Suspended sediment storage in river channels: a case study of the River Exe, Devon, UK

C.P. LAMBERT & D.E. WALLING
Department of Geography
University of Exeter
Exeter, Devon
EX4 4RJ, UK

ABSTRACT An investigation of the significance of channel storage processes in suspended sediment delivery has been undertaken in the River Exe, Devon, UK (drainage area 601 km^2). Storage has been examined indirectly by analyzing sediment yields for monitoring stations at several locations in the river basin and by employing a theoretical model to estimate the average travel distance of storm sediment. Channel storage has also been examined directly by undertaking empirical measurements of potential sediment release from the upper 10 cm of the river bed. Analysis of the physical and chemical properties of storm and river bed sediment has provided further information on delivery dynamics. The results of these investigations suggest that for the River Exe channel storage of suspended sediment is minimal and amounts to less than two percent of the annual sediment yield. Sediment delivery is continuous with no notable deposition and remobilization from the river bed. In this river the main channel acts primarily as an efficient conveyance system through which sediment is rapidly transported from the basin.

INTRODUCTION

The processes interposed between on-site erosion and sediment yield at a catchment outlet, which are subsumed in the concept of a sediment delivery ratio are poorly understood (Walling, 1983). Their elucidation represents an important contemporary research need in the field of erosion and sedimentation (cf. Wolman, 1977) and is essential if recent advances in modelling soil erosion are to be extended to permit prediction of downstream sediment loads. Furthermore, a knowledge of delivery processes is important for predicting sediment yield from a knowledge of local erosion rates, for evaluating the impact of particular land use scenarios on sediment yields, for investigating the movement of sediment-associated nutrients and contaminants through the fluvial system and, conversely, for using sediment load data to provide estimates of on-site rates of erosion or soil degradation.

Suspended sediment storage in river channels represents an important component of the sediment delivery sequence and there is a need for an improved understanding of its potential significance, as emphasized by Meade (1982) in his view that:

> "... any given sediment particle that has been entrained by a river is likely to spend very little time in actual transport and a great deal of time in storage. Perhaps models of sediment in river systems should place more emphasis on storage and less on the actual processes of transport."

The lack of empirical studies of channel storage can be partly explained by the practical problems faced by field investigations, but work undertaken to date has served to highlight the potential importance of such storage. For example, Madej (1985) has demonstrated the significant contribution of active sediment storage within the channel of the Redwood Creek, California, to the overall sediment budget; Meade et al. (1985) have emphasized the importance of suspended sediment storage and remobilization in the channel of the lower Amazon in regulating sediment transport by this river, while Goswami (1982) has provided evidence for the vast amounts of sediment stored within the channel of the Brahmaputra River in Assam, India. In other areas, however, field reconnaissance frequently provides little evidence of channel storage and there is a need for studies in a wider variety of fluvial environments.

In this context, a study of suspended sediment storage within the river channels of the Exe basin, Devon, UK, was commenced by the authors in 1982 and some preliminary results are presented in this paper. In view of the practical difficulties associated with field investigations of this facet of sediment delivery, several approaches have been adopted. These include analysis of sediment yield data for several locations within the river network, use of a theoretical model to estimate average travel distances of storm sediment, measurements of potential sediment release from the upper 10 cm of the river bed, and an examination of temporal variations in storm sediment properties at the basin outlet.

THE STUDY BASIN

The basin of the Middle and Upper Exe, within which the study has been undertaken, covers an area of 601 km^2 and embraces a diversity of rock types ranging from the resistant grits and slates of the Devonian through the shales and sandstones of the Carboniferous to the sandstones and breccias of the Permian (Fig. 1b). This geological diversity is paralleled by marked contrasts in relief (Fig. 1a) which are in turn reflected by hydrometeorological conditions. Annual precipitation and runoff vary from over 1800 mm and 1500 mm respectively in the northern upland area of Exmoor to less than 850 mm and 400 mm and the basin outlet (Figs. 1c & 1d).

The major river channels in the study area are predominantly of the gravel-bed type, but bed rock frequently outcrops in the floors of the channels upstream of the measuring site at Stoodleigh. There is little field evidence for substantial storage of fine material within the channel, although the surface of the gravel floor frequently exhibits a thin covering of clay- and silt-sized particles and appreciable quantities of fine material are contained within the gravel matrix. Long-term observations indicate that the channels are essentially stable and that scour and fill are of limited importance. In most locations a well developed flood plain borders the channel, but this is commonly at a considerable height above the present channel (2-4 m). Flood plain inundation occurs infrequently and is both restricted and localized in extent.

MEASUREMENT TECHNIQUES

Suspended sediment concentration has been continually monitored at six flow gauging sites in the study area using optical turbidity meters. This equipment has been shown to provide a reliable and effective means of measuring suspended sediment transport in the Exe basin (cf. Walling,

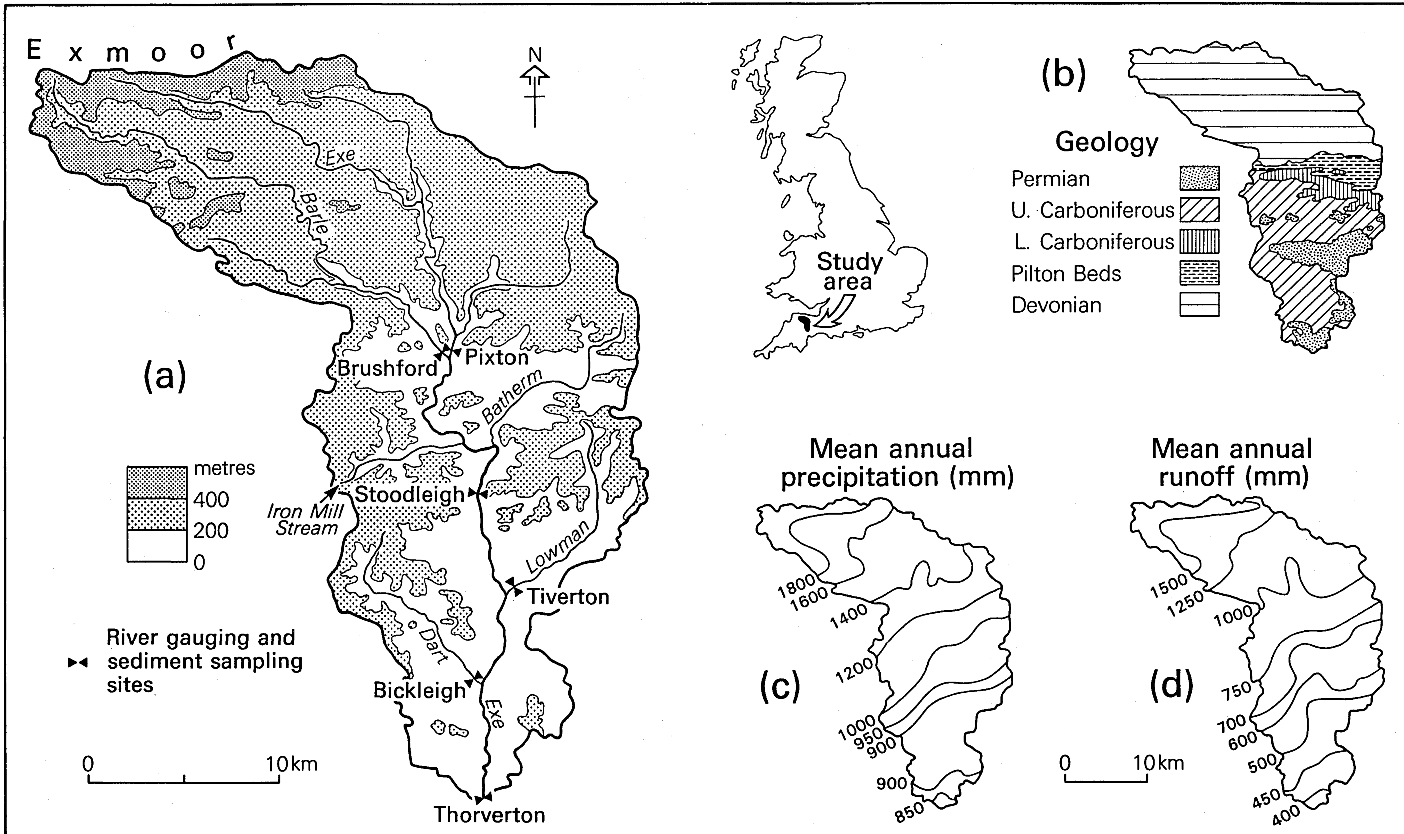

Exmoor
N
(a)
Exe
Barle
Brushford
Pixton
Batherm
metres
400
200
0
Iron Mill Stream
Stoodleigh
Lowman
Tiverton
Dart
Bickleigh
Exe
Thorverton
River gauging and sediment sampling sites
0
10km
Study area
(b)
Geology
Permian
U. Carboniferous
L. Carboniferous
Pilton Beds
Devonian
Mean annual precipitation (mm)
1800
1600
1400
1200
1000
950
900
900
850
(c)
Mean annual runoff (mm)
1500
1250
1000
750
700
600
500
450
400
(d)
0
10km

Figure 1

1978). The associated network of measuring points (Fig. 1a) affords a coverage of the major tributaries and permits the timing and load associated with the sediment pulse for an individual flood event to be monitored as it is routed downstream. Bulk samples of suspended sediment have also been collected at all six measuring stations over a wide range of flow conditions. The procedure employed involved use of a pump sampler to collect large (> 100 l) samples of river water which were returned to the laboratory where the suspended sediment was recovered by continuous flow centrifugation. The sediment was then freeze-dried prior to laboratory analysis. The centrifuge equipment provided highly efficient recovery of sediment < 0.45 μm (cf. Ongley et al., 1981) and the bulk samples typically provided between 30-100 g of sediment, depending on ambient suspended sediment concentrations. Large samples were required to permit analysis of a wide range of sediment properties.

In order to provide a direct estimate of sediment storage in the river channels, a technique which would allow an assessment of the amount of fine sediment contained on and within a specified area of the river bed was required. Extrapolation of these results could thus provide estimates of total sediment storage or potential sediment supply at the time of measurement. The procedure developed provided an estimate of the storage associated with both the bed surface and the upper 10 cm of the bed material matrix. In the latter case this storage could only be mobilized during periods of significant bed load transport. The equipment consisted of a one m high cylinder with a diameter of 0.48 m constructed from 20 gauge galvanized steel. The cylinder permitted a known area of the river bed (0.18 m^2) to be sampled when it was placed on the bed. The volume of water it enclosed was determined by obtaining a mean depth and surficial and interstitial sediment was then mobilized by manually disturbing the water and river bed surface within the cylinder. Three 500 ml samples were taken to provide an estimate of the mean sediment concentration within the cylinder after disturbance and an estimate of the total amount of sediment released from storage was obtained as the product of the sediment concentration and the water volume enclosed. A particular advantage of the technique was that the amount of sediment mobilized could be determined for differing degrees of turbulence and the following sequence was employed at each sampling site: water agitation, water and bed surface agitation, and water and subsurface bed material agitation. Following the final stage of agitation, several large polythene cans (22 l) were filled with water from within the cylinder to provide sufficient sediment for laboratory analysis of a selection of its properties. The sediment in the cans was recovered by sedimentation and centrifugation and was freeze-dried prior to analysis.

Two investigations of channel storage were undertaken in order to reduce problems of temporal representativeness. The first was conducted in November 1983 prior to the winter high flow period and the second was carried out in May 1984 at the start of the summer low flow. In view of the labor-intensive nature of these measurements, only a limited number of sites were studied and the 10 sites investigated were selected as providing a representative sample of the varying character and composition of the river bed within the study basin. At least three measurements of sediment release were taken at each site in order to account for variations in storage across the channel.

Laboratory analysis of sediment samples involved standard procedures which included determination of N and C by pyrolysis/thermal conductivity using a Carlo Erba analyzer, total-P by chemical

Table 1 Comparison of the suspended sediment yields at Thorverton with the input from upstream

Date of storm	Recorded load at Thorverton (t)	Recorded load from upstream (t)	Absolute loss or gain of suspended sediment (t)	Percentage loss or gain of suspended sediment
15.10.83	801.8	655.1	+ 146.7	+ 22
27.11.83	1664.6	849.9	+ 814.7	+ 96
9.12.83	707.1	387.2	+ 319.9	+ 83
15.12.83	1145.3	570.0	+ 575.3	+100
20.12.83	5808.6	3233.7	+2574.9	+ 80
3. 1.84	1734.1	1084.3	+ 649.8	+ 60
13. 1.84) 16. 1.84)	6388.4	3049.3	+3339.1	+110
24. 1.84	774.6	453.8	+ 320.8	+ 71
27. 1.84	5756.0	2431.1	+3324.9	+137
7. 2.84	2624.6	1176.9	+1447.7	+123
Total for 11 events	27 405.1	13 891.3	+13 513.8	+ 97

fractionation/UV spectroscopy, heavy metals by acid digestion and atomic absorption spectroscopy and particle size characteristics using a sedigraph apparatus.

RESULTS

Analysis of sediment load data

The availability of sediment load data for a number of measuring stations within the study basin provides one means of investigating the significance of channel storage of suspended sediment in the middle reaches of the River Exe. Suspended sediment loads for individual flood events measured at the study basin outlet (Thorverton) can be compared with the equivalent loads recorded at the upstream and tributary gauging stations (Stoodleigh, Bickleigh and Tiverton, Fig. 1a) to determine whether substantial sediment deposition has occurred during channel conveyance. A load at Thorverton that is less than the combined sediment input to the middle reaches of the River Exe measured at the three upstream sites would indicate that there has been substantial deposition. An increased yield at Thorverton would point to minimal deposition and the importance of additional sediment inputs from minor tributaries and bank erosion, although it would not preclude the existence of a quasi steady state situation in which sediment is deposited on the receding limb of a storm hydrograph and remobilized during the subsequent event.

Table 1 provides a comparison of the suspended sediment loads recorded at Thorverton for individual storm runoff events with the total load recorded at the upstream measuring stations. The loss or gain of suspended sediment during channel conveyance has been calculated and results evidence a downstream increase in sediment yield for all events. This increase varied from +22 percent to as much as +137 percent. It is important to recognize that the loads recorded at the four sites may involve measurement errors and that the lack of evidence of deposition could result from such errors. However, it is suggested that the measurements and procedures employed to calculate the suspended sediment loads possess an accuracy of ±10 percent. If the worst case situation involving overestimation of the load at Thorverton by 10 percent and underestimation of the upstream loads by a similar amount is assumed, an overall downstream increase in yield is still clearly apparent since only two storms would evidence a downstream decrease in sediment load and the losses involved are very small.

Although the results of this analysis are clearly limited in their degree of resolution, they suggest that no substantial deposition occurs within the middle reaches of the Exe basin and that the main channel provides an efficient conveyance route along which the sediment is rapidly transported.

Theoretical analysis of storm sediment travel distance

From their work on the Sandusky River in Ohio, USA, Verhoff & Melfi (1978) have suggested that suspended sediment is moved through the river channel system in a discontinuous manner. Each storm event entrains sediment from the river bed, banks and flood plain, transports it some distance downstream and redeposits it within the river channel. This sequence continues until the sediment finally reaches the receiving water body. In a later paper Verhoff et al. (1979) propose a model which can be used to calculate the average travel distance of a sediment pulse and this has been applied by other workers to investigate the dynamics of storm sediment transport (e.g. Chapman et al., 1982). Notwithstanding its limitations, the model can be applied to data from the River Exe to suggest whether discontinuous transport and therefore channel storage is likely to occur. If the model indicates travel distances for individual sediment pulses which exceed the mainstream length of the river system, then this may provide further evidence for a lack of substantial sediment storage and remobilization within the channel.

The model is based upon the difference between flood wave celerity and the velocity of water flow and assumes that the flood wave moves as a kinematic wave. A total of 20 runoff events were selected from the flow and sediment load records for the River Barle at Brushford and the River Exe at Pixton, Stoodleigh and Thorverton (Fig. 1a), and were used in subsequent analysis. These events embrace a considerable variation in magnitude, duration and season, but all evidence high discharges since this is a basic requirement of the model. The average travel distances of the suspended sediment pulses associated with the storm runoff events obtained from the model are listed in Table 2.

Before any attempt is made to interpret the results in Table 2, it must be recognized that the model proposed by Verhoff et al. (1979) is only valid in situations where the character and dimensions of the channel do not change significantly over long distances. This assumption is met reasonably well by the main channel of the River Exe, but the channel has a finite length to the point where it discharges into the estuary and travel distances in excess of this length have no real significance. The main channel distance between the measuring sites at Brushford and Pixton and the River Exe estuary is approximately 55 km, whilst the distances between the gauging stations at Stoodleigh and Thorverton and the estuary are approximately 40 km and 20 km respectively. Table 2 indicates that the average travel distances of storm sediment transported from the nothern headwaters estimated using the model commonly exceed the distance to the estuary. Only the storm

Table 2 Approximate travel distance of storm sediment passing the measuring stations in the Middle and Upper Exe basin, calculated according to the method suggested by Verhoff, et al. (1979)

Date of storm	Average travel distance (km) River Exe at Thorverton	River Exe at Stoodleigh	River Exe at Brushford	River Exe at Pixton
8.11.82	117.0	100.5	63.8	101.4
12.11.82	104.1	120.5	113.2	84.5
21.11.82	77.1	72.7	60.6	47.5
10.12.82	99.5	125.8	120.3	103.6
19.12.82	200.6	321.6	324.3	230.3
4. 1.83	383.9	592.9	692.3	419.3
31. 1.83	156.1	167.2	267.8	184.7
1. 5.83	103.7	116.5	30.8	90.6
16. 5.83	93.2	115.0	70.7	85.3
15.10.83	53.5	101.7	81.1	116.8
27.11.83	147.1	238.5	81.0	114.3
9.12.83	88.5	124.1	80.0	No storm
15.12.83	58.4	57.5	No storm	No storm
20.12.83	343.5	342.1	184.7	431.2
3. 1.84	106.8	134.4	78.5	107.0
13. 1.84	240.1	) 424.7	249.2	) 416.5
16. 1.84	233.3	)	147.8	)
24. 1.84	188.2	186.4	119.3	) 421.3
27. 1.84	240.4	294.6	50.0	)
7. 2.84	412.6	477.7	220.7	356.3

events of 1 May 1983 and 27 January 1984 at Brushford, and 21 November 1982 at Pixton provide average travel distances of less than 55 km.

The travel distances of storm sediment estimated using the model developed by Verhoff et al. (1979) suggest that little deposition and remobilization occurs within the main channel and that storage is unimportant. Instead, the model points to a situation of continuous sediment conveyance, with sediment being flushed through the river channel system during a single storm event. Table 2 indicates that the estimates of average travel distance of suspended sediment associated with some minor storm runoff events were insufficient to reach the estuary, but these events are of minimal importance to the overall sediment load transported through the system. These findings are consistent with those obtained from the analysis of sediment load data reported previously, but both approaches must be seen as providing only indirect evidence of the lack of importance of channel storage. Evidence of a more direct and empirical nature is provided by two further approaches for investigating the problem.

Field measurements of river channel storage

Table 3 summarizes the results of the direct measurements of channel storage or potential sediment release obtained using the sampling cylinder and various degrees of water and bed disturbance. The measurements undertaken in November 1983 and May 1984 have been averaged. The total sediment storage within the reach of the River Exe between Pixton and Thorverton associated with the different depths of

Table 3 Summary of results for the amount of sediment released from the bed of the River Exe during surface disturbance

	Degree of river bed disturbance		
	Water agitation	Water and bed surface agitation	Water and subsurface bed material agitation
Mean amount of sediment released from the river bed (g m^{-2})	166.0	238.5	401.7
Number of observations (n)	64	65	65
Standard deviation ($\hat{\sigma}$)	126.9	162.9	258.6
Coefficient of variation (%)	76.4	68.3	64.3
Standard error ($\hat{\sigma}_{\bar{x}}$)	15.9	20.2	32.1
Estimates of sediment storage in the bed of the River Exe*	135.8	195.2	328.7

*Assuming a river bed area of 818360 m^2

disturbance has been calculated as the product of the total area of river bed comprising the reach and the estimates of mean sediment release. The coefficients of variation of the individual measurements of sediment release for the three degrees of disturbance range between 64 percent and 76 percent and this degree of variability reflects firstly, variation between the individual measuring sites along the reach, secondly, at-a-site variation in response to differences in flow characteristics and bed material composition and, finally, the variability in the measurement technique itself which is unlikely to have a high degree of precision. The standard error statistic for the mean values of sediment release provide an index of the likely reliability of the storage estimates and Table 4 lists the estimates of total channel storage with a 95 percent confidence limit.

Table 4 Potential contribution of bed sediment to the annual storm sediment yield of the River Exe

Degree of surface disturbance	Mean storage estimates (t)	Storage estimates with a confidence limit of two standard errors (t)	Percentage of annual sediment load†
Water agitation	135.8	104.0–167.6	0.46–0.74
Water and bed surface agitation	195.2	154.8–235.6	0.68–1.04
Water and sub-surface and bed material agitation	328.7	264.4–392.9	1.17–1.73

† The storm sediment load for the River Exe during the period January 1983–December 1983 was 22 664 tonnes.

The storage estimates obtained using the bed disturbance method may not provide an accurate assessment of the amount of sediment that could potentially be mobilized at times of storm runoff. Problems posed by the spatial and temporal representativeness of the results have already been outlined and a further uncertainty surrounds the ability of the river to mobilize the "available" sediment. Furthermore, it may be capable of scouring or disturbing its bed to greater depths than the 10 cm employed in the measurement procedure. However, existing evidence from scour chains located on gravel bars in the channel of the River Exe indicates that bed material movement is very limited. The values of channel storage listed in Table 4 are therefore thought to provide a meaningful assessment of the total storage of fine sediment within the channel, although the extent to which this could be mobilized during a single event remains uncertain.

Table 4 indicates that the total amount of sediment stored in the bed of the River Exe is small in comparison to that transported at times of storm runoff. The maximum storage estimate is 393 tonnes and this represents less than two percent of the annual storm sediment load transported out of the middle reaches of the River Exe. This in turn demonstrates that the river bed is not an important sediment source or sink and that it plays only a very minor role in the overall sediment budget of the basin.

Analysis of temporal variation of suspended sediment properties at the basin outlet

Further empirical investigations of the role of channel storage in sediment delivery from the Exe basin were undertaken by examining the physical and chemical properties of suspended sediment transported out of the basin. Several workers have used sediment properties to "fingerprint" source areas within a basin (e.g. Oldfield et al., 1979; Ongley et al., 1981; Walling & Kane, 1984) and there is potential to expand this approach to elucidate delivery processes. If suspended sediment originating from different sub-basins can be distinguished on the basis of its physical and chemical properties, an investigation of the behavior of these properties at the basin outlet could shed light on the nature of channel conveyance processes. More particularly, if storm sediment is conveyed through the channel system without significant remobilization of sediment from channel storage, then the proportion of sediment collected at the basin outlet should vary from storm to storm and reflect the origin of the flood water. In the case of the River Exe, for example, the properties of storm sediment associated with a storm event confined to the southern part of the basin should be characterized by sediment diagnostic of the southern tributaries. Conversely a storm event dominated by flood waters originating in the northern headwaters on Exmoor should convey sediment diagnostic of the northern sub-basins. Alternatively, if deposition and remobilization are important, there will be no clear relationship between flood water origin and sediment properties for individual events. Sediment transported during a specific event may reflect the properties of material deposited during previous events.

Spatial and temporal variations of storm sediment properties have been examined within the study basin in order to determine which of the two situations outlined above most closely represents the behavior of the River Exe. In excess of 170 bulk suspended sediment samples were collected at the measuring sites within the basin in order to provide information on the properties of storm sediment. Sediment properties capable of distinguishing individual sub-basins were selected as natural

Table 5 Comparison between suspended sediment transported from sub-basins in the study area for C/N and silt/clay ratios

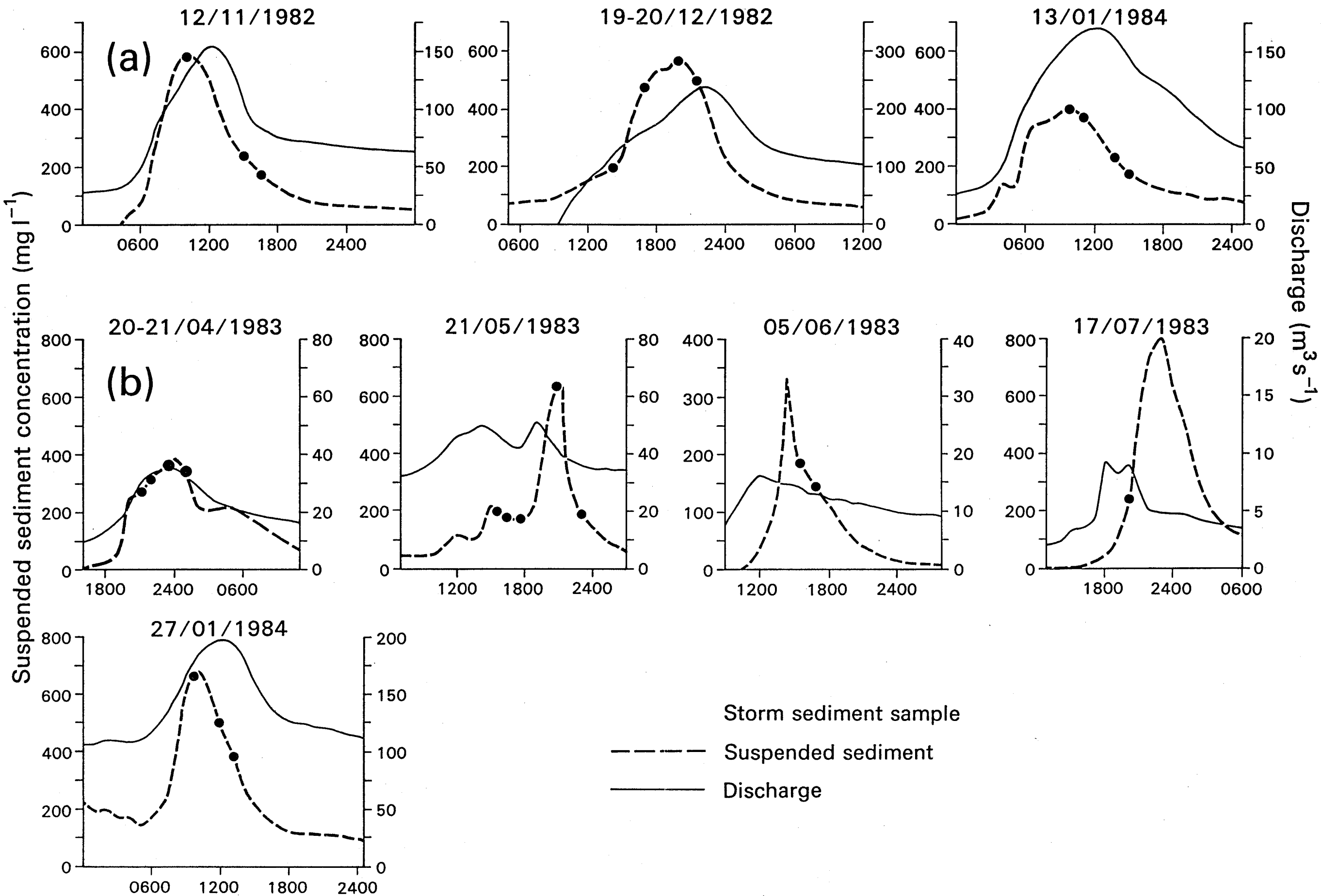
River measuring station		C/N ratio	Silt/clay ratio
Thorverton, River Exe	mean	9.958	0.82
	cv (%)	8	34
Bickleigh, River Dart	mean	9.898	0.56
	cv (%)	9	33
Tiverton, River Lowman	mean	9.050	0.49
	cv (%)	7	23
Stoodleigh, River Exe	mean	10.835	0.91
	cv (%)	5	35
Brushford, River Barle	mean	11.655	1.59
	cv (%)	8	13
Pixton, River Exe	mean	11.227	1.42
	cv (%)	6	20

tracers and these included the nature of the organic fraction as characterized by the C/N ratio, and particle size composition (Table 5). The C/N ratio was examined because Walling & Kane (1984) have suggested that elemental ratios are largely insensitive to enrichment effects and therefore provide good tracers. The C/N ratio clearly distinguishes suspended sediment originating from the northern headwaters by the higher values for this ratio which in turn reflect the widespread occurrence of organic soils on the moorland areas of Exmoor. Particle size composition also distinguished sediment originating from the northern and southern portions of the basin since the former is coarser and exhibits a higher silt/clay ratio (Table 5).

Several storm events for which an adequate number of bulk suspended sediment samples were collected have been selected and classified according to whether the storm runoff originated primarily in the north or the south of the basin. The floods of 12 November 1982, 19 December 1982 and 13 January 1984 (Fig. 2a) were classified as originating primarily from the northern headwaters draining Exmoor. In a situation of continuous conveyance without remobilization of channel storage the C/N ratio and silt/clay ratio of storm sediment collected at the basin outlet during these events should be higher than the mean levels for the site and closely similar to those characterizing sediment from the northern tributaries. Table 6 demonstrates that this is effectively the case, although a few anomalous values are apparent.

The floods of 20/21 April 1983, 21 May 1983, 5 June 1983, 17 July 1983 and 27 January 1984 (Fig. 2b) were classified as originating from the south of the study basin. Table 7 indicates that the C/N ratio values are almost all lower than the site mean for Thorverton and closely analagous to those of the Rivers Dart and Lowman. Similarly, the silt/clay ratio values are mostly lower than the mean and more in line with those of the southern tributaries.

The values of C/N ratio and silt/clay ratio associated with suspended sediment collected at Thorverton during these two sets of storm events clearly reflect the major source of flood water and therefore point to a situation where sediment is conveyed rapidly from the basin with only minimal deposition and remobilization. It must be accepted that some of the C/N and silt/clay ratios listed in Tables 6 and 7 do not conform to this general pattern and may reflect the influence of such factors as the additional inputs of sediment associated with bank erosion along the



12/11/1982
19-20/12/1982
13/01/1984
(a)
20-21/04/1983
21/05/1983
05/06/1983
17/07/1983
(b)
27/01/1984
Suspended sediment concentration (mg l^{-1})
Discharge (m^{3}s^{-1})
Storm sediment sample
Suspended sediment
Discharge

Figure 2

Table 6 Selected suspended sediment properties for storm samples collected at Thorverton; floods originating on Exmoor

Date of storm	Time of collection	C/N ratio	Silt/clay ratio
12.11.82	1003	9.75	1.00
	1505	10.08	1.00
	1630	10.89	0.85
19.12.82	1422	11.42	1.04
	1702	12.27	1.17
	1946	10.07	1.17
	2120	10.12	1.08
13. 1.84	0946	11.65	0.72
	1100	10.71	0.85
	1350	10.95	1.00
	1500	11.01	1.13

main channel. In combination, however, the results obtained from the two properties suggest that remobilization is of limited importance.

The conclusions drawn from this examination of the properties of suspended sediment transported from the basin can be further verified by comparing these propeties with those of the material collected from the river bed in the bed disturbance measurements. If large amounts of suspended sediment are stored in the river channel, the properties of the two sediment types should be very similar. A significant difference between the two would, however, suggest that sediment remobilized from

Table 7 Selected suspended sediment properties for storm samples collected at Thorverton; floods originating from the southern tributaries

Date of storm	Time of collection	C/N ratio	Silt/clay ratio
20/21.4.83	2100	9.77	0.72
	2153	9.65	0.72
	2337	9.47	0.82
	0051	9.06	0.82
21.5.83	1528	9.37	0.49
	1615	9.11	0.54
	1730	9.40	0.59
	2053	10.40	0.61
	2203	9.68	0.64
5.6.83	1532	8.35	0.37
	1651	8.34	0.33
17.7.83	2012	7.95	0.37
27.1.84	0937	9.79	0.69
	1150	9.25	0.54
	1300	9.45	0.72

Table 8 Comparison of selected properties of storm and bed sediment from the River Exe

Sediment properties	Storm sediment: Number of observations	Storm sediment: Mean	River bed sediment: Number of observations	River bed sediment: Mean	Sediment types exhibit a significant difference*
N (%)	62	0.954	20	0.442	Yes
C (%)	62	5.888	20	4.022	Yes
C/N ratio	62	9.958	20	9.150	Yes
Total-P (%)	62	0.153	20	0.143	No
Zn (mg kg^{-1})	58	162.430	20	257.140	Yes
Pb (mg kg^{-1})	56	47.589	20	48.719	No
Cu (mg kg^{-1})	60	38.900	20	48.939	Yes
Cr (mg kg^{-1})	62	25.706	20	20.564	Yes
Silt/clay ratio	61	0.816	20	2.020	Yes

*Calculated t value critical t value at the 0.05 level (two tail test)

the bed represents only a small proportion of the overall load. Measurements of the N, C. total-P, Zn, Pb, Cu and Cr content and of the particle size distribution were undertaken on both suspended sediment collected from the basin outlet at Thorverton and material resuspended from the river bed. The mean values for each material are compared in Table 8 using the difference of means test. The results indicate that the mean values for seven properties are significantly different at the 0.05 level. Suspended sediment has a higher content of organic constituents (N and C), Cr and clay and a lower content of Zn and Cu. Only Pb and total-P demonstrate similar concentrations in both sediment types. Again it can be suggested that channel storage and remobilization is of limited importance to the sediment budget of the River Exe.

CONCLUSION

Four approaches have been employed to determine the importance of suspended sediment storage within the main channel of the River Exe and the results presented indicate that such storage is of minimal importance to the sediment budget of this river. A comparison of upstream and downstream sediment loads for individual events shows no evidence of significant depositional losses but does not preclude the existence of a steady state situation where substantial quantities of sediment are deposited during the recession limb of one flood event and remobilized during the rising stages of the subsequent event. However, a theoretical analysis of average travel distances for storm sediment and an investigation of the properties of suspended sediment transported past the downstream gauging station at Thorverton both point to the absence of any significant deposition or remobilization during individual events. Furthermore, empirical estimates for the total amount of fine sediment currently stored within the main channel of the River Exe indicate that this is small in comparison with the annual storm sediment load output from the basin and is therefore unlikely to represent a significant component of the sediment budget.

The results from the Exe basin demonstrate that the main channel acts as an efficient conveyance route for suspended sediment discharged by the upstream tributaries and that channel storage is not an important component of sediment delivery. This is in contrast to results from other studies cited in the introduction and further evidence from a wider variety of fluvial environments is required in order to provide a clearer assessment of the potential importance of channel storage to sediment delivery.

ACKNOWLEDGEMENTS

The authors gratefully acknowledge the financial support of the Natural Environment Research Council in providing a research grant (DEW) and a postgraduate studentship (CPL) for work on the sediment dynamics of local rivers, the assistance of Mr. A. Ames in phosphorus fractionation and heavy metal analysis, and South West Water for permitting access to gauging installations and supplying river flow data.

REFERENCES

Chapman, T.G., Bliss, P.J. & Smalls, I.C. (1982) Water quality considerations in the hydrological cycle. In: Prediction in Water Quality (ed. by E.M. O'Loughlin & P. Cullen). Australian Academy of Science, Canberra, 27-68.

Goswami, D.C. (1982) Brahamaputra River, Assam (India): Suspended sediment transport, valley aggradation and basin denudation. Ph.D. Thesis, John Hopkins Univ., Baltimore, Maryland.

Madej, M. (1985) The quantity and rate of movement of sediment storage in Redwood Creek, north coastal California. In: Abstracts of Papers for the First International Conference on Geomorphology (ed. by T. Spencer), Manchester, Univ., UK>

Meade, R.H. (1982) Sources, sinks and storage of river sediment in the Atlantic drainage of the United States. J. Geol. 90(3), 235-252.

Meade, R.H., Dunne, T., Richey, J.E., Santos, U. de M. & Salati, E. (1985) Storage and remobilization of suspended sediment in the Lower Amazon River of Brazil. Science 228, 488-490.

Oldfield, F., Rummery, T.A., Thompson, R. & Walling, D.E. (1979) Identification of suspended sediment sources by means of magnetic measurements: some preliminary results. Wat. Resour. Res. 15, 211-218.

Ongley, E.D., Bynoe, M.C. & Percival, J.B. (1981) Physical and geochemical characteristics of suspended solids, Wilton Creek, Ontario. Can. J. Earth Sci. 18, 1365-1379.

Verhoff, F.H. & Melfi, D.A. (1978) Total phosphorus transport during storm events. J. Environ. Engng. Div. ASCE 104, 1021-1026.

Verhoff, F.H., Melfi, D.A. & Yaksich, S.M. (1979) Storm travel distance calculations for total phosphorus and suspended materials in rivers. Wat. Resour. Res. 15, 1354-1360.

Walling, D.E. (1978) Suspended sediment and solute response characteristics of the River Exe, Devon, England. In: Research in Fluvial Systems (ed. by R. Davidson-Arnott & W. Nickling). Geobooks, Norwich, UK, 169-197.

Walling, D.E. (1983) The sediment delivery problem. J. Hydrol. 65, 209-237.

Walling, D.E. & Kane, P. (1984) Suspended sediment properties and their geomorphological significance. In: Catchment Experiments in Fluvial Geomorphology (ed. by T.P. Burt & D.E. Walling). GeoBooks, Norwich, UK, 311-334.

Wolman, M.G. (1977) Changing needs and opportunities in the sediment field, Wat. Resour. Res. 13(1), 50-54.