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The settling behaviour of fine sediment particles: some preliminary results from LISST instruments

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Abstract The settling velocity of suspended particles is a dominant factor in controlling the transfer and fate of sediment and sediment-associated substances. The properties of fine particles can vary significantly throughout a catchment, especially in terms of the degree of aggregation/flocculation, but relatively little is known about the consequences this has on settling velocity. This study attempts to explore the significance of the particle size distribution in influencing the settling behaviour of natural particles. Particles were collected from a range of sources across two contrasting catchments, giving natural variability in the grain size composition and degree of aggregation/flocculation of the samples. Particle size and settling velocity were measured using novel LISST-100 and LISST-ST laser diffraction devices. Significant differences in settling velocity were found between samples, notably between aggregated/flocculated and dispersed samples, and between individual size classes. The results emphasize the importance of aggregation/flocculation in the hydraulic behaviour of sediment.

Key words aggregate; fine sediment; floc; LISST-100; LISST-ST; particle size; settling velocity

INTRODUCTION

The transport and fate of fine sediment play a key role in the transfer of nutrients and contaminants in river basins, and in the physical degradation of aquatic habitats in the hyporheic zone. Several recent studies have investigated the spatial variation of the physical and chemical characteristics of fine sediment, including particle size (Walling & Moorehead, 1987, 1989), nutrient and organic matter content (Droppo *et al.*, 1997; Walling *et al.*, 2001; Ankers *et al.*, 2003) and trace elements (Foster & Charlesworth, 1996; Ankers *et al.*, 2003; Krein *et al.*, 2003). Source tracing studies have highlighted the importance of the catchment surface as a source of fine sediment in aquatic systems (Collins & Walling, 2002). However, relatively few studies have specifically considered the transport mechanisms involved in the transport of this material, which are critical to the understanding and modelling of the movement of fine sediment and associated substances. In part, this reflects a limited understanding of the hydraulic significance and effects of aggregation and flocculation, the importance of which has been demonstrated by comparisons of effective size distributions sampled *in situ* with equivalent absolute (dispersed) size distributions measured in the laboratory (Walling & Moorehead, 1987, 1989; Phillips & Walling, 1995, 1999; Droppo *et al.*, 1997, 1998, 2000). Aggregates are densely packed, well rounded composite particles, formed by non-aqueous processes, which retain their structure during transport through the system (Walling & Woodward, 2000). In contrast, flocs are composite particles formed by inter-particle interactions within the water column, which are known to be much more loosely bound, irregular in shape and of relatively low density (Droppo, 2001). While it is assumed that the two classes of composite particle are structurally and functionally different, few studies have been able to explore the implications of these differences for their hydraulic behaviour. The fate of particles during transport can be inferred from their settling velocity; a measure of the potential for transport or deposition. The settling velocity of a suspension is dependent on a range of variables, including particle size, density and shape, the concentration of the suspension and the viscosity of the suspending medium. However, the dominant control can be assumed to be particle size, which in turn is dependent on particle composition and source. This study uses novel laser diffraction devices to investigate the settling behaviour of structurally contrasting particles, representative of sediment from a range of sources. Particular attention is paid to particle size and size distribution, with reference to aggregated/flocculated and dispersed samples.

METHODS

Samples of fine-grained bed sediment (surficial fine-grained laminae (SFGL), Droppo & Stone, 1994), storm suspended sediment, bank sediment and soils from a range of land uses were collected from two contrasting catchments in southern England. The River Dart is a tributary of the River Exe, lying approximately 15 km north of Exeter, Devon. It has a catchment area of 46 km^2. The catchment is developed on Upper Carboniferous sandstones, shales and mudstones, with some alluvial deposits in the steep valley bottoms. Soils are predominantly brown earths and surface-water gleys. The dominant land use is pasture, with some permanent deciduous woodland and some arable agriculture. The Chilfrome catchment forms part of the headwaters of the River Frome in Dorset, located approximately 10 km northwest of Dorchester. It has an area of approximately 36 km^2. The catchment is entirely underlain by chalk, and is characterized by argillic brown earth and brown rendzina soils. Land use is primarily pasture, with areas of arable farming and some deciduous woodland.

Soil samples collected from both catchments were classified as ploughed, pasture, deciduous woodland, or track/bridleway. The soil sampling locations were selected to represent sites that had been observed to generate surface runoff, and were generally gateways from fields on the steeper slopes. Samples were collected using a polyethylene scoop and stored in large, unsealed polyethylene bags. Although these were stored in dark, refrigerated conditions, it should be noted that they can only provide an approximate representation of field conditions, given the period of storage required when running numerous lengthy settling experiments.

Soil aggregates were isolated by placing the soil sample into a plastic tray fixed at a 30° angle and spraying the tray with filtered river water from the appropriate catchment, in order to simulate the generation of sediment-rich saturated overland flow. Runoff from the trays was collected in 500 ml polyethylene bottles, kept well mixed by gentle agitation and analysed as soon as possible. Samples of true bed sediment from the study rivers were collected in 500 ml polyethylene bottles. Fine bed sediment was entrained into the water column by disturbing the SFGL prior to sampling. The samples were stored in a dark refrigerator and resuspended by gentle agitation prior to analysis in the laboratory. Suspended sediment samples were collected from the water column during storm events, stored and resuspended in the same way. Duplicates of all samples were mechanically dispersed by ultrasonication to provide the absolute size distributions. Sodium hexametaphosphate was not used for dispersion because of its potential effects on water buoyancy and viscosity.

The grain size distributions of all samples were measured using a LISST-100 (Type C) laser diffraction particle sizer, which provides results in 32 logarithmically spaced size classes in the range of 2.5 to 500 μm. Settling velocity was measured using a LISST-ST (Type C), which permits the measurement of fall velocity for eight separate size classes in the same overall range. Both instruments employ the principle of small angle forward laser scatter to measure particle size. The sensing area in the LISST-100 is designed to be non-intrusive for *in situ* field deployment, whereas in the LISST-ST it is located at the bottom of a 30-cm settling column. Fall velocity is calculated from the evolution of particle size spectra, with reference to a preliminary measurement of the initially well-mixed sample. Repeat measurements are taken at known time increments, with a size class that was measured at the beginning of the experiment being deemed to have settled out of suspension as soon as it is no longer detected. Since the LISST-ST only resolves settling velocity for eight size classes and does not provide detailed information on size distributions, it was used in conjunction with the LISST-100, which provides a higher resolution size distribution. Volumetric mean particle size was calculated from the LISST-100 size results, but detailed size distributions are not presented here. Since both instruments use the same operating principles, results from the two can be directly compared. Further details of these instruments are provided by Agrawal & Pottsmith (2000).

Prior to laboratory measurements, suspensions of each sample were diluted to produce a concentration of 400 $\mu l\ l^{-1}$, using filtered river water from the appropriate catchment. The value of 400 $\mu l\ l^{-1}$ was selected as close to the instrument's minimum optical transmission of $\tau = 0.3$, when using a 50% optical path reduction module. One hundred discrete measurements of the diluted sample were made at a rate of 4 Hz and the mean 32-class size distribution recorded before the sample was transferred to the LISST-ST and the settling velocity measured over an 11-h duration. Sample preparation and handling, as described above, are assumed to have had no significant impact on the structure of the composite particles. Floc structure is known to evolve in response to changing hydraulic conditions (e.g. Phillips & Walling, 1995), but is thought to be essentially stable for at least 80 s (Phillips & Walling, 1995). The timescale of sample preparation in the adopted methodology was therefore considered acceptable.

It is necessary to dilute samples so that they can be accurately measured using the LISST devices, and because concentration is one of several potential controls on settling behaviour. Water viscosity was assumed to be constant, since temperature was essentially constant in the laboratory. It was not possible to measure particle shape and it was therefore assumed that the only significant variation between samples was the particle size distribution. This encompasses grain size and density, because the experimental set up considers the effects of changes in density due to aggregation and flocculation.

RESULTS

The relationships between particle size and settling velocity for all samples are presented in Fig. 1. Particle size refers to the volumetric mean, calculated from the 32-class size distribution provided by the LISST-100. Mean settling velocity is calculated from the eight class values provided by the LISST-ST. Mean values therefore refer to the 2.5 to 500 μm size range of the instruments. Figure 1 illustrates the broad variation in both mean particle size and mean settling velocity associated with a range of sediments and potential source

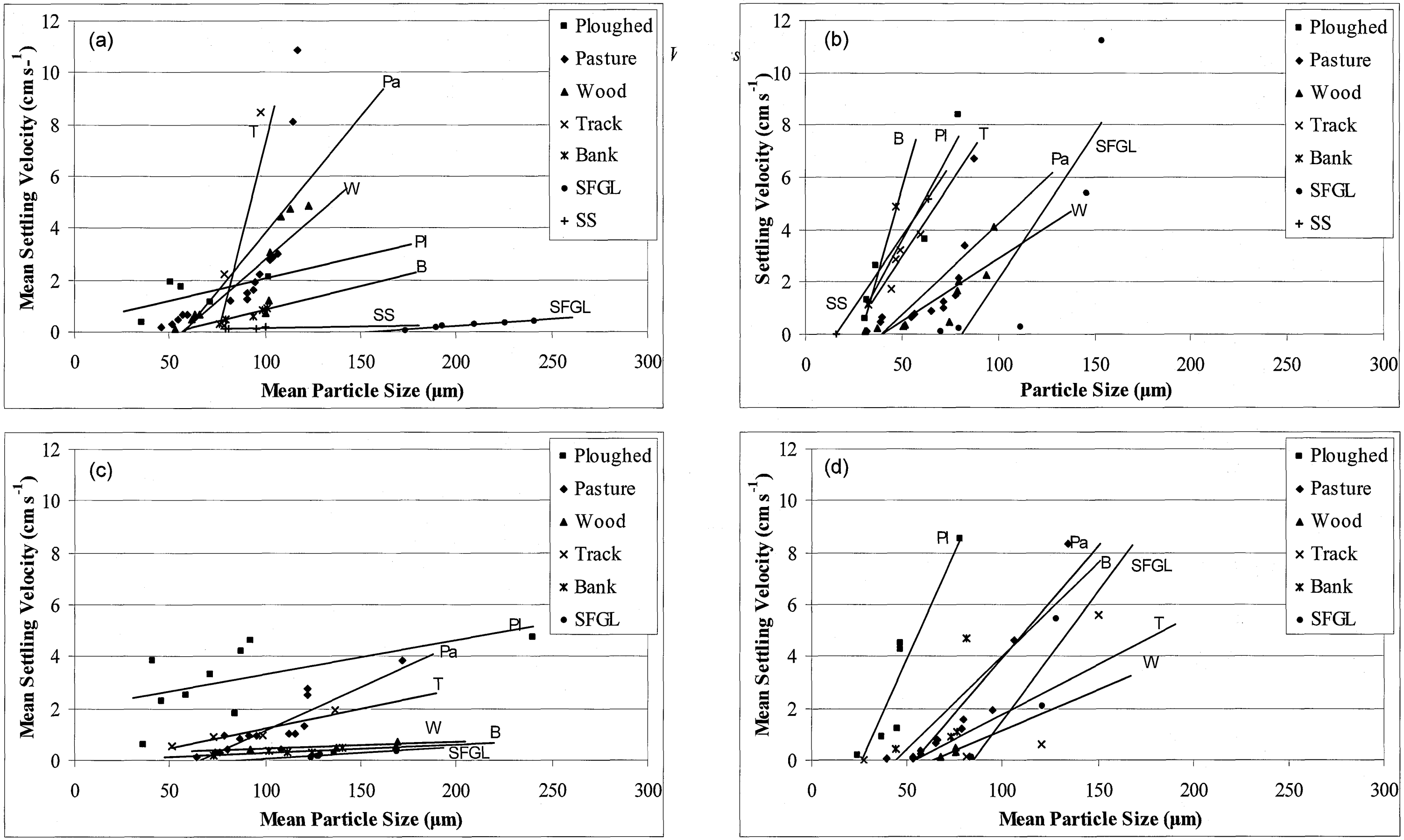

Fig. 1 Regression lines for the relationships between mean settling velocity and mean particle size for sediment from different sources distinguished by catchment and by APSD or EPSD. (a) Dart effective size distributions, (b) Dart absolute, (c) Chilfrome effective, (d) Chilfrome absolute. For all plots Pl = sediment from ploughed areas, Pa = pasture, W = wood, T = track, B = bank, SFGL = fine bed sediment and SS = suspended sediment. Lines have been extrapolated for visual clarity.

materials collected from within relatively small catchments. However, it is also apparent that significant trends exist when samples are grouped according to sediment type. Intra-group variation in both fall velocity and particle size is significantly less than inter-group variability. This is true for both the effective particle size distribution (EPSD) (Figs 1(a) and 1(c)) and absolute particle size distribution (APSD) (Figs 1(b) and 1(d)). Within all sample groups, it is apparent that mean settling velocity increases with mean particle size.

The rate of increase in settling velocity with particle size is generally more rapid for absolute distributions than effective size distributions. This can be attributed to the effects of aggregation/flocculation and the associated decrease in particle density caused by inefficient particle packing, and to the increased porosity of composite particles compared to discrete particles of equivalent size. This assertion is reinforced by the fact that the largest shift in regression gradient between the EPSD and APSD is for suspended sediment and SFGL flocs in both catchments. Flocs are much more loosely bound than aggregates, with relatively high water content within the floc matrix, whereas aggregates are densely packed particles. The dominant effect of dispersing aggregates is therefore to reduce fall velocity as a consequence of lower particle size as opposed to the more radical structural effects of dispersing flocs. It is particularly interesting to note the similarity in overall scatter of points for dispersed samples between the two catchments, when untreated samples show pronounced inter-catchment variation. This highlights the effect of particle structure (a consequence of source, composition and formation mechanisms) on sediment hydraulic behaviour. Non-dispersed (natural) samples from the Chilfrome catchment (chalk) generally exhibit a lower mean settling velocity and slightly larger mean particle size than samples from the Dart catchment (sandstone/shale/mudstone). This can be attributed to material from the Chilfrome drainage basin being of relatively low density, due to the dominance of chalk and a higher organic content of the soil.

The discrepancies between the EPSD and APSD for individual size classes are explored in Fig. 2. This emphasizes the positive trend between particle size and fall velocity. It also shows that the greatest disparity in settling rate between the APSD and EPSD is at the upper end of the size range. This is attributable to flocculation/aggregation and decreasing density with increasing size.

In both catchments, the greatest differences between the EPSD and APSD behaviour are found for the SFGL, where the low density blanket of fine sediment is preferentially entrained from larger bed material during resuspension in the form of large flocs, with relatively low numbers of equivalent sized individual grains. SFGL flocculated particles appear to settle faster than the equivalent size discrete particles up to around 80 μm. This is suggested to be because of a strong bias towards the high end of each size class for the EPSD because of the number of fine particles constituting a single floc, which has the effect of increasing fall velocity until a threshold density is reached. Similar patterns exist for all samples from ploughed land and tracks, and for samples from pasture land, in the Chilfrome catchment. This is attributed to the selection of sampling sites, which were depositional points within areas that generate extensive surface runoff over bare soils. It is likely that extensive sorting and preferential transport of fine particles occurs during overland flow, leading to a bias towards finer particles and an upward-fining depositional profile, the surface of which is more likely to be sampled. If size spectra evolve by *in situ* aggregation between storm events then the same effective/absolute trends as in SFGL will be seen within the settling size classes.

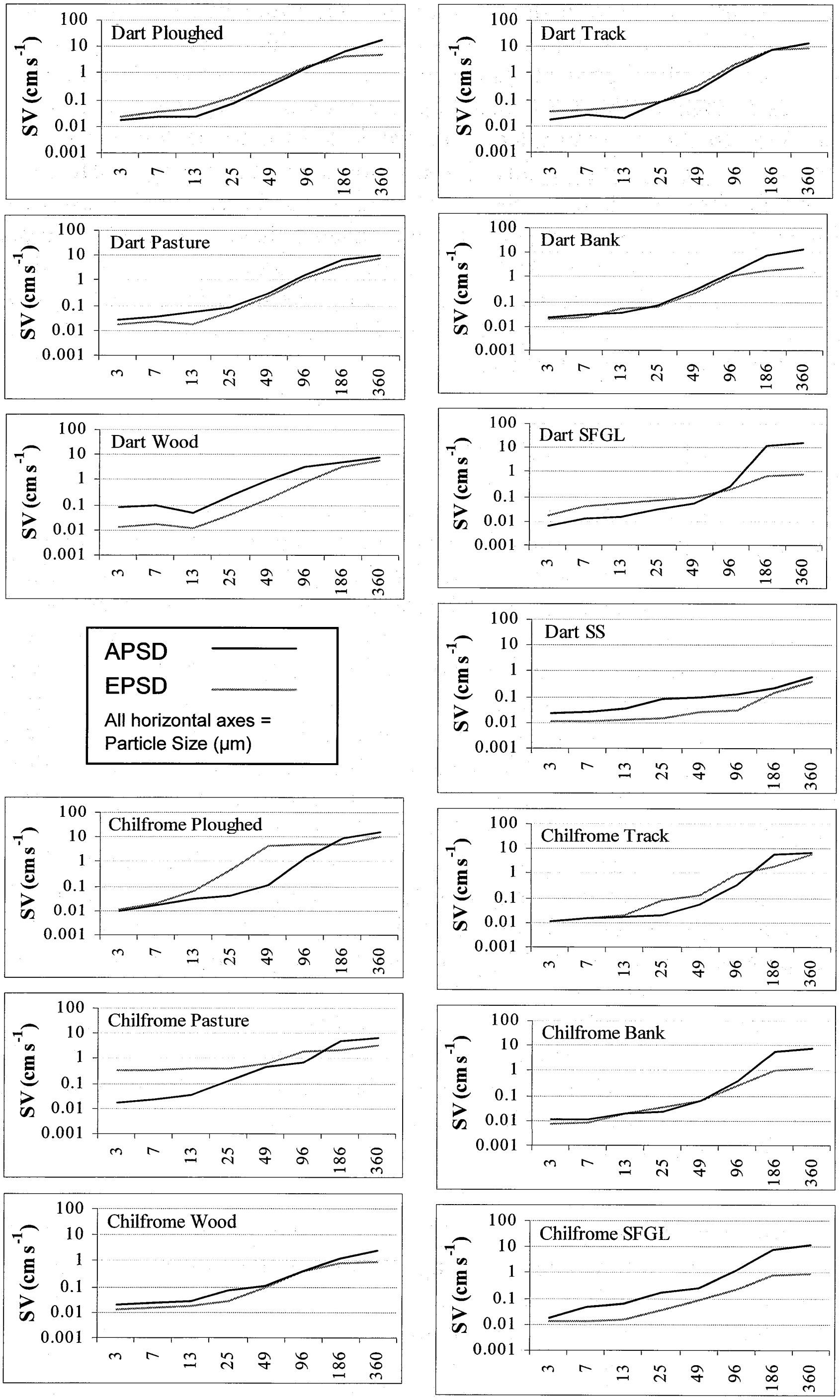

Fig. 2 Comparisons of the relationship between settling velocity (SV) and particle size for effective and absolute size distributions for representative samples of each type. Note that particle size is plotted as the median of each of the eight size classes of the LISST-ST, where the instrument range is 2.5 to 500 μm.

Samples of suspended sediment and from woodland soils in the Dart drainage basin and of SFGL in the Chilfrome catchment show the most significant increases in settling velocity by size class as a result of particle dispersal (Fig. 2). The mean absolute size of Chilfrome SFGL is greater than in the Dart, negating the effects of aggregation-enhanced settling within the finer fractions. Suspended sediment is known to be low density and loosely bound, due to the mechanics of fluvial transport, resulting in large differences between effective and absolute distributions. Sediment from wooded areas can be assumed to contain a much higher proportion of low density organic material than other land use types, giving a low overall effective settling velocity for fine particles bound to larger organic detritus.

In all cases it should be stressed that mean settling velocity is higher for the APSD than for the EPSD. This is due to the effects of particle structure and density changes, brought about by the dispersal of flocs/aggregates.

CONCLUSIONS AND IMPLICATIONS

The LISST devices are useful tools for investigating the complex relationships between settling velocity and particle size, particularly as fall velocity is reported for a range of size classes within a sample. It has been shown that mean particle size is a significant control on mean settling rate, but general empirical relationships cannot be established, due to the complexities induced by particle composition and structure. This is most pronounced in the differences between effective and absolute size distributions, and is also evident in the differences between flocs and aggregates. The upper end of the particle size range is most likely to be significantly affected by flocculation/aggregation, and this likely to represent a large proportion of the sample volume, though not necessarily particle numbers. Observations of settling rate versus particle size for separate fall velocity classes show that aggregation/flocculation may have the effect of increasing or decreasing settling velocity, although for the overall size ranges of natural particles, mean effective settling velocity is always lower than mean absolute settling velocity. This may be a useful aid in interpreting particle formation processes. The discrepancies in particle fall velocity that result from differences between APSD and EPSD have important implications for the understanding of particle settling, and therefore transport characteristics, and for the modelling of such processes, since fluvial particle size research has traditionally focused on the absolute particle size range, with a reliance on derivations of Stokes' law in estimations of fall velocity. The time taken to run a large number of settling experiments prohibits the generation of very large data sets, but the findings herein suggest that the subject clearly warrants further investigation.

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REFERENCES

Agrawal, Y. C. & Pottsmith, H. C. (2000) Instruments for particle size and settling velocity observations in sediment transport. *Marine Geology* **168**, 89114.

Ankers, C., Walling, D. E. & Smith, R. P. (2003) The influence of catchment characteristics on suspended sediment properties. *Hydrobiologia* **494**, 159–167.

Collins, A. L. & Walling, D. E. (2002) Selecting fingerprint properties for discriminating potential suspended sediment sources in river basins. *J. Hydrol.* **261**, 218–244.

Droppo, I. G. (2001) Rethinking what constitutes suspended sediment. *Hydrol. Processes* **15**, 1551–1564.

Droppo, I. G. & Stone, M. (1994) In-channel surficial fine-grained sediment laminae (Part I); physical characteristics and formational processes. *Hydrol. Processes* **8**, 101–111.

Droppo, I. G., Leppard, G. G., Flannigan, D. T. & Liss, S. N. (1997) The freshwater floc: a functional relationship of water and organic and inorganic floc constituents affecting suspended sediment properties. *Water Air and Soil Pollut.* **99**, 43–53.

Droppo I. G., Walling, D. E. & Ongley, E. D. (1998) Suspended sediment structure: implications for sediment and contaminant transport modelling. In: *Modelling Soil Erosion, Sediment Transport and Closely Related Hydrological Processes* (ed. by W. Summer, E. Klaghofer & W. Zhang) (Proc. Vienna Symp., 1998), 437–444. IAHS Publ. 249. IAHS Press, Wallingford, UK.

Droppo I. G., Walling, D. E. & Ongley, E. D. (2000) The influence of floc size, density and porosity on sediment and contaminant transport modelling. In: *The Role of Erosion and Sediment Transport in Nutrient and Contaminant Transfer* (ed. by M. Stone) (Proc. Waterloo Symp., 2000), 141–147. IAHS Publ. 263. IAHS Press, Wallingford, UK.

Foster, I. D. L. & Charlesworth, S. M. (1996) Heavy metals in the hydrological cycle: trends and explanation. *Hydrol. Processes* **10**, 227–261.

Krein, A., Petticrew, E. & Udelhoven, T. (2003) The use of fine sediment fractal dimensions and colour to determine sediment sources in a small watershed. *Catena* **53**, 165–179.

Phillips, J. M. & Walling, D. E. (1995) An assessment of the effects of sample collection, storage and resuspension on the representativeness of measurements on the effective particle size distribution of fluvial suspended sediment. *Water Res.* **29**, 2498–2508.

Phillips, J. M. & Walling, D. E. (1999) The particle size characteristics of fine-grained channel deposits in the River Exe Basin, Devon, UK. *Hydrol. Processes* **13**, 1–19.

Walling, D. E. & Moorehead, P. W. (1987) Spatial and temporal variation of the particle size characteristics of fluvial suspended sediment. *Geografiska Ann.* **69A**, 47–59.

Walling, D. E. & Moorehead, P. W. (1989) The particle size characteristics of fluvial suspended sediment: an overview. *Hydrobiologia* **176/177**, 125–149.

Walling, D. E. & Woodward, J. C. (2000) Effective particle size characteristics of fluvial suspended sediment transported by lowland British rivers. In: *The Role of Erosion and Sediment Transport in Nutrient and Contaminant Transfer* (ed. by M. Stone) (Proc. Waterloo Symp., 2000), 129–139. IAHS Publ. 263. IAHS Press, Wallingford, UK.

Walling, D. E., Russell, M. A. & Webb, B. W. (2001) Controls on the nutrient content of suspended sediment transported by British Rivers. *Sci. Total Environ.* **266**, 113–123.