In-channel storage of fine sediment in rivers of southwest England

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Abstract The in-channel storage of fine sediment is an important, yet relatively poorly understood, component of sediment transfer through river systems. Previous research has shown it to be a significant factor in controlling the suspended sediment flux through aquatic systems. Additionally, it may also be of significance in the degradation of aquatic ecosystems. This paper presents the results of a comparative investigation of in-channel fine sediment storage and deposition rates for four contrasting rivers in southwest England over a period of 27 months. The results obtained demonstrate significant spatial and temporal variations in the amounts of fine sediment deposited and remobilized from the beds of the study rivers and indicate that the potential role of in-channel fine sediment storage in regulating the suspended sediment flux varies significantly between the study rivers.

Keywords fine sediment; in-channel sediment storage; sediment deposition; suspended sediment loads

INTRODUCTION

The transport of fine sediment in suspension through river systems is commonly an intermittent process, with sediment transfer occurring primarily during flood events and with sediment often being stored on the channel bed between transport episodes. The in-channel storage of fine sediment is thus potentially a significant component of the drainage basin sediment budget, due to its capacity to regulate the transmission of material to the basin outlet. In addition, such storage may also be of ecological significance in the degradation of aquatic ecosystems through the siltation of salmonid spawning gravels (Walling *et al.*, 2003a), clogging of aquatic vegetation and accumulation and release of sediment bound pollutants, such as phosphorus and heavy metals (Walling *et al.*, 2003b) The in-channel storage of fine (<0.063 mm) sediment within UK river systems has been examined by several studies. However, these studies have involved either medium-term investigations of a single drainage basin (e.g. Lambert & Walling, 1988; Walling *et al.*, 1998; Walling & Amos, 1999) or river reach (e.g. Smith *et al.*, 2003), or short-term "snapshot" investigations comparing a number of drainage basins (e.g. Heywood, 2002). There remains a need to undertake medium-term investigations of several drainage basins, in order to assess inter-river variability in the dynamics of in-channel storage of fine sediment. Furthermore, previous investigations have focused primarily on either the role of fine sediment in environmental degradation or the flux of contaminants through river systems. Less attention has been given to the role of in-channel fine sediment storage within the overall drainage basin sediment budget. The study reported here focused on this latter consideration, providing a medium-term study of several catchments with contrasting characteristics and comparing their response.

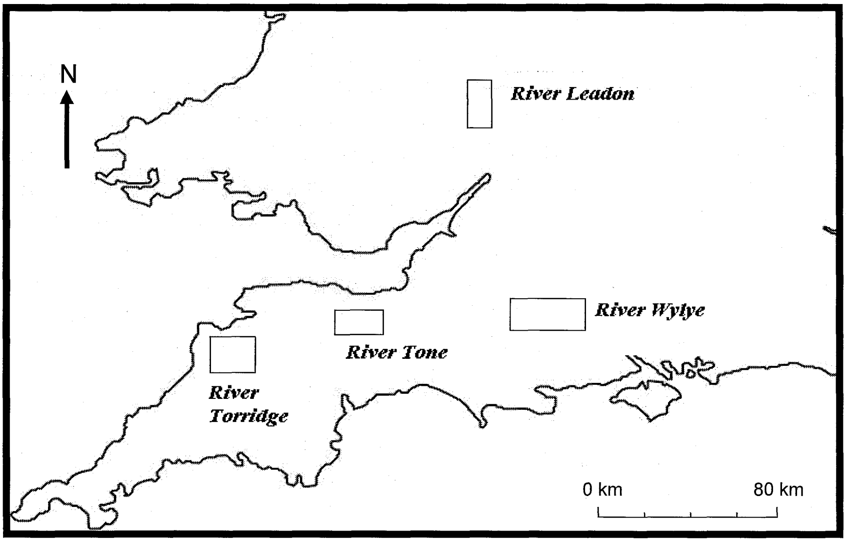

Fig. 1 Location of the study rivers in southwest England.

Table 1 The main characteristics of the study basins.

Drainage basin	Basin size (km^2)	Max. altitude (m AOD)	Basin geology	Basin land use	Mean annual rainfall (mm)	Mean daily flow (m^3 s^{-1})	Max. storm flow (m^3 s^{-1})
Leadon	293	180	Devonian sandstones, Triassic mudstones	Rural, mixed agriculture	685	4.14	63.21
Tone	84	390	Devonian shales and slates, Triassic sandstones	Rural, mixed agriculture	851	1.14	49.84
Torridge	258	220	Carboniferous shales and sandstones	Rural, 80 % pasture	1186	7.54	109.06
Wylye	443	270	Cretaceous Chalk 90%, Cretaceous Upper Greensand 10%	Rural, mixed agriculture, military firing range	830	2.02	24.71

THE STUDY BASINS

The study reported examined the in-channel storage of fine sediment in four representative, but contrasting, drainage basins; their locations are shown in Fig. 1. The selection of the Rivers Leadon, Tone, Torridge and Wylye was primarily based on their contrasting drainage basin characteristics, although logistical considerations were also important. Further details regarding the characteristics of the individual basins are presented in Table 1.

METHODS

Suspended sediment concentrations were continuously monitored in each river between spring 2001 and May 2003, using Hydrosphere$^{\text{TM}}$ self-cleaning optical-backscatter turbidity probes coupled to data loggers. Continuous records of suspended sediment concentration were obtained from the turbidity records via calibration relationships developed using manually collected suspended sediment samples. Suspended sediment loads were calculated by combining the suspended sediment records with the continuous discharge records obtained from adjacent Environment Agency gauging stations.

A river reach approximately 100 m long was selected in the lower reaches of each basin, close to the suspended sediment monitoring site, for measuring fine sediment deposition and storage. Each reach encompassed a pool and riffle sequence in order to account for the local variability in river behaviour. These reaches were all of similar gradients (~2 m km^{-1}). The deposition and storage of fine sediment are difficult to measure precisely, because of the problems of replicating natural conditions and the difficulty of documenting a continuous process with periodic measurements. In the absence of generally accepted techniques, two different approaches were adopted.

Firstly, sediment deposition was documented directly, by means of tray traps (0.107 m^2 surface area, 9.0 cm, deep) similar in design to those described by Frostick *et al.* (1984) and Walling & Amos (1999). The trays were installed flush with the bed and subsequently filled with representative bed material cleaned to exclude all sediment of less than 2 mm. One tray was installed at the beginning and end of the pool and riffle in each river reach. Traps were emptied on a monthly basis, although the outbreak of Foot and Mouth disease prevented measurements in three of the catchments during the period March to August 2001. One limitation of this monthly interval is that the estimates of the mass of sediment deposited during the preceding month will represent a *minimum* estimate of fine sediment deposition during the period between trap emplacement and emptying, since some of the sediment deposited during the measurement interval could have been remobilized prior to the emptying of the trap. Nevertheless, the approach is seen as providing an effective means of comparing the individual study rivers.

Secondly, fine sediment storage was quantified using the resuspension technique described by Lambert & Walling (1988). This entailed placing a 1-m high galvanized steel cylinder (area 0.18 m^2) on the river bed. Both the water within the cylinder and the upper 10 cm of the gravel bed were then agitated to resuspend the fine sediment stored on and within the upper part of the channel bed and a sample of the turbid water was taken. The sediment content of this sample was assumed to reflect the remobilization of fine sediment mantling the surface and contained within the bed material matrix. By knowing the area of bed enclosed by the cylinder and the volume of water in the cylinder (derived from a measurement of mean depth) it was possible to calculate the quantity of stored sediment from the values of sediment concentration obtained from the samples. These measurements of the bed storage of fine sediment were made at points close to where the deposition trays were installed, again at monthly intervals. As such they provide periodic instantaneous estimates of the total amount of fine sediment stored on the channel bed. The amount of sediment stored on the channel bed can clearly be expected to vary during the periods between measurements and the estimate obtained could therefore under- or over-estimate the mean value for the period. By calculating the change in fine sediment storage between the individual monthly measurements, it was possible to estimate whether the intervening period had been one of net remobilization or net deposition and to produce corresponding estimates of sediment deposition (or remobilization).

An attempt was also made to estimate the total amount of fine sediment stored on the channel bed of the main channel system of each study basin, by using a modification of the approach described by Lambert (1986). First, the main channel network upstream of the study reach was subdivided into reaches. Second, at a representative point within each upstream reach, fine sediment storage was measured using the resuspension technique at both a pool and riffle site. The channel geometry of each upstream reach was also documented, to assist determination of the total channel bed area in the reach and the relative proportions of this area occupied by pools and riffles. The total fine sediment storage in each upstream reach was then calculated by extrapolating the measured values and the estimates were summed to provide an estimate for the entire main channel system. This value represented an estimate of instantaneous storage at the time of sampling in August 2002. It was adjusted to provide an estimate of the mean storage over the study period by multiplication by the ratio of mean monthly storage to storage in August 2002 derived for the main study reach.

After transfer to the laboratory, the sediment recovered from the deposition trays was wet sieved through a 0.063 mm sieve and the <0.063 mm fraction was freeze dried. The samples provided by the resuspension technique were filtered through 1.2 μm membrane filters, in order to determine the suspended sediment concentration.

RESULTS

Suspended sediment response

Table 2 presents summary information on suspended sediment concentrations and loads derived from the continuous records of suspended sediment concentration for the four study catchments, provided by the recording turbidity meters. The results highlight substantial variation between the study rivers. Maximum concentrations were found in the River Tone, where storm-period concentrations exceeded 2000 mg l^{-1}, more than eight times the maximum concentrations found in the River Wylye. Discharge-weighted mean concentrations ranged between 13 mg l^{-1} for the River Wylye and 77 mg l^{-1} for the River Leadon. Specific annual suspended sediment yields (November 2001–October 2002) varied by more than an order of magnitude, from 4 t km^{-2} $year^{-1}$ for the River Wylye to approximately 90 t km^{-2} $year^{-1}$ for the River Tone. By UK standards, the suspended sediment yield of the River Wylye is low, whilst the sediment yield of the River Tone is high (cf. Walling & Webb, 1981). The sediment yields of the Rivers Leadon and Torridge are more typical of those for UK river systems.

Table 2 Suspended sediment characteristics of the study basins.

River	Mean discharge weighted suspended sediment concentration (mg l^{-1})	Max. suspended sediment concentration (mg l^{-1})	Annual sediment load (t $year^{-1}$)	Annual specific sediment yield (t^{-1} km^2 $year^{-1}$)
Leadon	77	1513	12748.6	43.51
Tone	22	2137	7512.6	89.65
Torridge	37	1501	16929.2	65.67
Wylye	13	230	1756.3	3.96

Sediment deposition

Figure 2 and Table 3 and indicate that the estimates of fine sediment deposition provided by the tray traps demonstrate significant differences between the four study rivers. Table 3 presents

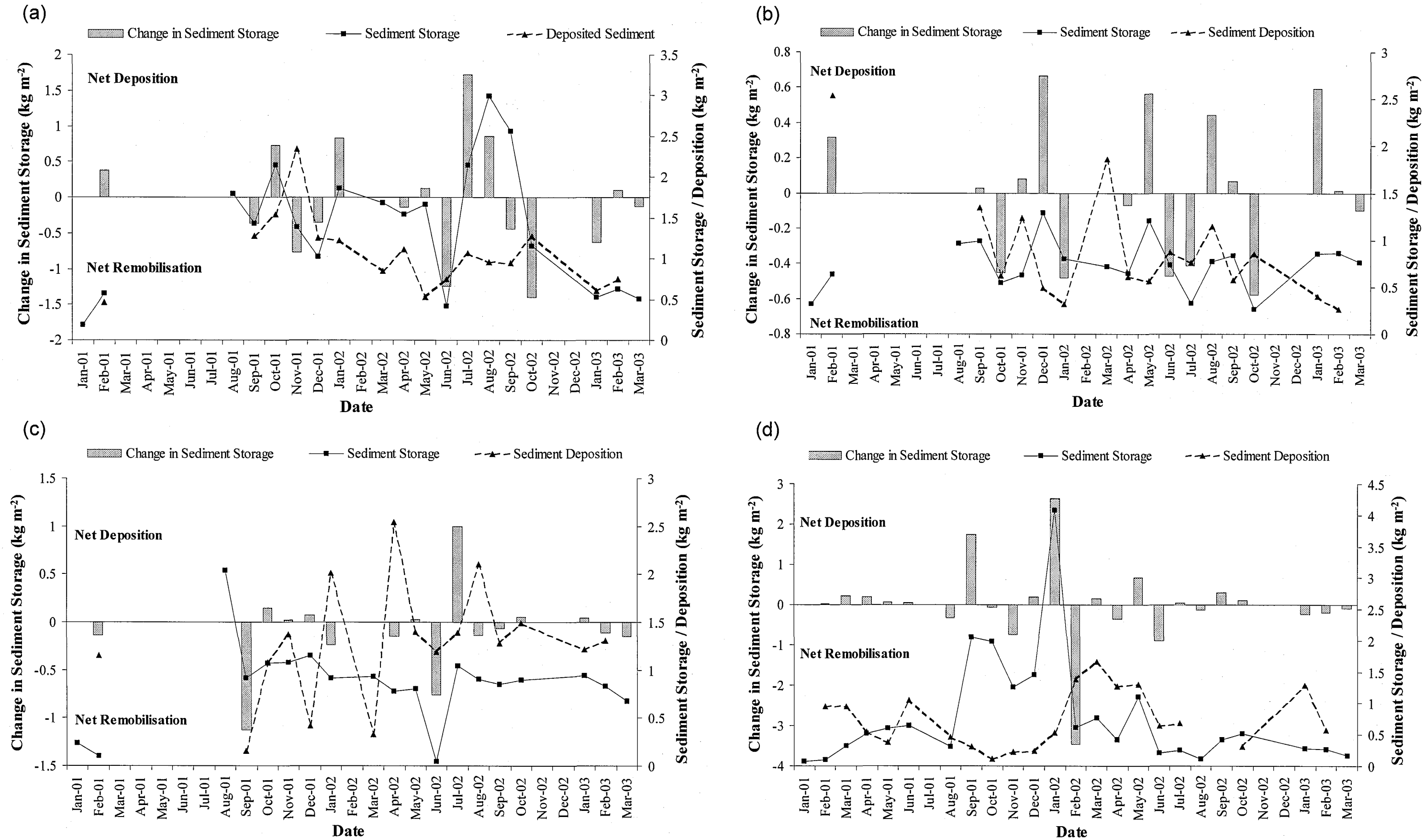

Fig. 2. Monthly measurements of fine sediment deposition and storage and estimates of net deposition and remobilisation derived from the monthly storage measurements, for the study rivers. (a) River Leadon, (b) River Tone, (c) River Torridge, (d) River Wylye.

Table 3 The maximum, minimum and mean monthly values of fine (<0.063 mm) sediment deposition and storage for the study rivers.

River	Fine sediment deposition (kg m^{-2})				Fine sediment storage (kg m^{-2})			
	Max.	Min.	Mean	Standard deviation	Max.	Min.	Mean	Standard deviation
Leadon	3.54	0.52	1.56	0.71	3.00	0.42	1.48	0.78
Tone	2.54	0.26	0.90	0.61	1.28	0.26	0.74	0.29
Torridge	2.54	0.15	1.28	0.63	2.04	0.10	0.87	0.26
Wylye	1.67	0.12	0.74	0.46	2.05	0.07	0.82	1.05

the maximum, minimum and mean of the average deposition amounts measured for all the tray traps within the study reach of a particular river, for each measurement interval, with the standard deviation of the average values for each measurement interval providing a measure of the temporal variability of sediment deposition. The highest maximum and mean values of 3.54 and 1.56 kg m^{-2}, respectively, were recorded for the River Leadon, whereas the lowest maximum and mean values of 1.67 and 0.74 kg m^{-2}, respectively, were recorded for the River Wylye. The broad similarity between the values obtained for the four study rivers is, however, worthy of note. Whereas the values of maximum suspended sediment concentration and specific sediment yield reported in Table 2 vary by around an order of magnitude, the values of maximum and mean deposition listed in Table 3 vary by a factor of only ~2. Equally, although the lowest values of sediment deposition are found in the River Wylye, and therefore coincide with the lowest values of maximum concentration and specific suspended sediment yield, the maximum values of deposition are found in the River Leadon, which is characterized by only intermediate values of maximum suspended sediment concentration and specific suspended sediment yield.

Figure 2 presents estimates of monthly deposition amounts obtained from both the tray traps (measured) and from the monthly measurements of sediment storage (inferred). The measured values suggest that sediment deposition is a continuous process in each river, because some fine sediment was always recovered from the tray traps at each measurement. However, these results are somewhat inconsistent with the estimates of net deposition and remobilization inferred from the monthly measurements of sediment storage, since several periods are shown to be characterized by net remobilization, and no deposition might therefore be expected. Furthermore, in several cases, high values of net remobilization coincide with relatively high measured values of deposition. These apparent inconsistencies are evident for all four rivers and undoubtedly reflect the nature and basis of the measurements employed. In the case of the tray traps, episodes of both deposition and remobilization could be included within the measurement period and, if the period of remobilization occurred at the beginning of the measurement period, this would not be reflected by the amount of sediment collected. Equally, significant periods of both deposition and remobilization could have occurred between the measurements of sediment storage and these would not necessarily be reflected by the storage measurements undertaken at the beginning and end of the period involved. Despite these limitations, and the need for careful interpretation of the results obtained, the results presented in Fig. 2 are seen as providing a useful indication of contrasts in fine sediment deposition and storage between the four study rivers.

Perhaps the two most important features of the results presented are, firstly, the temporal variation in the amounts of sediment recovered from the tray traps and the alternation of periods of net deposition and net remobilization as inferred from the storage measurements, and, secondly, the lack of a common temporal pattern or trend for the four rivers. Periods of increased or reduced deposition and gains or losses from storage occur at different times in the individual rivers, despite the similar hydrometeorological conditions experienced by their catchments. An example of these contrasts is provided by the period of increased measured fine sediment deposition occurring in the Rivers Leadon, Tone and Torridge during the late autumn and early winter of 2001, which coincides with a period of reduced measured deposition in the River Wylye.

Sediment storage

Table 3 presents summary results for the monthly measurements of fine sediment storage on and within the upper part of the river bed, undertaken on the four rivers. Maximum, minimum and mean values of the monthly average values and the associated values of standard deviation are presented. Clear contrasts are apparent between the catchments. As with the measurements of fine sediment deposition provided by the tray traps, the highest maximum and mean values are found in the River Leadon. Interestingly, however, the lowest values of maximum and mean storage are those for the River Tone, the river with the highest specific suspended sediment yield and maximum suspended sediment concentration. Similarly, almost identical intermediate values of maximum and mean storage are listed from the Rivers Torridge and Wylye, despite the marked differences in specific sediment yield and maximum and mean suspended sediment concentration evident between these catchments (cf. Table 2). As with the values of sediment deposition provided by the tray traps, there is no clear relationship between the magnitude of the measurements of sediment storage reported for the individual rivers and the magnitude of the associated values of specific sediment yield and suspended sediment concentration. The standard deviation values indicate that the Wylye and Leadon are characterized by substantial temporal variation in fine sediment storage, whereas the storage values recorded for the Rivers Tone and Torridge evidence much less temporal variability. Figure 2 provides further information on this temporal variability and shows that the increased variability associated with the Rivers Wylye and Leadon reflects the marked increase in sediment storage documented between August 2001 and February 2002 in the River Wylye and between June and October 2002 in the River Leadon. Perhaps more importantly, however, Fig. 2 shows that, although each of the rivers shows evidence of cyclical variations in storage, with periods of accumulation separated by periods of remobilization, there is little evidence of any common temporal (seasonal) pattern of increase and decrease in storage for the four rivers. The only common trend appears to be that more sediment was stored in the river channels during winter 2001 as compared to winter 2002.

Table 4 presents estimates of the mean total fine sediment storage, on and within the upper part of the river bed, for the entire main channel system of each of the four rivers. Values range from 278.7 t in the River Wylye to 66.7 t in the River Tone. The differences between the four rivers can be largely explained in terms of differences in basin size, since storage must be expected to increase with increasing basin size and channel length. Previous studies (e.g. Walling *et al.*, 1999) have examined the total amount of fine sediment stored on the channel bed and related it to the annual suspended sediment load, in an attempt to assess

Table 4 Average in-channel fine sediment storage in the main channel systems of the study rivers expressed as a percentage of the annual suspended sediment load.

River	Average in-channel sediment storage (t)	% of annual suspended sediment load
Leadon	193.2	1.5
Tone	66.7	0.9
Torridge	239.7	1.4
Wylye	278.7	15.9

its role in the basin sediment budget and its potential significance in terms of a conveyance loss. These values are also reported in Table 4 and indicate that, although there is little difference in magnitude between the values reported for the Rivers Leadon, Tone and Torridge, that for the River Wylye is substantially greater. This in turn suggests that channel storage plays a greater role in the sediment budget for the catchment of the River Wylye, since the mean total storage amount is equivalent to ~16% of the total annual sediment output from the basin. Because the total amount of sediment moving into, and out of, storage is likely to be substantially greater than the estimate of mean total storage, it is clear that channel storage can potentially exert an important influence on the transmission of fine sediment through the channel system of this river, through storage and attenuation of the sediment transfer. However, the contrast between the River Wylye and the other catchments primarily reflects the much lower suspended sediment yield of the River Wylye, rather than increased channel storage in this catchment (cf. Table 4).

CONCLUSION

In reviewing the findings presented above, three key findings merit emphasis. First, the four rivers exhibit significant contrasts in both the magnitude and the temporal behaviour of fine sediment deposition and storage. Although their catchments experience similar hydrometeorological regimes, there is little evidence of common temporal patterns. Second, there is no clear link between the relative magnitude of fine sediment deposition and storage in the four rivers and the relative magnitude of their specific suspended sediment yields and concentrations. Furthermore, the major differences between the four rivers evidenced by their sediment yields and concentrations are not matched by equivalent differences in fine sediment deposition and storage. Factors other than the magnitude of the suspended sediment loads and the ambient concentrations appear to control the magnitude of fine sediment deposition and storage and the contrasts between the catchments noted previously. Further work is clearly required to elucidate these controls. Thirdly, the results suggest that for three of the catchments channel storage is of limited importance in the overall basin sediment budget, whereas such storage is likely to exert an important influence on the sediment response of the River Wylye. However, the significant amounts of fine sediment deposition and storage documented for all four rivers, and particularly in the Rivers Leadon and Wylye, could impact on their aquatic ecology, through siltation of spawning gravels, clogging of vegetation and the accumulation and release of pollutants. Again, further work is required to develop an improved understanding of the dynamics of fine sediment deposition and storage in these and similar rivers.

Acknowledgements The support of the Natural Environment Research Council and CEH Wallingford in providing a postgraduate studentship for A. J. Wilson, the valuable assistance of local landowners in permitting access to field sites and the generosity of the Environment Agency in permitting the siting of turbidity monitoring equipment at the river gauging stations and in providing flow data, are gratefully acknowledged.

REFERENCES

Frostick, L. E., Lucas, P. M. & Reid, I. (1984) The infiltration of fine matrices into coarse-grained alluvial sediments and its implications for stratigraphical interpretation. *J. Geol. Soc. London* **141**, 955–965.

Heywood, M. J. T. (2002) Sedimentation of salmonid spawning gravels: an investigation of associated sediment dynamics in the Hampshire Avon catchment. PhD Thesis, University of Exeter, Exeter, UK.

Lambert, C. P. (1986) The suspended sediment delivery dynamics of river channels in the Exe basin. PhD Thesis, University of Exeter, Exeter, UK.

Lambert, C. P. & Walling, D. E. (1988) Measurement of channel storage of suspended sediment in a gravel bed river. *Catena* **15**, 65–80.

Smith, B. P. G., Naden, P. S., Leeks, G. J. L. & Wass, P. D. (2003) Characterising the fine sediment budget of a reach of the River Swale, Yorkshire, UK during the 1994 to 1995 winter season. *Hydrobiologia* **494**, 135–143.

Walling, D. E. & Amos, C. M. (1999) Source, storage and mobilisation of fine sediment in a chalk stream system. *Hydrol. Processes* **13**, 323–340.

Walling, D. E. & Webb, B. W. (1981) Water quality, In: *British Rivers* (ed. by J. Lewin), 126–129, George Allen & Unwin, London, UK.

Walling, D. E., Collins, A. E. & McMellin, G. K. (2003a) A reconnaissance survey of the source of interstitial fine sediment recovered from salmonid spawning gravels in England and Wales. *Hydrobiologia* **497**, 91–108.

Walling, D. E., Owens, P. N. & Leeks, G. J. L. (1998) The role of channel and floodplain storage in the suspended sediment budget of the River Ouse, Yorkshire, UK. *Geomorphology* **22**, 225–242.

Walling, D. E., Owens, P. N., Carter, J., Leeks, G. J. L., Lewis, S., Meharg, A. A. & Wright, J. (2003b) Storage of sediment-associated nutrients and contaminants in river channel and floodplain systems. *Applied Geochemistry* **18**, 195–220.