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Effective particle size characteristics of fluvial suspended sediment transported by lowland British rivers

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Abstract The alluvial flood plains of lowland Britain contain thick sequences of fine-grained sediment that result from the deposition of suspended sediment during flood events. These environments constitute important storage zones for a wide range of sediment-associated nutrients and contaminants and many of the geochemical properties of the deposited sediment are strongly related to particle size. Recognition of the importance of composite suspended sediment particles in fluvial environments has generated a need for new field equipment and monitoring strategies capable of measuring the effective particle size characteristics of fluvial suspended sediment. This paper presents effective and absolute particle size data derived from a range of sampling and measurement techniques for five rivers in central and southern Britain. The study catchments cover a range of geological and hydrological conditions that are representative of lowland Britain more generally. All the rivers display marked contrasts between the effective and absolute particle size distributions of suspended sediment samples. Data from field-based water elutriation systems and scanning electron microscopy (SEM) show that composite particles dominate the suspended sediment load. Composite particles also contain significant clay and fine silt components which are an important control on the nutrient and contaminant loading of the sediment load. Understanding the nature and role of composite particles is essential to the study of the transfer and fate of nutrients and contaminants in the freshwater fluvial environment. Research in the Exe basin suggests that the time-integrated data produced by the water elutriation apparatus are to be preferred for estimating the role of composite particles in suspended sediment flux and for calibrating models of sediment transport and deposition.

INTRODUCTION

The alluvial flood plains of lowland British rivers constitute important depositional sinks. Many of these river systems contain thick sequences of fine-grained alluvium that result from the deposition of suspended sediment during overbank flood events. These environments constitute both important storage zones for a wide range of sediment-associated nutrients and contaminants as well as major non-point sources of these substances where lateral channel migration and flood-plain reworking take place (Macklin, 1996). Many of the geochemical properties of the deposited sediment are strongly related to particle size and understanding the behaviour and fate of the fine particle fraction of sediment deposited from suspension is essential to the study of the transfer of nutrients and contaminants through the aquatic environment (Ongley *et al.*, 1992; Milligan & Loring, 1997). The importance of fluvial suspended sediment as a vector for the transport of nutrients and many natural and anthropogenic pollutants, such as radionuclides, pesticides and heavy metals, is now well established and the concentration of many substances bound to suspended solids can be at least an order of magnitude higher than their concentration in the dissolved phase (Horowitz, 1991). However, even though it is clear that the particle size characteristics of suspended sediment can exert a major influence on the concentration and bioavailability of many substances, most water quality monitoring programmes do not include assessments of suspended sediment flux or sediment quality. Particle size is also a fundamental control on the dynamics of sediment entrainment, transport and deposition, and information on the particle size characteristics of suspended sediment is an essential requirement for investigations of the flux and storage of sediment-associated substances in the channel and riparian zone.

Against this background, recognition of the significance of composite suspended sediment particles in freshwater fluvial environments has generated a need for new field equipment and sampling strategies capable of measuring the effective or *in situ* particle size distribution and providing representative samples to facilitate analysis of composite particle form and structure (Woodward & Walling, 1992; Droppo & Ongley, 1992; Walling & Woodward, 1993; Phillips & Walling, 1995a). Composite suspended sediment particles are also known as aggregates or flocs and they typically contain a significant clay and fine silt component (Woodward & Walling, 1999) with organic matter present in various forms (Droppo *et al.*, 1997). These components are particularly important controls on the contaminant and nutrient loading of the suspended load (Ongley *et al.*, 1992). Because discrete primary particles that would not settle in a given flow may be deposited when incorporated within a composite particle (Droppo *et al.*, 1997), new models of flood-plain sedimentation have been developed which account for the presence of composite particles in fluvial suspended sediment loads. Nicholas & Walling (1996) have shown that the presence of composite particles helps to account for the poor agreement between theoretical and observed trends in relationships between mean deposit grain size and distance from the main channel that has been reported for several lowland flood plains.

In the Exe basin of southwest England the median grain size of the effective size distribution of suspended sediment is typically an order of magnitude larger than that of the absolute or ultimate distribution produced by conventional laboratory analysis of the dispersed mineral fraction (Walling & Moorehead, 1987; Walling & Woodward 1993; Phillips & Walling, 1995a). Composite particles dominate the suspended sediment load and catchment lithology and soil type are thought to be important controls on the effective particle size characteristics of suspended sediment mobilized from the main sub-catchments (Woodward & Walling, 1999). This paper presents data derived from a series of sampling techniques that have been employed in the Exe and Culm basins in Devon, UK and within a less extensive programme of reconnaissance sampling conducted at four sites in central and southern England aimed at exploring the significance of composite particle transport in lowland British rivers more generally across a wide range of geological, pedological and hydrological conditions. Each of the sampling sites is located within a well-developed alluvial flood plain in the middle and lower reaches of the catchment, where conveyance losses due to the deposition of fine-grained sediment from suspension represent the dominant depositional process.

FIELD AND LABORATORY METHODS

Suspended sediment sampling was conducted at six sites in central and southern England. The sample sites range in elevation from *c.* 5 m (upstream of Throop) to just over 34 m above mean sea level (a.m.s.l.) (Stratford) and the catchment areas range from 273 km^2 (Rewe) to 2210 km^2 (Evesham) (Table 1).

In the Exe and Culm basins 1-litre samples of turbid river water were collected during flood events over a range of flow conditions at Thorverton and Rewe and these were immediately transported to the laboratory to permit direct measurement of the effective particle size distribution. The samples were placed in a bottle rack that was suspended in the back of a Landrover. The motion of the rack prevented the particles from settling and the particle size distributions were measured without pretreatment within one hour of collection using a Malvern Mastersizer laser diffraction particle size analyser. Repeat measurements were made on each sample contained in the Mastersizer sample bath to ensure that the circulatory pump did not cause the break up of composite particles. For the other rivers, bulk samples of suspended sediment were collected in 20-litre containers from Evesham and Stratford on the Warwickshire Avon and from sites on the Dorset Stour and the Hampshire Avon

Table 1 Sampling points in central and southern England where the effective particle size characteristics of fluvial suspended sediment have been analysed. Ordnance Survey grid reference and gauging station elevations above sea level are shown for each site.

River basin	Sampling station	Drainage area (km^2)	Mean flow ($m^3 s^{-1}$)	Maximum elevation (m)	Methods employed*
Hampshire Avon	Fordingbridge SU158144 (25.6 m)	1478	15.18	294	①②③
Dorset Stour	Throop SY113958 (4.4 m)	1073	13.21	277	①②③
River Exe (Devon)	Thorverton SS936016 (25.9 m)	601	15.88	519	①②③④⑤
River Culm (Devon)	Rewe SX946992 (23.0 m)	273	3.7†	293	①②③④⑤
Warwickshire Avon	Stratford SP205549 (34 m)	1273	No data	320	①②③
Warwickshire Avon	Evesham SP040438 (19.5 m)	2210	15.35	320	①②③

* Not all techniques have been applied at each sampling point. Samples were collected at or close to the gauging station site listed. Sampling methods employed (see text): ① re-suspension of composite particles from bulk (20-l) samples; ② samples collected for SEM analysis; ③ bulk samples collected for the measurement of absolute particle size; ④ rapid transport of bottle samples for Mastersizer analysis; ⑤ use of a water elutriation apparatus.

† Mean flow from Woodmill gauging station (226 km^2).

(Table 1). These samples were returned to the laboratory and the suspended sediment was gently agitated, re-suspended and stirred prior to direct measurement of their effective particle size characteristics (without pre-treatment) using the Malvern Mastersizer. Phillips & Walling (1995b) have conducted a detailed investigation of the particle size characteristics of re-suspended samples and have demonstrated that this approach can produce a meaningful approximation of the effective particle size characteristics of a suspended sediment sample. Suspended sediment samples were also collected using the Perspex settling tube and filter membrane assembly described by Woodward & Walling (1992) using Whatman cellulose nitrate filters with a pore size of 5 μm. This technique allows selective separation of a suspended sediment sample so that the structure and composition of composite particles can be observed using scanning electron microscopy (SEM). A field-based water elutriation apparatus (WEA) was also installed at Thorverton and Rewe and this approach has been described in detail by Walling & Woodward (1993). In brief, this involves drawing sediment-laden water directly from the river channel through a series of glass sedimentation chambers for several hours during the course of a flood event using a peristaltic pump. A sequential reduction in flow velocity is achieved by increasing the cross-sectional area of the sedimentation chambers and these were calibrated to separate suspended sediment into five effective size classes: >63 μm, 63–32 μm, 32–16 μm, 16–8 μm and <8 μm. In contrast to the other sampling methods that yield instantaneous samples, the WEA may be operated for up to eight hours producing a time-integrated sample of suspended sediment that is representative of sediment flux throughout a flood event (Woodward & Walling, 1999). The absolute particle size characteristics of the sediment in each effective class were determined using the Mastersizer. A summary of the methods employed at each site is provided in Table 1.

RESULTS AND DISCUSSION

Figure 1 presents typical effective and absolute particle size distributions from each of the six sample locations. While it is important to remember that these represent instantaneous samples taken across a range of flow conditions, some generalizations can be made. All the rivers display marked contrasts between the effective and absolute distributions, demonstrating that composite particles are an important component of suspended sediment transport in a wide range of lowland British Rivers. The headwaters of the Dorset Stour are dominated by the Oxford and Kimmeridge clays and the median size of the effective and absolute distributions is 39.8 μm and 5.8 μm respectively. The Hampshire Avon drains a large chalk catchment and evidences the smallest contrast between the effective and absolute distributions; the median grain size of the absolute distribution is the coarsest (13.3 μm) of those shown in Fig. 1. While the effective grain size distributions for the Exe and Culm are quite similar, with a D_{50} of 33.5 and 41.8 μm respectively, the absolute grain size characteristics of the Culm are much finer than those from the Exe. The proportion of the effective size distribution >63 μm ranges from 8% (Warwickshire Avon at Stratford) to 43% (Warwickshire Avon at Evesham) with a mean value of 31% for the six size distributions shown in Fig. 1. The mean value of the sand

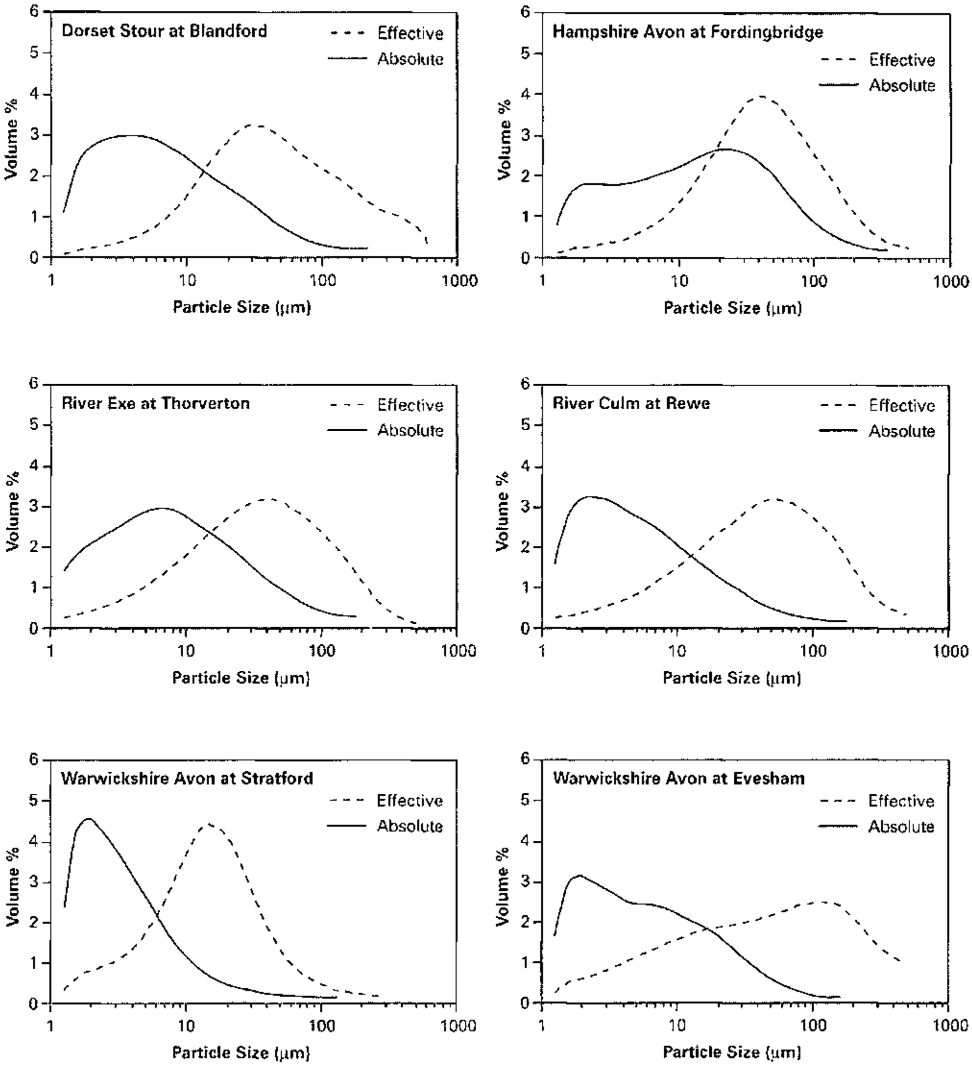


Fig. 1 Typical effective and absolute particle size distributions for suspended sediment samples collected from six locations on five British rivers (Table 1). Data were obtained using a Malvern Mastersizer Laser Diffraction Particle Size Analyser; see text for explanation).

content of the absolute size distribution is 10% indicating that large composite particles are an important part of the suspended sediment load. Woodward & Walling (1992) have reported the presence of composite particles >200 μm in size in suspended sediment samples collected from the River Exe at Thorverton.

Figure 2 shows four scanning electron micrographs of composite sediment particles from the Hampshire Avon and the Rivers Exe and Culm. These samples were collected using the apparatus described by Woodward & Walling (1992). It is worth noting that we use the term aggregate to describe composite particles derived from catchment source materials (e.g. from soil and channel bank erosion) that enter the fluvial system in an aggregated form and retain that structure during transport. In contrast, flocs are composite particles that form within the channel zone due to various physical, biological and chemical processes (cf. Droppo *et al.*, 1997). Aggregates may also become parts of flocs and each may break up to produce smaller composite forms and discrete particles. The term composite particle affords a useful non-genetic term that includes all multi-component suspended particles and we do not attempt to differentiate between modes of formation in this paper. This sampling method preferentially collects sediment particles at the coarser end of the effective particle size distributions shown in Fig. 1 because of the short settling times involved in sample collection that prevent the masking of the filter paper by a veneer of fine sediment particles (Woodward & Walling, 1992). The clean filter paper mesh is clearly visible in the background of each of the micrographs and this demonstrates that artificial composite particles have not been created during the sampling process. Composite particles were present and readily identifiable across the surface of all the filter papers collected. Figure 2 shows composite particles that are made up of a range of constituent particle sizes including fine silts and clays which are important for the transport of sediment-borne substances because of their large surface areas (Horowitz, 1991). The largest composite particle shown in Fig. 2 is >80 μm across and has probably undergone some shrinkage during sample drying and coating. Such particles are clearly an important component of the suspended sediment load of the rivers shown in Fig. 1, although the effective particle size curve for the

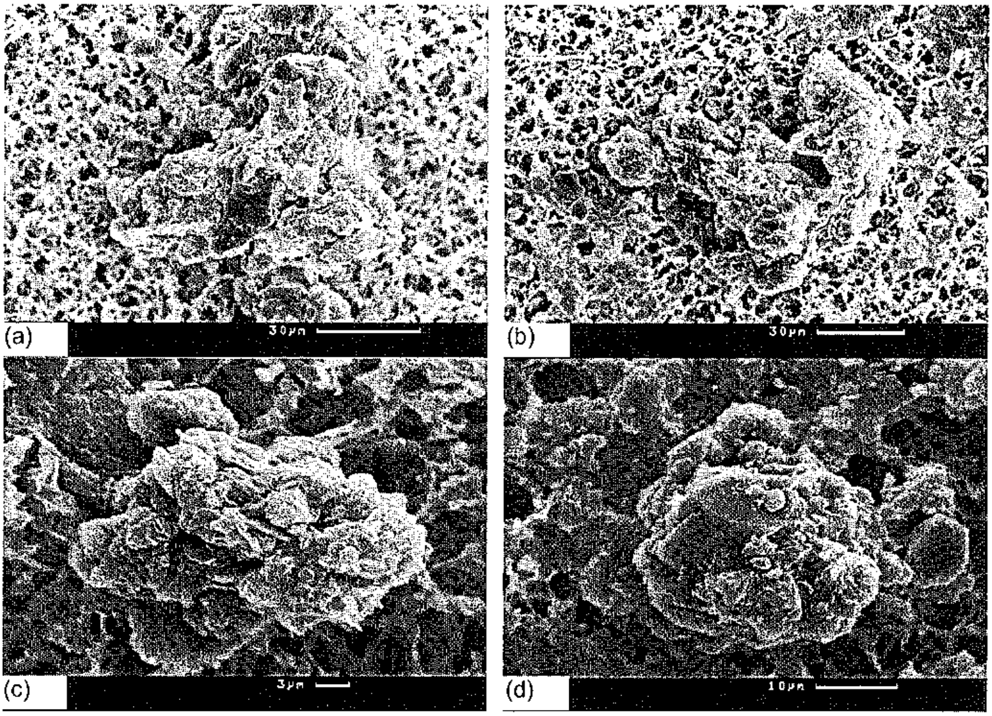
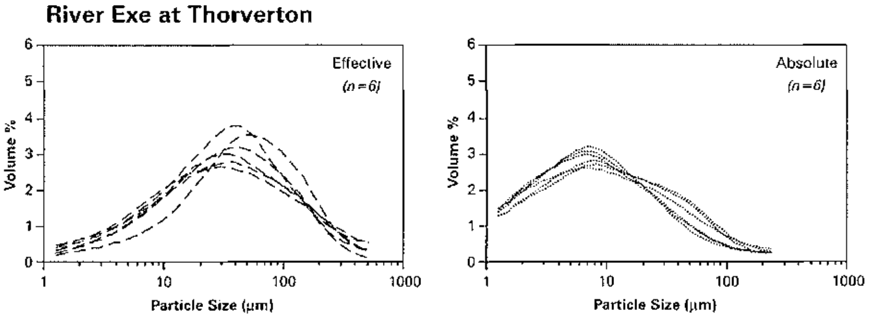


Fig. 2 Scanning electron micrographs of composite suspended sediment particles from three of the rivers shown in Table 1: (a) and (b) River Exe; (c) River Culm; (d) Hampshire Avon.

Warwickshire Avon at Stratford is much finer than the others and large (>63 μm) composite particles form a relatively minor part of this sample. The effective size distribution for the same river at Evesham is much coarser, with a significant proportion >100 μm (Fig. 1). The two samples were collected during different flood events but further work is required to determine whether this downstream coarsening in the effective size distribution is a feature of this system and whether it reflects in-stream flocculation processes or the input of larger composite particles from tributary sources or channel bank erosion.

Figure 3 presents six effective grain size distributions and their absolute equivalents from the River Exe at Thorverton and the River Culm at Rewe (Table 1). The absolute size distributions from the Culm are finer than those for the Exe with average median grain sizes of 5.9 μm and 9.1 μm respectively. The sand content of the Exe samples is also greater than that of the Culm samples and this is in good agreement with other absolute particle size data for suspended sediment from these catchments (Walling & Moorehead, 1987). The nature of the absolute size distribution is strongly controlled by catchment lithology, soil type and sediment delivery dynamics, including sediment source variations. The absolute curves for the Exe and Culm catchments display only limited temporal variability (Fig. 3) while the effective curves have median particle sizes ranging from 23.4 to 51.3 μm for the River Culm at Rewe (mean = 38.6 μm) and from 28.4 to 46.1 μm for the River Exe at Thorverton (mean = 35.6 μm).


River Exe at Thorverton

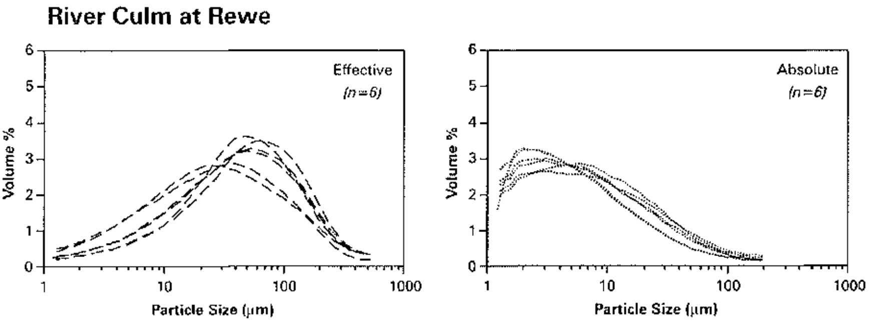

River Culm at Rewe

Fig. 3 Effective and absolute particle size distributions for samples of suspended sediment collected during a range of flow events at Rewe (River Culm) and Thorverton (River Exe). These data were obtained using a Malvern Mastersizer Laser Diffraction Particle Size Analyser after rapid transport to the laboratory.

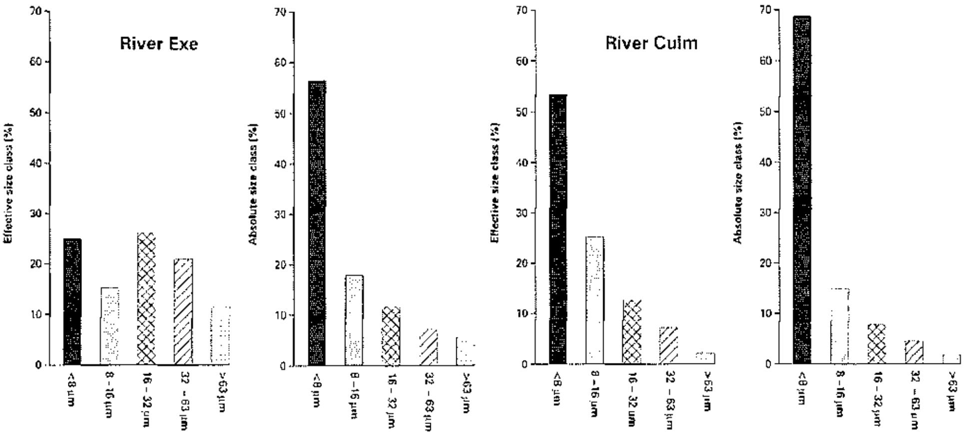


Fig. 4 Effective and absolute particle size distributions from the rivers Exe and Culm obtained using the water elutriation apparatus.

The data presented in Fig. 4 are derived from the water elutriation systems installed at the Thorverton and Rewe gauging stations. These data represent mean values based on 10 flood events at Thorverton and eight events at Rewe. The effective size distributions are based on the mass of sediment collected from the base of each of the sedimentation chambers (see Walling & Woodward, 1993). The equivalent absolute size distributions were computed from the absolute size characteristics of the sediment collected in each of the sedimentation chambers and weighted according to the mass of each sample (Walling & Woodward, 1993). Each of the effective size classes contains a significant clay component (Fig. 5) and this is supported by observations using SEM (Fig. 2). For the River Culm, the effective size classes >8 µm contain between 10 and 23.7% clay and this material exerts an important influence on the contaminant and nutrient loading of the composite particles (Droppo *et al.*, 1998). The effective size distributions derived from the WEA for the Exe and Culm display significant differences with the <8 µm class being dominant at Rewe and the 16–32 µm and 8 µm classes the most important at Thorverton (Fig. 4). Table 2 shows the proportion of discrete mineral particles present within the four largest effective classes that are finer than the lower size limit of that class. These data provide an estimate of the proportion of inorganic sediment incorporated into composite particles within the four coarsest effective size classes. The values for these rivers commonly exceed 70 or 80% and are, in fact, likely to be underestimates, because many of the particles within a class that are larger than the lower limit of that class will also be incorporated within composite particles (Walling & Woodward, 1993). It is not possible to obtain an equivalent estimate for the <8 µm

Table 2 The proportion of dispersed mineral particles (%) in each effective size class finer than the lower size limit of that effective size class. A typical example from each catchment is given.

River	Sampling station	Date of event	Effective size class (µm): 8–16	16–32	32–63	>63
River Culm	Rewe	29/11/92	74	58	66	81
River Exe	Thorverton	31/10/91	68	85	83	80.5

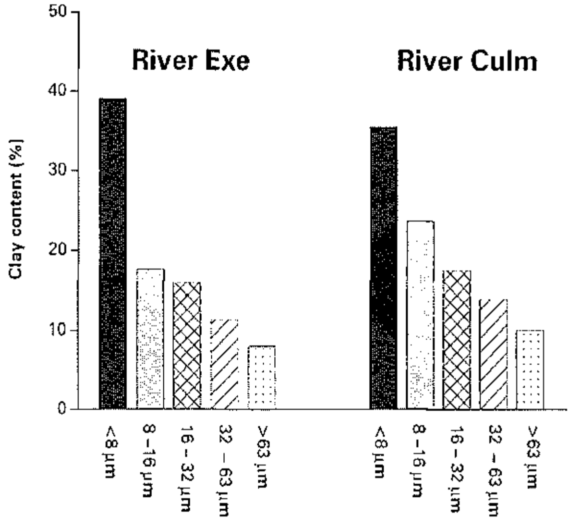


Fig. 5 The mean clay content of each of the effective size classes represented in Fig. 4. These data were derived from the absolute particle size distributions (chemically dispersed mineral fraction) of each of the effective size classes separated in the field by the water elutriation apparatus (cf. Walling & Woodward, 1993).

effective class, but it is reasonable to assume that composite particles finer than 8 µm are also important and the limited SEM data available support this view.

The elutriation data highlight the very significant role played by composite particles in suspended sediment transport in the study rivers and it is useful to consider the relative importance of large (>32 µm), medium (8–32 µm) and small (<8 µm) composite particles in the Exe and Culm basins (Fig. 6). In common with the particle size data derived from the instantaneous suspended sediment samples for these catchments shown in Fig. 3, the effective size data for the Exe at Thorverton display rather less temporal variability than those for the Culm at Rewe (Fig. 6) (Woodward & Walling, 1999). There are marked and systematic differences between the two basins and the eight flood events shown for the River Culm show effective size distributions that are significantly finer than the ten events shown for the River Exe. Large (>32 µm) composite particles account for between 26.4 and 41.1% of the suspended sediment load of the River Exe while the equivalent range for the River Culm at Rewe is 5.5–17.5% (Fig. 6). The inter-basin contrasts are not as marked for the effective size curves derived from instantaneous samples analysed using the Mastersizer shown in Fig. 3 and this may be partly explained by contrasts in the density of the largest composite particles (cf. Nicholas & Walling, 1996). Furthermore, the water elutriation apparatus classifies particles on the basis of hydraulic equivalence through sedimentation in water while the Mastersizer measures particle diameter using laser diffraction. Differences must also be expected between time-integrated samples collected over several hours and an essentially random selection of instantaneous samples collected over a range of flow conditions. Furthermore, the role of organic particulates in the suspended load has not been studied in detail in this context. Organic particulates can be sized by laser diffraction and may form an important part of the effective particle size distribution produced by the Mastersizer. However, this low

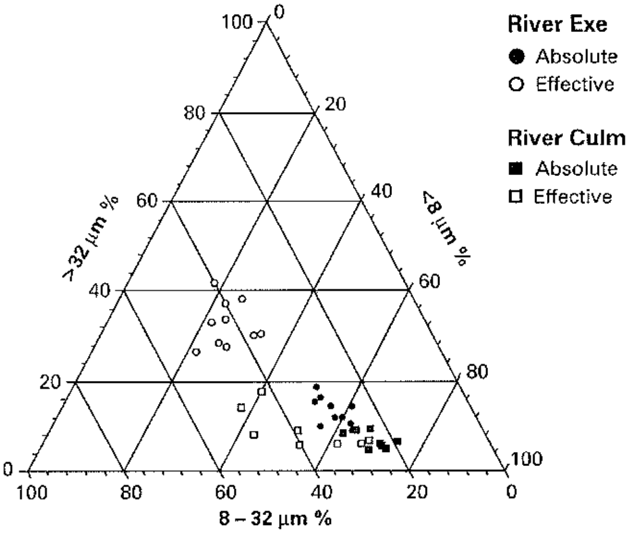


Fig. 6 A ternary plot of the water elutriation data for the Exe and Culm catchments to illustrate the degree of spatial and temporal variability in the occurrence of large (>32 µm), medium (8-32 µm) and small (<8 µm) composite particles, with the equivalent absolute classes provided for comparison.

density material will be classified on the basis of hydraulic equivalence in the WEA (particle shape is also important) and this may partly account for the importance of the <8 µm effective class in the River Culm WEA data (Fig. 4).

It is important to appreciate that all particle size measurement techniques are operationally defined and the different measurement principles employed should not be expected to produce the same results for identical samples (Horowitz, 1991). The density of composite particles is difficult to determine and the water elutriation apparatus is calibrated on the basis of Stokes' law (Walling & Woodward, 1993). The largest composite particles may be less dense than smaller composite particles and their settling velocities may not increase appreciably with particle diameter (Nicholas & Walling, 1996). The Malvern Mastersizer uses laser diffraction for size classification and this may account for the greater proportion of sediment in the >63 µm class which is evident using this method in comparison to the data obtained from the water elutriation apparatus (Figs 3 and 4). It may be possible to estimate composite particle density using SEM data, but the impact of particle desiccation and shrinkage during the SEM preparation process has not yet been quantified. Nonetheless, the SEM analysis provides a very valuable complement to the other techniques currently employed in the measurement of effective size and one means of validating the WEA data.

CONCLUSIONS

The data presented in this paper demonstrate that composite particles are an important feature of suspended sediment transport in lowland British rivers and the effective particle size distribution contrasts markedly with the equivalent absolute distributions derived from the dispersed mineral fraction at all of the sample sites. The effective particle size distributions obtained for instantaneous samples using the Malvern Mastersizer provide a very useful and rapid way of estimating the importance of composite particles in suspended sediment flux. This sampling strategy is useful for reconnaissance sampling over large areas in catchments where the database on effective size is limited or non-existent. However, longer-term studies in the Exe basin suggest that the time-integrated data produced by the water elutriation apparatus are to be preferred for estimating the role of composite particles in suspended sediment and nutrient and contaminant flux and for calibrating models of sediment transport and deposition (cf. Nicholas & Walling, 1996; Woodward & Walling, 1999).

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