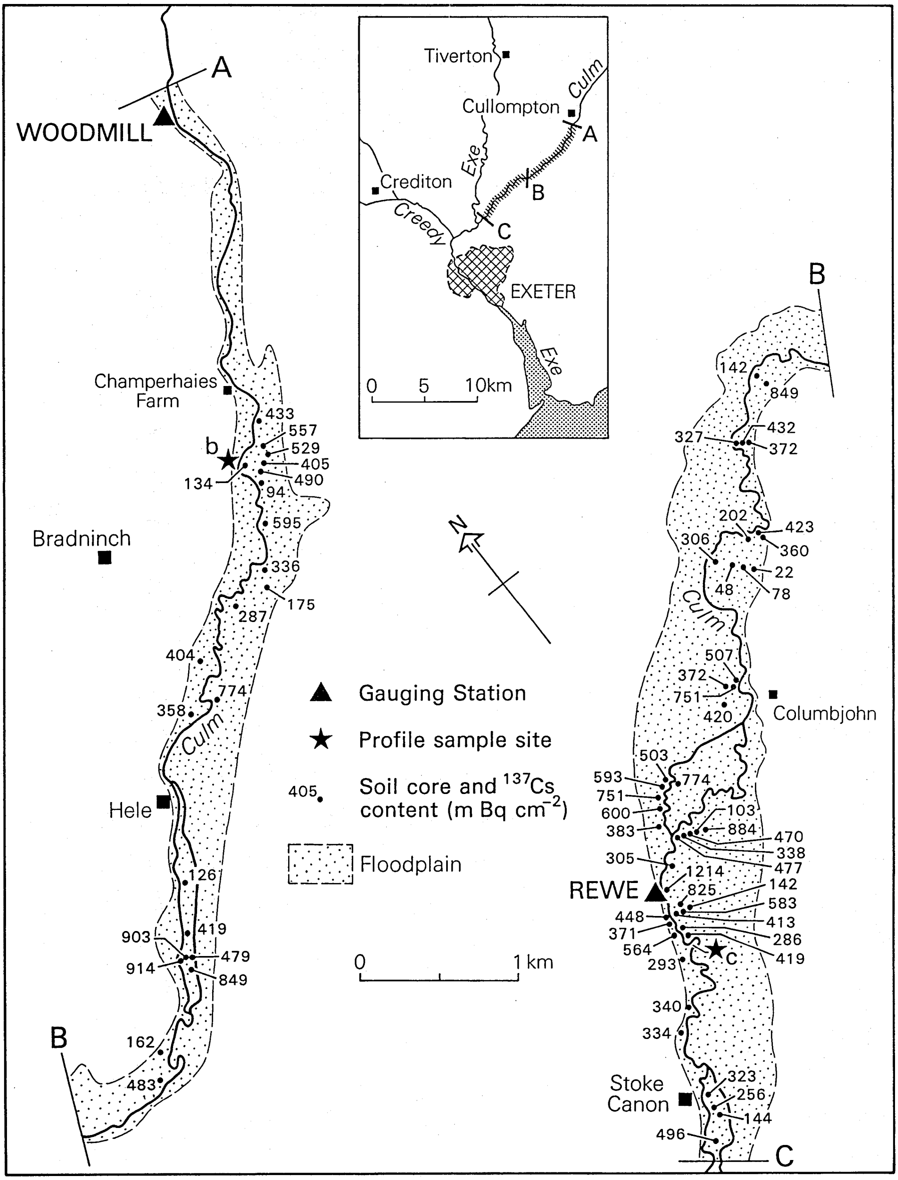

Figure 5.

and this may be ascribed to deposition of 4-6 cm of sediment during the past 30 years. This in turn provides an estimated sedimentation rate at these two sites of approximately 1.3-2.0 mm $year^{-1}$ or 1300-2000 gm^{-2} $year^{-1}$ based on a bulk density of 1.0 gcm^{-3} for the flood plain soil.

Alternatively, an estimate of the amount of deposition may be based on an assessment of the ^{137}Cs activity of deposited sediment and the amount of sediment required to account for the excess activity of 65 $mBqcm^{-2}$. The mean ^{137}Cs concentration in suspended sediment currently transported by the River Culm is approximately 20 $mBqg^{-1}$. No measurements of the variation of this concentration over the past 30 years are available, but if, following the arguments of Walling et al., 1986 relating to another local drainage basin, it is assumed that the ^{137}Cs content of suspended sediment is directly proportional to the ^{137}Cs activity of surface soils within the basin and therefore to the cumulative ^{137}Cs fallout adjusted for decay, then the average ^{137}Cs content of suspended sediment over that period adjusted for decay to the present can be estimated at approximately 15 $mBqg^{-1}$. Based on these assumptions, the ^{137}Cs excess of 65 $mBqcm^{-2}$ represents an annual rate of deposition of ca. 1400 gm^{-2} $year^{-1}$ or 1.4 mm $year^{-1}$. These values are in close agreement with those of 1300-2000 gm^{-2} $year^{-1}$ and 1.3-2.0 mm $year^{-1}$ obtained above. Both these estimates are consistent with the short-term estimate of current average rates of deposition throughout the entire flood plain of 500 gm^{-2} year obtained from the measurements of conveyance loss.

In order to obtain further information concerning the spatial variation of deposition within the flood plain, 67 whole-core samples 42 cm^2 surface area) of flood plain soil were collected from a variety of locations. The sites from which these cores were collected and the ^{137}Cs activity of each core are depicted on Fig. 5. More cores would clearly be required to permit a detailed analysis of the pattern of sedimentation throughout the study reach, but a number of observations can be advanced. Firstly, the range of values of ^{137}Cs activity associated with the individual cores points to considerable local variation in sedimentation rates. Twenty three sites exhibit a ^{137}Cs activity less than the baseline value of 340 $mBqcm^{-2}$ and these can be identified as locations experiencing scour or erosion. The remaining 44 sites possess ^{137}Cs activities spanning the range up to 1214 $mBqcm^{-2}$. This maximum value represents an excess ^{137}Cs activity of 874 $mBqcm^{-2}$, which, using the arguments developed previously, could represent a total sedimentation depth of approximately 58 cm or 19 mm $year^{-1}$ averaged over the past 30 years. Secondly, considering the overall reach, the evidence provided by the ^{137}Cs data suggests that deposition rates show some tendency to increase in a downstream direction. Such a trend could be accounted for in terms of the downstream increase in flood plain width and dcrease in gradient and therefore reduced flow velocities. Thirdly, at a more detailed scale, the considerable variability in ^{137}Cs activity amongst adjacent cores suggests that deposition rates are extremely variable, even within a small area. A more detailed sampling program is planned with a view to elucidating the precise relationship between deposition rates and the microtopography of the flood plain, and the variation of rates of deposition across the flood plain from the channel margin to the outer boundary. Further investigation of those zones evidencing ^{137}Cs depletion could also provide useful information on the distribution of surface scour within the flood plain system.

IV EVIDENCE FOR SELECTIVE DEPOSITION

The results from this study indicate an annual depositional loss of approximately 2500 t $year^{-1}$ within the study reach, with local rates of accretion possibly exceeding 19 mm $year^{-1}$. It is important to consider whether the material involved represents merely a simple proportion of the load entering the reach or whether selective deposition occurs. The latter situation could be of considerable significance where sediment-associated contaminants were associated with a particular fraction of the load. A preliminary investigation of this facet of the conveyance losses occurring within the study reach has involved a comparison of the particle size characteristics of suspended sediment transported through the upstream and downstream gauging stations.

Table 3 A comparison of the mean particle size characteristics of suspended sediment collected from the gauging stations at Woodmill and Rewe and an estimate of the associated conveyance losses

	Particle size fraction				
	< 2 µm	2-6 µm	6-20 µm	20-63 µm	> 63 µm
A) Particle size composition					
Woodmill (upstream)	68	15	9	4.5	3.5
Rewe (downstream)	80	12	5	1.5	1.5
B) Conveyance loss					
Magnitude (t)	10.4	6.4	5.4	3.4	2.4
Composition (%)	37	23	19	12	9

Bulk samples of suspended sediment have been collected at both sites over a range of flow conditions in order to characterize the particle size distribution. 100 l samples of river water were collected using a pump sampler and transported to the laboratory where a continuous flow centrifuge was used to recover the sediment. Particle size analysis was undertaken on the chemically dispersed mineral fraction of this sediment using a Sedigraph instrument. Results indicating the average particle size characteristics of sediment entering and leaving the study reach are presented in Table 3. These demonstrate that suspended sediment passing the downstream gauging station at Rewe is appreciably finer than that entering the study reach and that preferential deposition of the coarser particles must occur. However, if due account is taken of the 28 percent conveyance loss measured within this reach, these generalized data indicate that nearly 40 percent of the depositional loss is comprised of clay-sized (< 2 µm) material (Table 3). This situation may reflect the importance of aggregates in the natural transport process (cf. Walling & Kane, 1984) and that much of the clay is deposited in association with such aggregates.

Further work is required to relate the results obtained from a comparison of the particle-size characteristics of the upstream and downstream suspended sediment loads to measurements of the particle size characteristics of the flood plain deposits. Furthermore, it is clearly important to extend this area of investigation to embrace other aspects of the sediment load including its chemical and mineralogical characteristics.

CONCLUSIONS

The results of this preliminary investigation of conveyance losses within the lower reaches of the River Culm indicate that these are of considerable significance, amounting to approximately 2500 t $year^{-1}$ or 28 percent of the suspended sediment load entering the reach. As an average rate of deposition over the entire flood plain this loss is equivalent to 500 gm^{-2} $year^{-1}$ or 0.5 mm $year^{-1}$. This is consistent with the limited results obtained from a number of sedimentation traps deployed at one location on the flood plain and with the values obtained from a detailed analysis of the ^{137}Cs content of two flood plain soil profiles (1.3-2.0 mm year^{-1}). Measurements of the ^{137}Cs activity of flood plain soils offer considerable scope for investigating the spatial variation of rates of flood plain deposition over the past 30 years, and the initial results presented here provide evidence of a downstream increase in depths of deposition and of considerable local variability of sedimentation rates. The results of a comparison of the particle size characteristics of suspended sediment collected from the upstream and downstream gauging stations indicates that the conveyance losses are associated with preferential deposition of coarser size fractions, although appreciable quantities of clay (< 2 m) are also deposited. Further work is in progress to provide a more detailed analysis and understanding of the preliminary conclusions presented here.

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