Hydrobiologia **176/177**: 125–149, 1989.
P. G. Sly and B. T. Hart (eds) Sediment/Water Interaction.

The particle size characteristics of fluvial suspended sediment: an overview

D. E. Walling & P. W. Moorehead
Department of Geography, University of Exeter, Exeter, EX4 4RJ, UK

Key words: suspended sediment, particle size, ultimate and effective particle size, selective erosion and delivery, spatial and temporal variation

Abstract

The particle size characteristics of suspended sediment are of fundamental importance in understanding its role in a variety of environmental processes. Existing knowledge concerning the spatial and temporal variability of the grain size composition of suspended sediment is, however, relatively limited. At the global scale, major contrasts may exist between individual rivers in the calibre of their suspended load and this may be related to a number of controls including climate, catchment geology and basin scale. Any attempt to understand the precise relationship between the grain size characteristics of suspended sediment and those of its source material must also take account of the selectivity of erosion and delivery processes. A local case study undertaken by the authors in the 1500 km^2 basin of the River Exe in Devon, UK is used to illustrate the considerable spatial variability that may occur within a relatively small area and the complexity of the associated controls.

Available evidence concerning the temporal variability of the grain size characteristics of suspended sediment emphasises the diverse patterns of behaviour that may exist and the complexity of the controls involved. In some rivers the sediment may become coarser as flow increases, in others it may become finer, whilst in others it may exhibit a relatively constant grain size composition. Data from the local case study in the Exe basin are again used to highlight the considerable diversity in response to changing discharge that may occur within a relatively small area.

Any attempt to understand the dynamics of sediment movement through a river system must also take account of the potential contrast between the ultimate and effective particle size distribution of suspended sediment in response to aggregation. Results from the Exe basin study indicate that even in rivers with relatively low solute concentrations, almost an order of magnitude difference may exist between the median particle size associated with the ultimate and effective grain size distributions.

Introduction

The significance of the particle size characteristics of fluvial suspended sediment to its role in the transport of sediment-associated nutrients and contaminants and in sediment-water interactions has been emphasized by many workers (e.g. Allan, 1979; Forstner & Wittmann, 1981; Horowitz, 1985; Moore & Ramamoorthy, 1984). The particle size of mineral suspended sediment exerts a fundamental control over its mineralogy and geochemistry. Thus for example, the $< 2\ \mu$m fraction will be composed primarily of secondary silicate minerals, whereas quartz will dominate in the larger fractions. The specific surface area of sediment, which is a major control on its surface chemistry, also increases markedly with decreasing particle size (Fig. 1(a)), such that typical values for clay (20–800 m^2g^{-1}) are several orders of magnitude greater than those for silt and sand. Cation exchange capacity is in turn closely related to particle size (Fig. 1(b)) and the importance of particle size in influencing the heavy metal and contaminant content of both river and reservoir sediments is clearly demonstrated by Figs. 1(c) and 1(d).

A knowledge of the factors governing spatial and temporal variations in the particle size composition of suspended sediment is therefore of primary importance in developing an improved understanding of sediment-water interactions and interest in this topic must represent an important interface between the work of the hydrologist and fluvial geomorphologist and that of the geochemist. However, faced with a need to explain and account for the particle size composition of fluvial suspended sediment and its variation in space and time in order to assist the geochemist, the hydrologist and fluvial geomorphologist will encounter many uncertainties and problems. Much of their work has focussed on the overall magnitude of suspended sediment loads rather than their physical properties (cf. UNESCO, 1985). This paper attempts to review existing

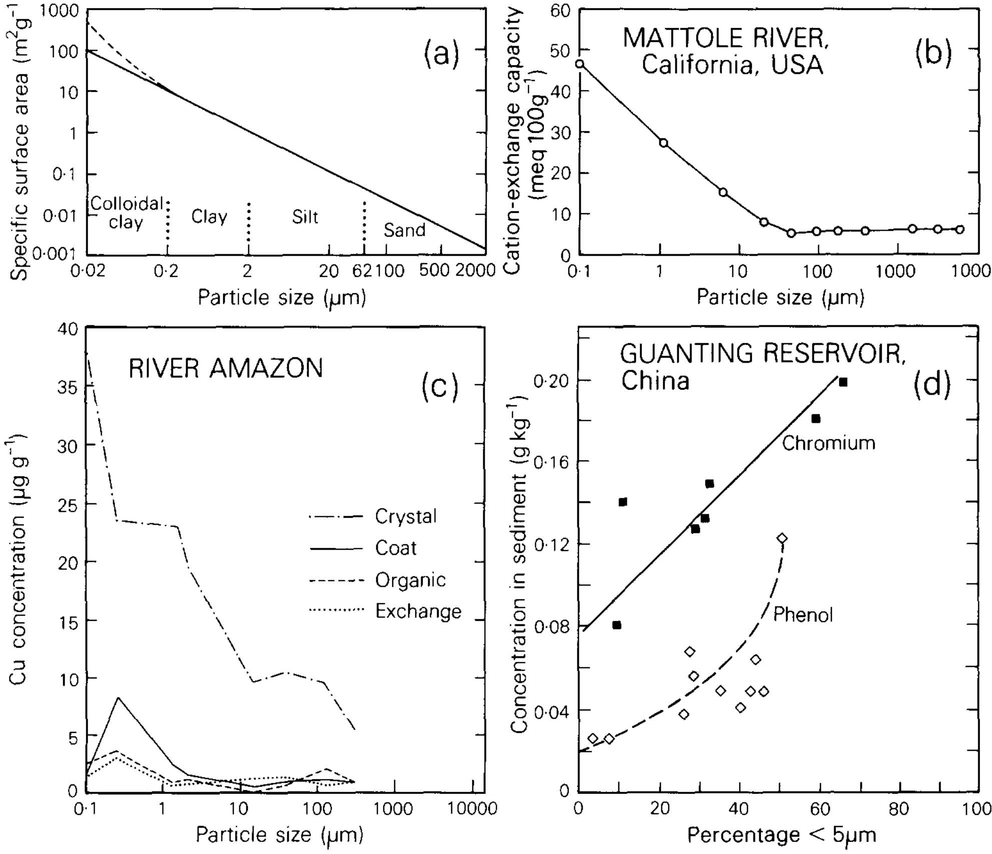

Fig. 1. The significance of the particle size composition of suspended sediment. (a) illustrates a typical relationship between particle size and specific surface area, (b) depicts the relationship between particle size and cation exchange capacity reported by Malcolm & Kennedy (1970) for suspended sediment from the Mattole River, California, (c) presents examples of the relationships between grain size and the metal content of suspended sediment reported by Gibbs (1977), and (d) illustrates the significance of particle size composition in influencing pollutant levels in reservoir sediment deposits (based on Zhang *et al.*, 1986).

knowledge of this important aspect of fluvial transport and to highlight several of the uncertainties involved.

Spatial variability in the particle size of suspended sediment

A global perspective

Although the availability of particle size data from the world's rivers is limited, existing information serves to emphasise the very considerable variability that exists at the global scale. Characteristic particle size distributions of suspended sediment from a sample of these rivers are presented in Fig. 2 to demonstrate the degree of variability involved. These evidence a range from the Barwon River in Australia where more than 80 percent of the suspended sediment is < 2 μm to the Huangfu River in the Peoples' Republic of China where more than 60 percent of the sediment is > 63 μm. The median particle size values for this sample of 10 rivers span a range of two orders of magnitude from < 1 μm to almost 100 μm.

Explanation of the variability evidenced in Fig. 2 must involve a number of factors, including the effects of climate, river basin lithology and delivery or transport processes. The coarse nature of the suspended sediment transported by the Huangfu River in the Peoples' Republic of China and the Limpopo River in Zimbabwe can, for example, be ascribed to the coarse loess deposits and the Kalahari sands which respectively mantle their basins. Conversely, the extremely fine suspended sediment transported by the Barwon River in New South Wales, Australia may be related to the deep chemical weathering and associated clay-rich soils which characterize its basin and to the inefficient sediment delivery system associated with the low gradients of the upstream area (cf. Olive & Rieger, 1986). Suspended sediment transported in the lower reaches of major rivers such as the Nile and Amazon could also be expected to be relatively fine due to the preferen-

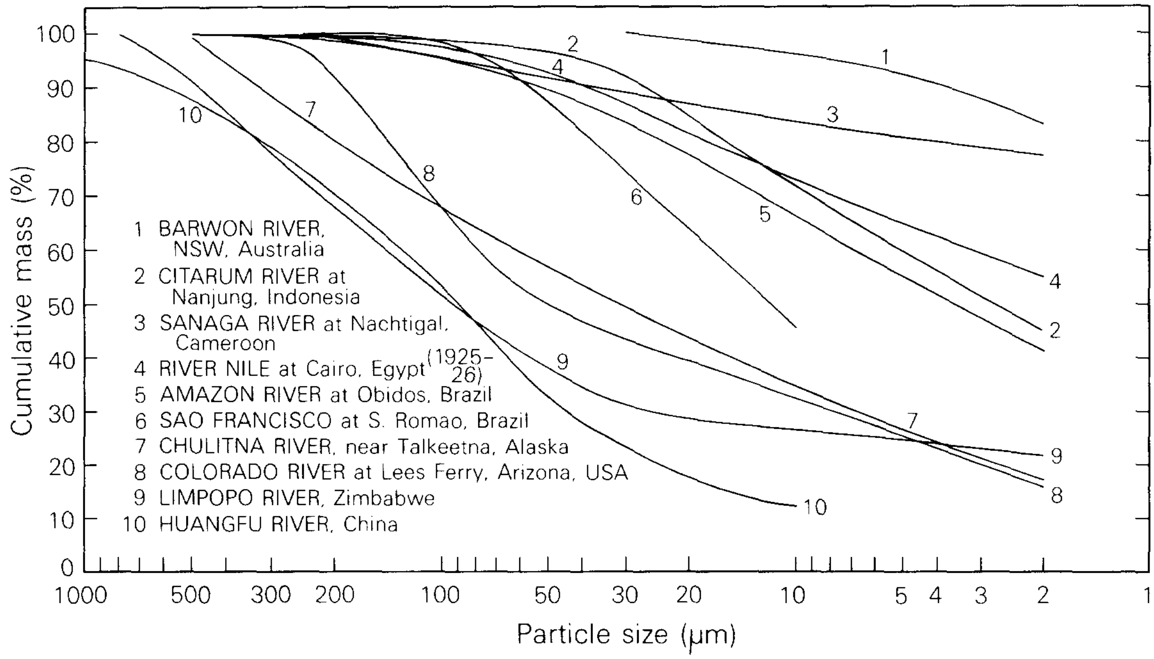

Fig. 2. Global variation in the particle size composition of fluvial suspended sediment. Characteristic particle size distributions for the individual rivers are based on data provided by Walker *et al.*, 1974; Soeharto, 1982; Nouvelot, 1969; Ball, 1939; Meade, 1985; Ward, 1980; Gong & Xiong, 1980; US Geological Survey data compilations and other unpublished data. The distributions generally relate to ultimate particle size data.

tial deposition of the coarser fractions during downstream transport.

Existing knowledge concerning the role of these and other factors in accounting for the considerable range of particle size evidenced by suspended sediment transported by the world's rivers may be briefly reviewed.

Climate and relief

Although many workers have pointed to the general importance of climate and relief in controlling fluvial denudation (e.g. Fournier, 1960; Strakhov, 1967) there has been little attempt to consider the potential influence of these factors on the particle size characteristics of fluvial suspended sediment. A notable exception is the work of the Soviet scientists Dedkov & Mozzherin (1984), who attempted to account for spatial variations in the median particle size of suspended sediment transported by rivers in the Soviet Union. These authors distinguished plains and mountain rivers and suggested that a general zonal influence was apparent within these two groups (Fig. 3). For plains rivers, Dedhov & Mozzherin (1984) cited a range of characteristic median particle sizes for individual geographical zones ranging from 150 μm in the tundra zone to less than 40 μm in the forest steppe and broadleaved forest zones. In the mountain regions of the USSR, the characteristic median grain size ranged from 64 μm in the steppe and forest-steppe zone to 37 μm in the subtropical steppe and semi-desert zones. This pattern was linked to the relative importance of channel and slope erosion in the various zones, with the latter generating finer sediments evidencing a lower degree of sorting. These results are heavily dependent upon the representativeness of the rivers included in each zone and a more rigorous analysis would clearly be necessary to distinguish the effects of climate from the influence of other factors such as geology and catchment scale. These effects could also include the relative importance and efficiency of chemical and mechanical weathering processes operating within a drainage basin. Furthermore, the limited degree of variability evident between the zones in Fig. 3 must be contrasted with the much greater range of median particle size values exhibited by the sample of rivers included in Fig. 2. This could suggest that factors other than climate are of greater importance in accounting for global variations in the particle size of suspended sediment.

Geology and soils

A priori reasoning must inevitably point to a close dependence of the particle size characteristics of the suspended sediment transported by a river on those of the soil and parent material within its drainage basin. The importance of the geology of a catchment in influencing the grain size characteristics of the material available for fluvial trans-

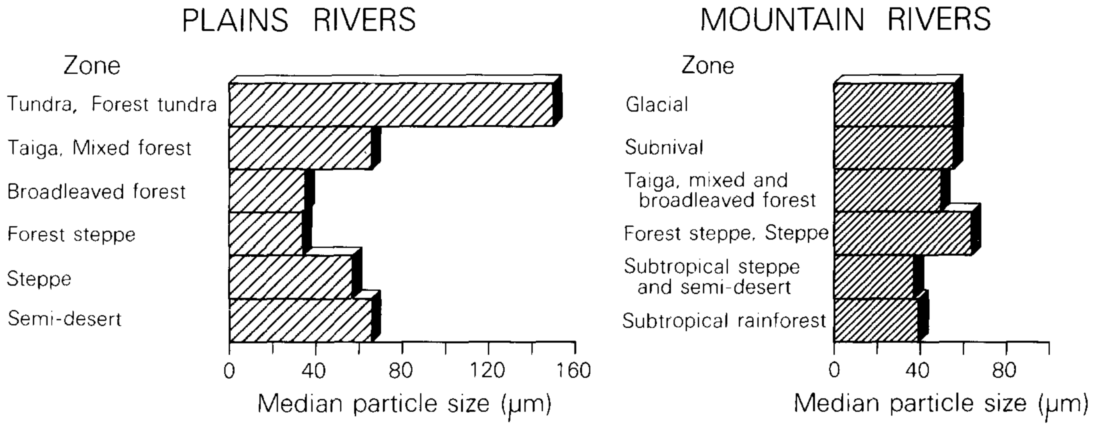

Fig. 3. The geographical zonation of the median particle size of suspended sediment in rivers of the USSR proposed by Dedkov & Mozzherin (1984).

port has already been indicated in accounting for the relative coarse size distributions associated with the Huangfu and Limpopo Rivers on Fig. 2. A further useful example which underscores the significance of this control is provided by the work of Ward (1980) who investigated the sediment yields of several rivers in Zimbabwe and their associated particle size characteristics. He provides data for four intermediate-sized rivers, the Gwai, the Hunyani, the Umsweswe and the Odzi which are located within a relatively small area, but which demonstrate markedly different grain-size characteristics (Fig. 4). Although there is some variation in mean annual rainfall between the catchments (570–950 mm), the contrasts are primarily a reflection of differences in catchment geology. The Hunyani and Odzi basins are underlain predominantly by granite, whereas the dominant lithology in the Gwai basin is sandstone. Both major lithologies are found in the Unsweswe basin, but the influence of the granite appears to be dominant.

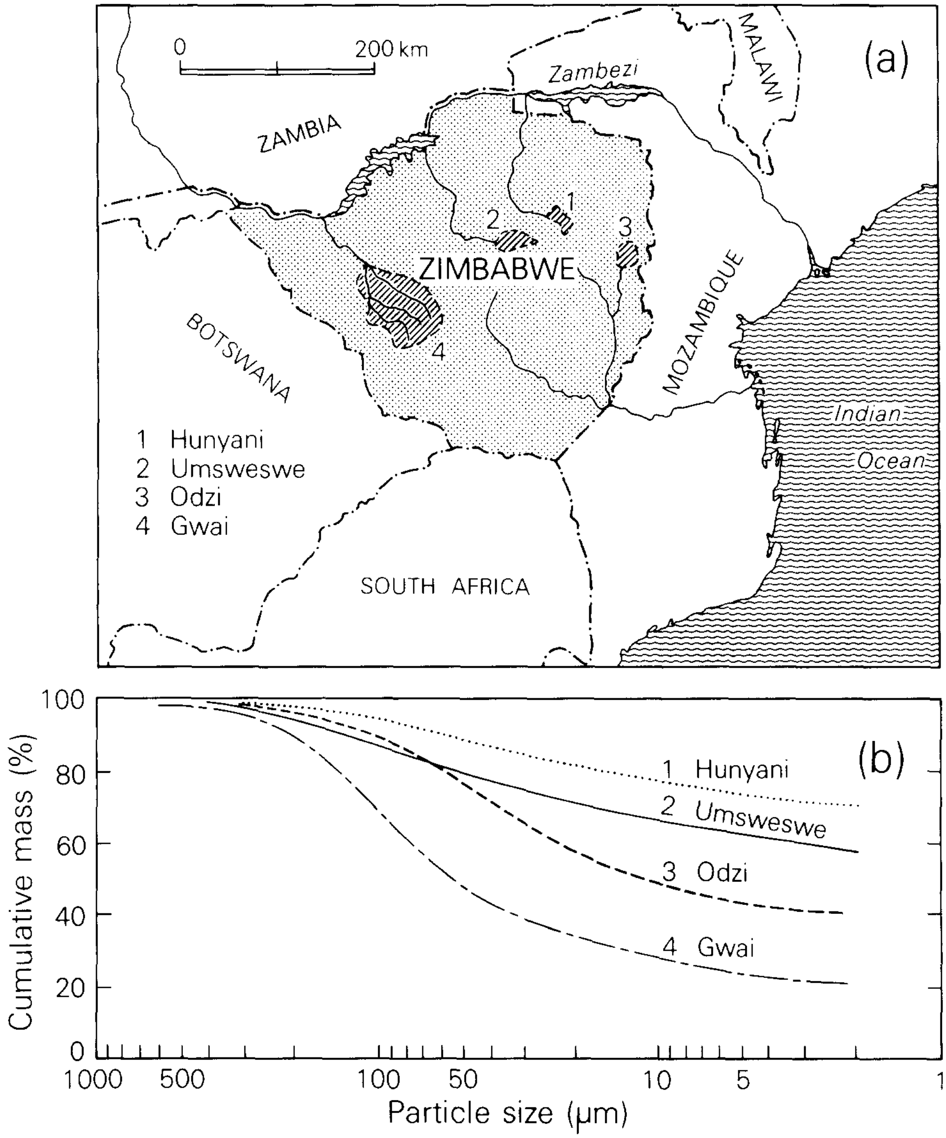

Fig. 4. A comparison of the characteristic particle size composition of suspended sediment from four Zimbabwe rivers. (Based on data reported in Ward, 1980).

Basin scale and selective deposition

As the scale of a drainage basin increases there will be increasing potential for transport processes to modify the particle size characteristics of sediment moving downstream through selective deposition of the coarser fractions. The significance of this mechanism in accounting for the relatively fine grained suspended sediment transported by the Nile at Cairo has already been cited, and merits further comment. Data on sediment transport by the Nile compiled by Ball (1939) indicate that during the period before the construction of the Aswan Dam, approximately 30 percent of the suspended sediment load passing the measuring station at Wadi Halfa was deposited before it reached Cairo, 1000 km downstream (Fig. 5a). This loss was associated with the preferential deposition of coarser particles. The median particle size of suspended sediment collected at Wadi Halfa was typically in the range of 5–10 μm and decreased to < 2 μm at Cairo (Fig. 5b). A somewhat similar situation is reported by Long & Qian (1986) for the Lower Yellow River in China. About 25 percent of the total suspended sediment load transported by this river is deposited in the 600 km reach between Sanmenxia and Lijin some 100 km from the delta. The majority of the deposited sediment is in the > 50 μm fraction and Long & Qian (1986) indicate that during the period 1955–1959, before the construction of the major reservoir at Sanmenxia, the magnitude of the > 50 μm fraction typically decreased from 20 to 13 percent between Sanmenxia and Lijin whereas the < 25 μm fraction increased from 54 to 64 percent.

Relating sediment and source material characteristics

In small- and intermediate-sized river basins, the particle size characteristics of suspended sediment will inevitably reflect the grain size of the eroded source material to some degree. However, it must be recognised that the precise relationship between the particle size characteristics of suspended sediment and those of the soils and other sediment sources within a drainage basin will be influenced by the selectivity of the erosion and transport processes. Existing evidence clearly demonstrates that suspended sediment will commonly be enriched in the finer fractions and depleted in the coarser fractions relative to the source material. Such enrichment is, for example, apparent in Fig. 5 which compares the proportions of clay, silt and sand in suspended sediment

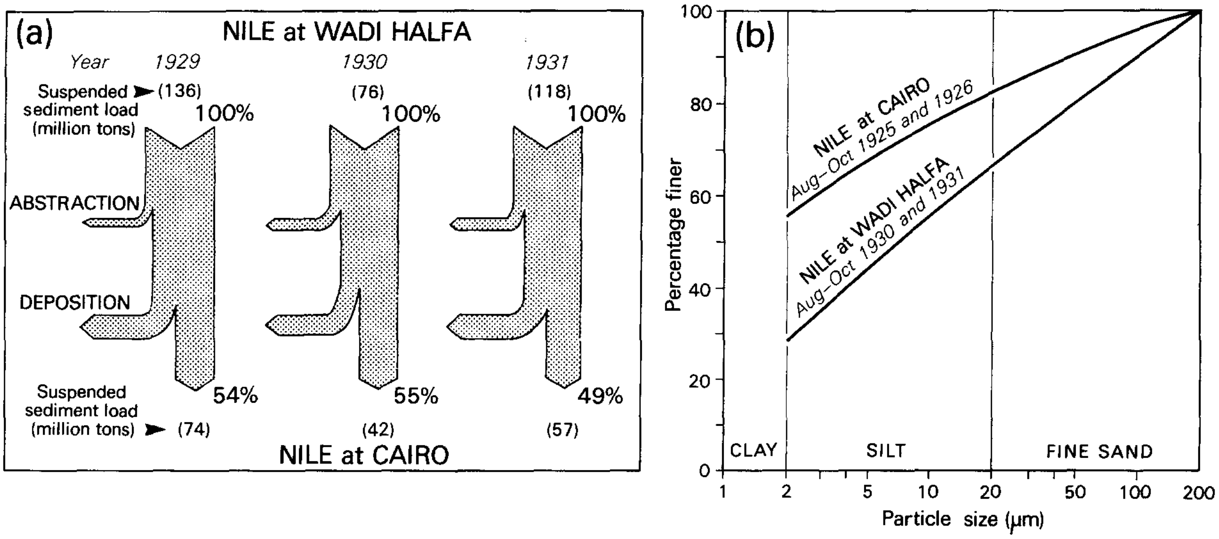

Fig. 5. Reductions in the suspended load of the River Nile between Wadi Halfa and Cairo and associated changes in the average particle size distribution. (Based on data reported by Ball, 1939).

samples collected by the US Geological Survey from four small basins, with equivalent information on the soils based on their textural classification. The composition of the sediment still reflects soil character, since the proportion of sand is directly related to the sandiness of the soil, but, equally, it can be seen that there is considerably less variation in the sediment properties between the four basins than in their soil texture. Further examination of the relationship between the properties of suspended sediment and those of the source material must consider, firstly, the effects of selective erosion in preferentially mobilising the finer fractions and, secondly, the preferential deposition or loss of the coarser fraction during the transport or delivery of sediment from its source to the basin outlet.

Selective erosion

Available information from erosion plots and similar experiments, which enable the composition of eroded material to be compared with that of the source material, suggests that mechanisms of selective erosion are of relatively minor importance in accounting for the contrasts between the particle size characteristics of sediment and source material noted above. Foster *et al.* (1985), for example, suggest that the high enrichment

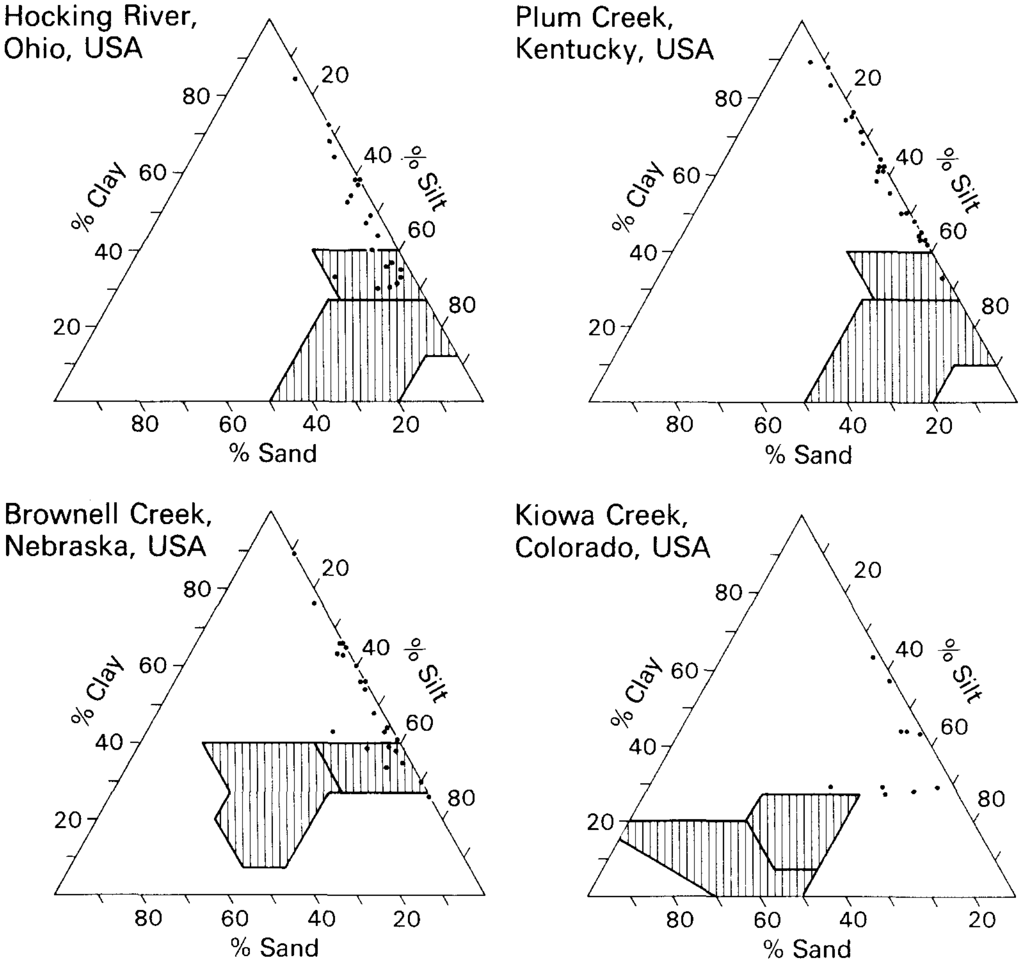

Fig. 6. Comparison of the particle size composition of suspended sediment and soils for four small drainage basins in the USA. The textural classes of the dominant soils are denoted by shaded zones. (Based on data contained in Flint, 1972; Anttila, 1970; and Mundorff, 1964, 1966).

ratios frequently associated with sediment eroded from agricultural land result from the selectivity of the transport and deposition processes rather than the detachment processes. Similar conclusions indicating that the grain size composition of eroded soil may not differ markedly from that of the matrix soil have been presented by Young & Onstad (1976).

Some workers have, however, presented data indicating that selective erosion may be significant in certain situations. Meyer *et al.* (1975), for example, report the results of erosion plot studies of Russell silt loam at Purdue, Indiana, USA which indicate that whereas the sediment eroded from a plot that was susceptible to rilling exhibited grain size characteristics similar to those of the original soil, that eroded from a rill-resistant plot, where inter-rill areas provided the dominant source, was significantly enriched in silt-sized particles and depleted in sand. Studies undertaken on erosion plots at Ibadan, Nigeria reported by Lal (1976) also demonstrate significant contrasts between the grain size composition of eroded sediment and the original soil, with the former commonly exhibiting enrichment in both the clay and silt fractions. Lal (1976) also demonstrated that the degree of enrichment varied according to slope angle (Fig. 7(a)) and in response to differences in land use practice (Fig. 7(b)), further emphasing the complexity of the relationship between the particle size characteristics of the eroded sediment and those of the original soil.

Selective delivery

In considering the effects of selective delivery in influencing the relationship between the particle size characteristics of suspended sediment and source material, attention must be directed to the potential for selective losses of the coarser fractions in a wide range of depositional environments associated with the transport of sediment from its source to the measuring point. In a recent review of sediment delivery dynamics, Walling (1983) indicated that in most circumstances only a relatively small fraction of the sediment eroded within a drainage basin will reach its outlet, and it is inevitable that such losses will be associated with selective deposition. The influence of overbank depositional losses in the lower reaches of a river in causing an increase in the relative importance of the finer fraction has already been cited using examples from the River Nile and the Yellow River. Similar selective deposition could be expected to occur throughout the channel network. Furthermore large depositional losses will commonly be expected during the downslope transport to the stream of sediment eroded from hillslopes. The selectivity of such depositional losses is largely responsible for the contrasts between the particle size characteristics of soils and suspended sediment demonstrated in Fig. 6 for several small drainage basins in the USA.

Any attempt to account for, or model, the selectivity of downslope transport processes must consider a wide range of controls reflecting the character of the soil, surface condition and local topography, which will influence depositional processes. Additional complexity is introduced by the fact that eroded sediment may move as aggregates rather than as primary particles (e.g. Young, 1980). Thus in a situation where deposition of primary clay is unlikely to occur, significant quantities of clay may nevertheless be deposited if this is incorporated within larger aggregates.

Foster *et al.* (1985) report results from a variety of soil types in the USA which indicate that only about 25 percent of the primary clay in a soil will be represented as primary clay in eroded sediment, the remainder being incorporated into larger aggregates. These authors present a series of empirical relationships which may be used to predict the likely composition of eroded sediment at the point of detachment, in terms of both primary particles and aggregates, from information on the texture of the matrix soil. Fig. 8(a) illustrates a hypothetical example of the application of these relationships to a matrix soil composed of 25 percent clay, 60 percent silt and 15 percent sand. Foster *et al.* (1985) have also employed hydraulic sediment transport and deposition equations to route eroded sediment downslope by particle size classes (primary and aggregates) and to compute changes in the dis-

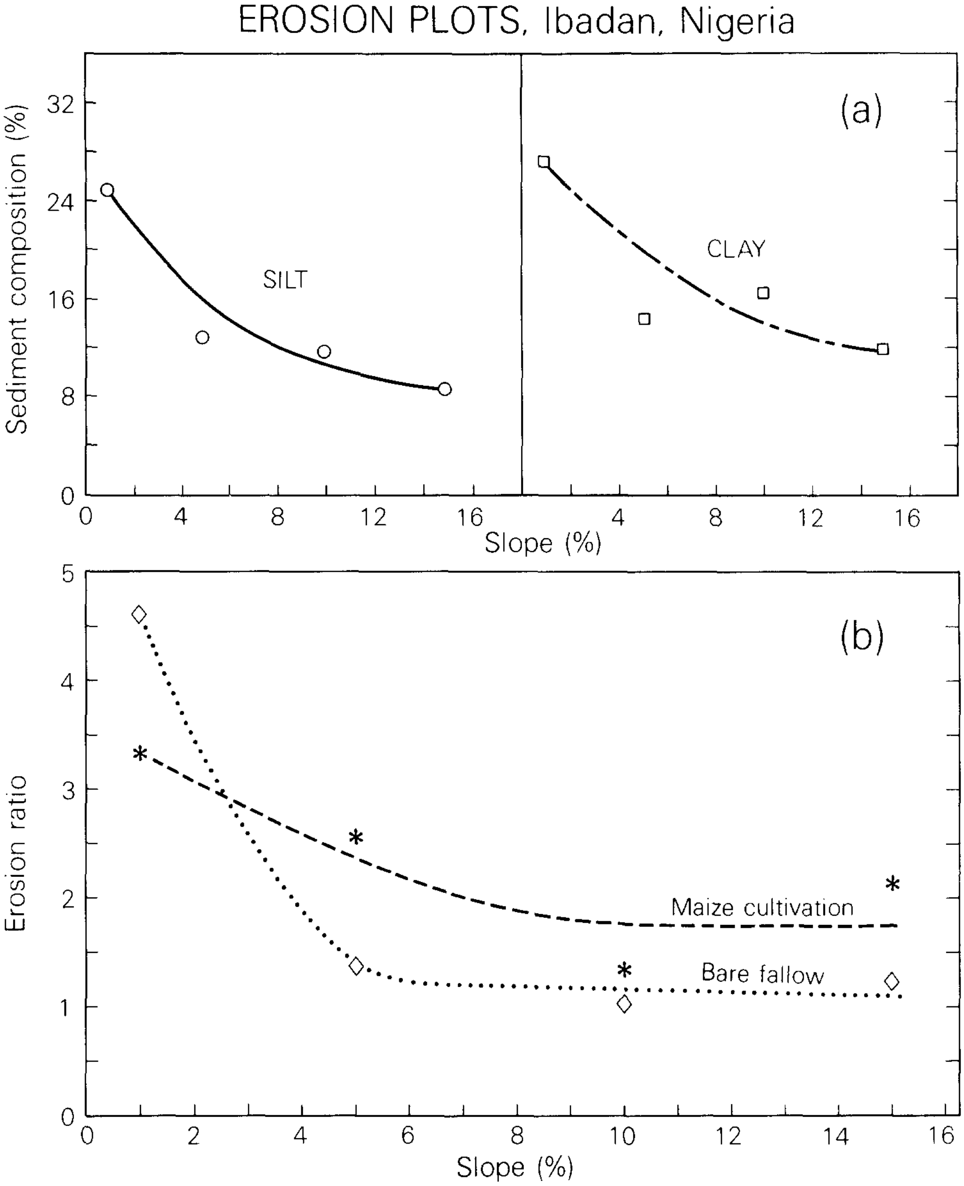

Fig. 7. The influence of slope angle and land use on the particle size composition of eroded sediment reported by Lal (1976). The erosion ratio is defined as the ratio of the proportion of silt + clay in the eroded sediment to that in the field soil.

tribution of these particle size classes. These changes in the particle size distribution were subsequently used to calculate the enrichment of the transported sediment relative to the matrix soil. In this case enrichment ratios were expressed in terms of the ratio of the specific surface area of the primary particles in eroded sediment to that of the matrix soil.

These relationships and transport equations were used by Foster *et al.* (1985) to simulate erosion and sediment delivery from field-sized areas and to produce a series of schematic relationships between sediment delivery ratio (the ratio of the amount of sediment reaching the watershed outlet to the total amount eroded) and the enrichment ratio of the transported sediment (based on specific surface area) for several matrix soils. These relationships are depicted in Fig. 8(b). Although schematic, they clearly demonstrate the significance of the sediment delivery

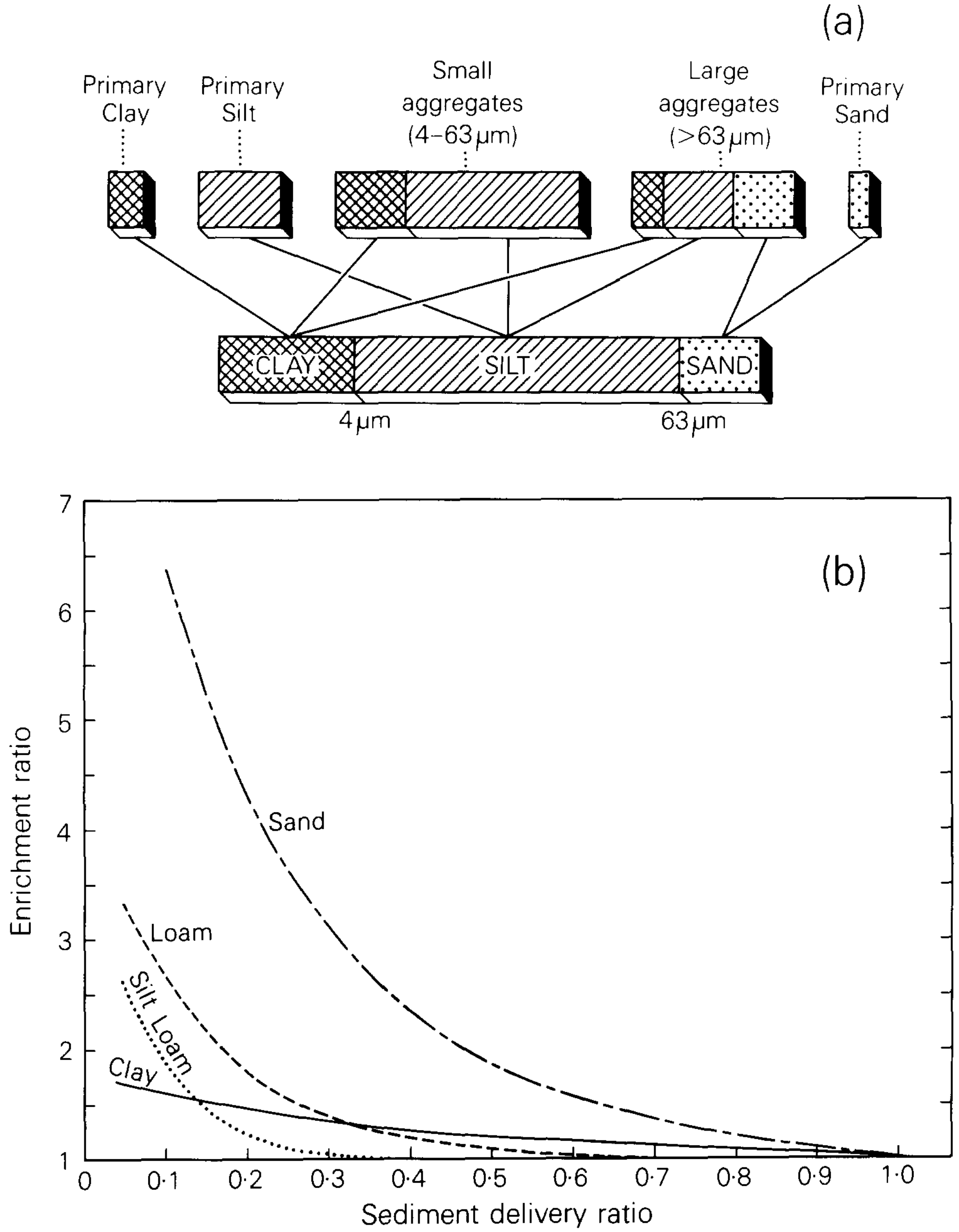

Fig. 8. Schematic examples of the aggregate content of eroded soil (a) and of the relationship between sediment delivery ratio from field-sized areas and enrichment ratio for soils of varying texture (b), based on relationships proposed by Foster *et al.* (1985). (In this example the enrichment ratio expresses the ratio between the specific surface area of transported sediment and that of the original soil).

process in influencing the relationship between the particle size characteristics of suspended sediment and source material. Maximum enrichment is associated with sandy soils, since they are poorly aggregated and little of the clay is lost by deposition during transport. Conversely, sediment from soils with a high clay content evidences little enrichment since a large proportion of the clay is associated with aggregates and is therefore liable to deposition.

A local case study

Additional evidence of the extent of spatial variation in the particle size characteristics of suspended sediment and the controlling factors can be introduced by considering the results of a local study undertaken by the authors within the 1500 km^2 basin of the River Exe in Devon, UK. This basin embraces a considerable diversity of physiographic conditions (Fig. 9) and samples of suspended sediment were collected over a wide range of flows from eight sites (Table 1) in order to investigate the degree of spatial variability in their particle size distributions. In all cases, the suspended sediment samples contained only small proportions of sand and the sand fraction rarely exceeded 10 percent. Comparison of the particle size distributions for the individual sites has therefore focussed on the detailed information available for the < 63 μm fraction. Fig. 10 presents characteristic particle size distributions (chemically dispersed mineral fraction) for each

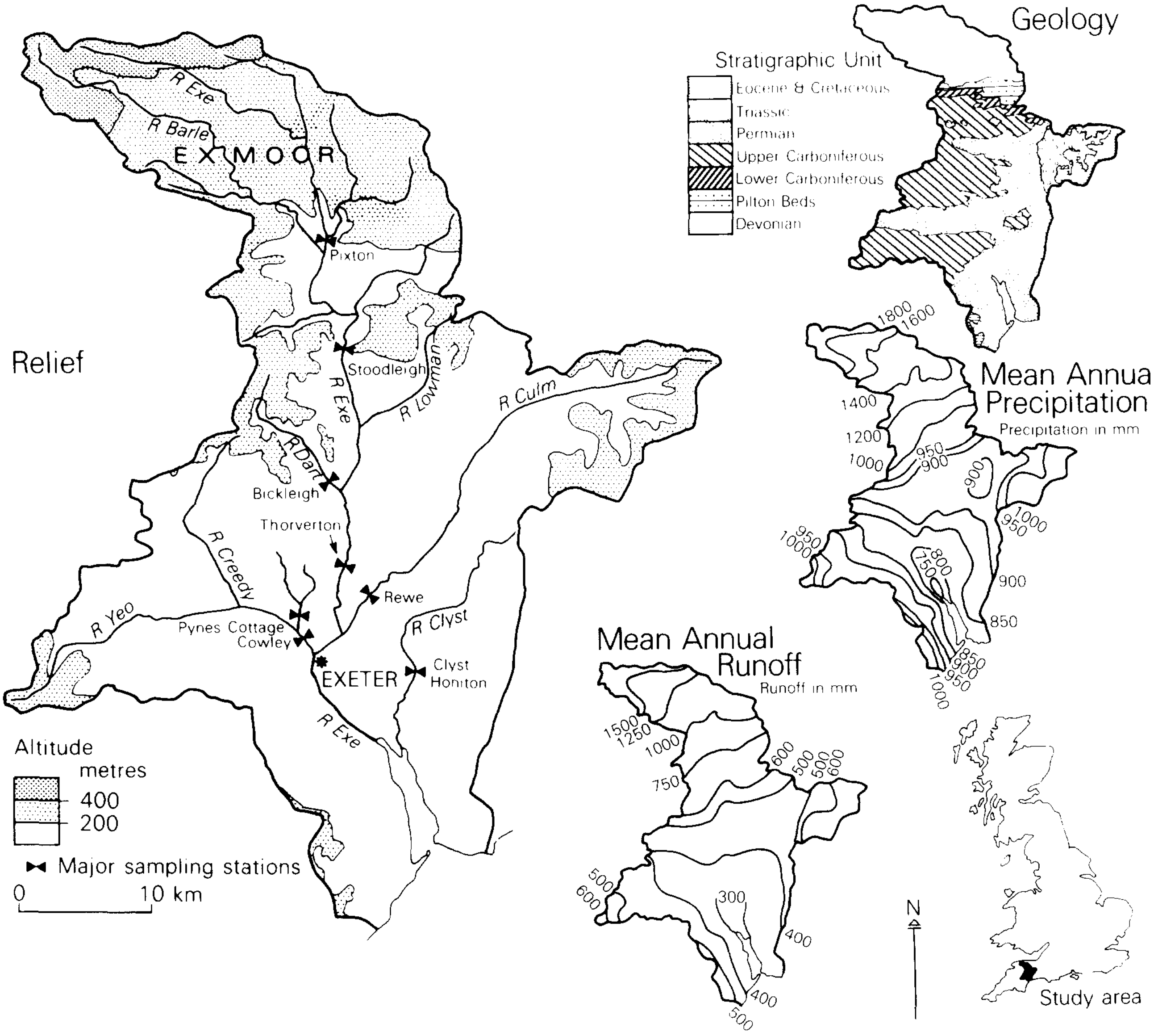

Fig. 9. The Exe basin and the network of measuring sites.

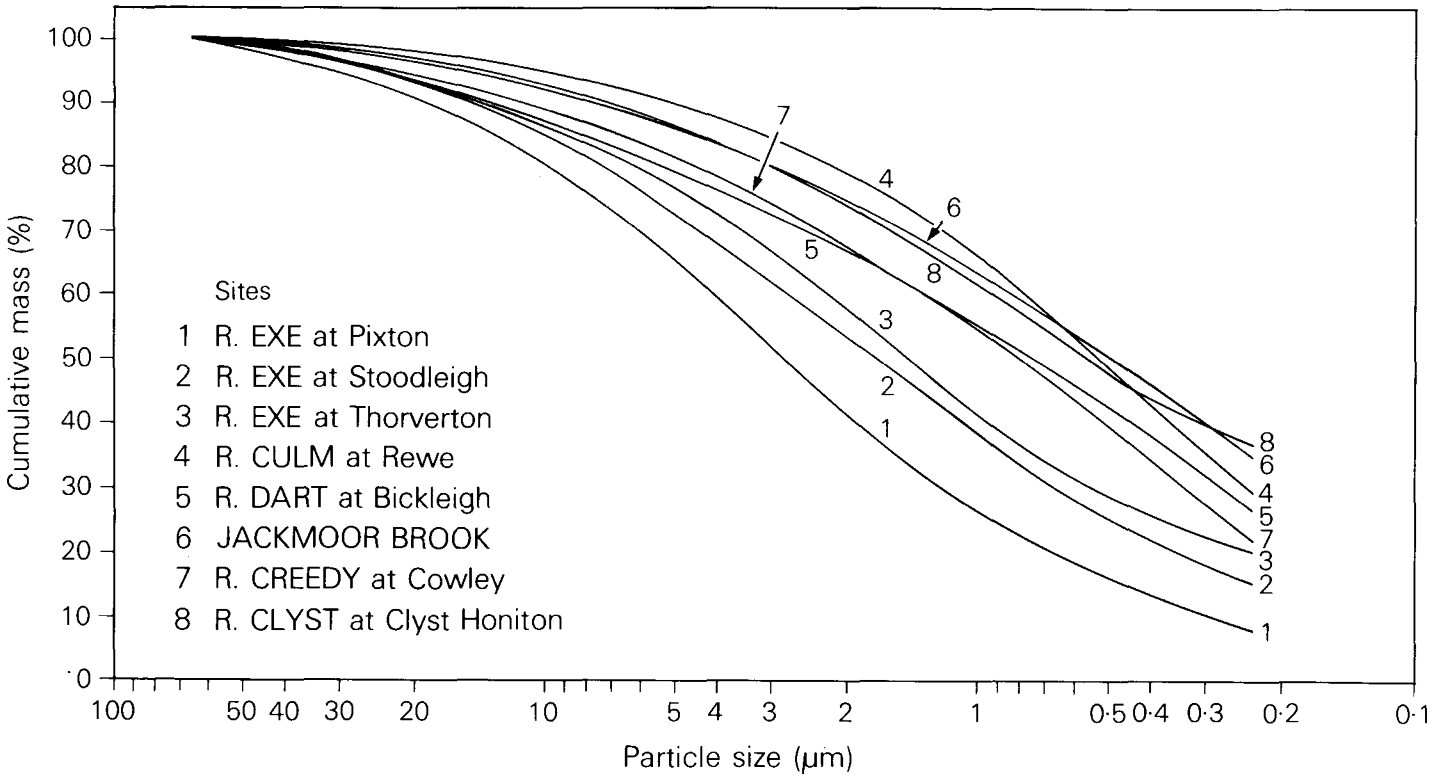

Fig. 10. Average particle size distributions for the < 63 μm fraction of suspended sediment collected at the eight sampling sites in the Exe River basin.

Table 1. Measuring sites in the Exe basin shown on Fig. 9.

Site no.	River and location	Drainage area (km²)
1	River Exe at Pixton	160
2	River Exe at Stoodleigh	422
3	River Exe at Thorverton	601
4	River Culm at Rewe	273
5	River Dart at Bickleigh	46
6	Jackmoor Brook	9.8
7	River Creedy at Cowley	262
8	River Clyst at Clyst Honiton	98

of the eight sites. Although not evidencing the same degree of variability as embraced by the sample of rivers represented in Fig. 2, these curves nevertheless highlight the considerable spatial variation that may exist within a relatively small area. Median particle sizes (d_{50}) range over nearly an order of magnitude from approximately 0.5 to 3.0 μm.

Much of the variation between the sites apparent from Fig. 10 can be accounted for by a geological control. Sediment from site 1, which drains an area underlain exclusively by Devonian strata (sandstones, gritstones and slates) is considerably coarser than that from site 5 which is derived from a basin underlain entirely by Carboniferous rocks (sandstones and shales). Sediment from both of these sites is in turn coarser than that associated with sites 6 and 8 whose upstream basins are developed almost exclusively on less resistant Permian outcrops (sandstones, breccias and marls). The distributions for sites 2, 3 and 7, which receive sediment from two or three of these major rock types plot consistently at appropriate intermediate positions.

The influence of selective delivery can also be discerned in Fig. 10, where it is superimposed onto the basic geological control discussed above. The very fine suspended sediment collected from site 4 (River Culm at Rewe) partly reflects a geological control, since a large part of the basin is underlain by Permian rocks. However, a recent study reported by Walling *et al.* (1986) has shown how sediment collected from a site at Woodmill, 13 km upstream of Rewe, is significantly coarser (Table 2) and more similar to that from sites 5 and 7. This difference was accounted for by conveyance losses associated with floodplain inundation and deposition in the 13 km reach between the two sites. These losses are associated with preferential deposition of the coarser fractions so that the sediment collected at Rewe is considerably finer than that sampled at Woodmill.

The influence of selective delivery processes in controlling the particle size characteristics of suspended sediment transported by rivers in the study area is further demonstrated by Fig. 11. This compares the mean particle size characteristics of suspended sediment (chemically dispersed mineral fraction) from four measuring sites with those of typical source materials (i.e. surface soil and channel bank material) from their upstream catchment areas. The inherent spatial variability of source material properties inevitably introduces problems into any attempt to characterise such material by a single distribution and the data presented in Fig. 11 must therefore be viewed as highly generalised. Comparison of the grain size distributions of source material and suspended sediment for the individual rivers indi-

Table 2. A comparison of the mean particle size characteristics of suspended sediment collected from the gauging stations of Woodmill and Rewe (based on Walling *et al.*, 1986).

Site	Particle size fractions (% total)				
	< 2 μm	2–6 μm	6–20 μm	20–63 μm	> 63 μm
Woodmill (upstream)	68	15	9	4.5	3.5
Rewe (downstream)	80	12	5	1.5	1.5

cates the degree to which the sediment is enriched, in fines or depleted in its coarser fractions. Enrichment ratios for individual particle size classes plotted in Fig. 11 have been calculated as the ratio of the proportion of a particular particle size fraction in suspended sediment to that in the source material.

The importance of floodplain deposition in accounting for the very fine suspended sediment collected from the River Culm at Rewe is further

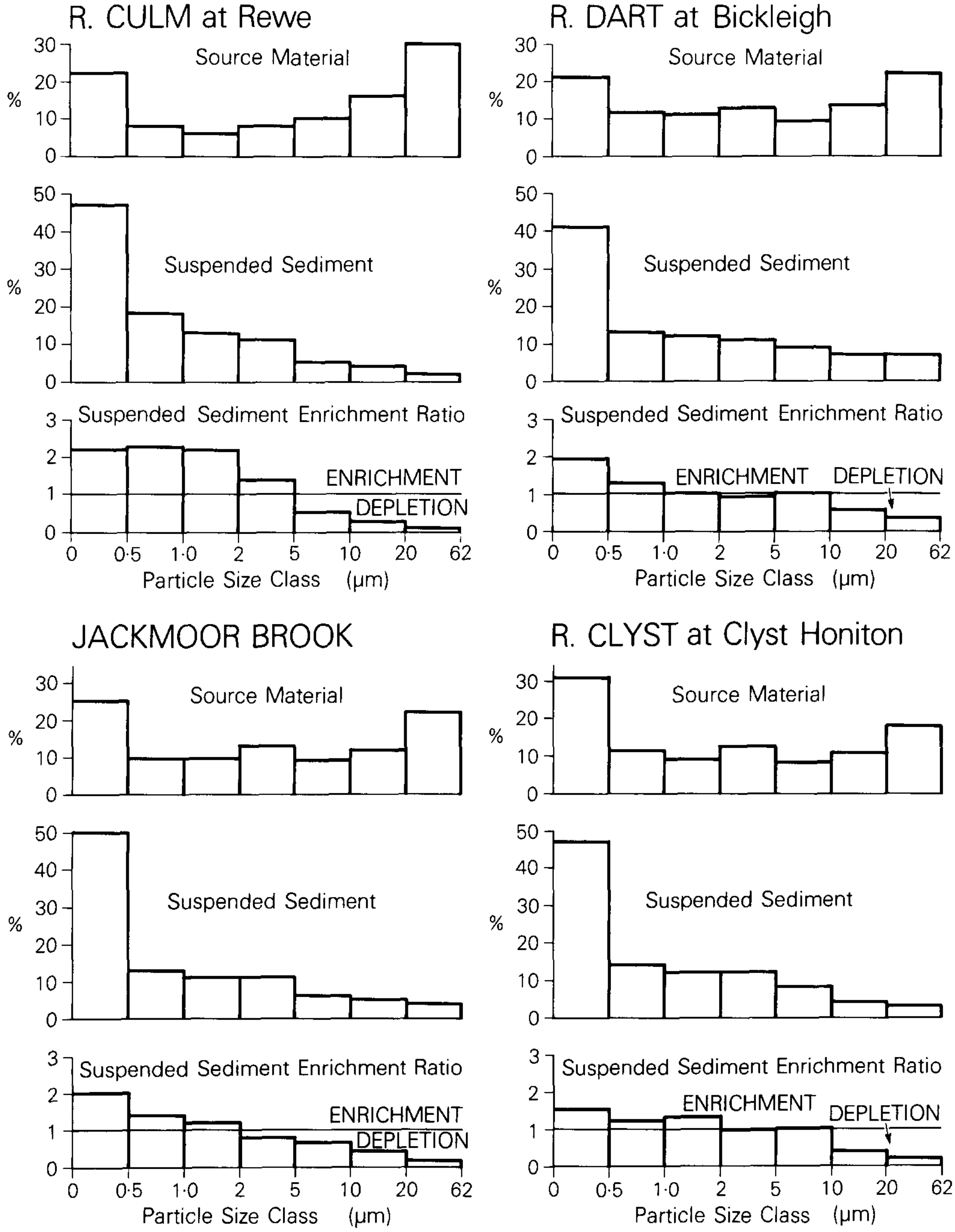

Fig. 11. Comparison of typical particle size distributions for the < 63 μm fraction of source material and suspended sediment for four of the measuring sites. Enrichment ratios have been calculated for individual size fractions as the ratio of the proportion of that size fraction in the suspended sediment to that in the source material.

emphasised by the high degree of enrichment evident for this site in Fig. 11 for all fractions below 5 μm. The enrichment is considerably greater than that for the other sites where floodplain conveyance losses in the upstream reaches are less significant. Considering the other three measuring sites illustrated in Fig. 11, the influence of selective delivery in causing enrichment of fines is least marked in the case of the River Dart at Bickleigh and progressively increases in the Jackmoor Brook and the River Clyst. This trend is consistent with existing knowledge concerning the efficiency of sediment delivery systems. The basin of the River Dart evidences much steeper slopes and channel gradients than the catchments of the Jackmoor Brook and the River Clyst. In turn, the more subdued topography, the greater drainage area and the more extensive floodplain development in the Clyst basin could cause this catchment to have the least efficient delivery system and therefore the most pronounced enrichment of fines.

Temporal variability in the particle size characteristics of suspended sediment

A review

The grain size characteristics of the suspended sediment transported by a river can clearly be expected to vary temporally in response to variations in water discharge and other envrionmental variables. Traditionally, hydrologists and geochemists have reasoned that water discharge will exert a dominant control, that the increased shear velocities associated with increased discharge will permit the transport of larger particles, and that a positive relationship will therefore exist between water discharge and the magnitude of the coarse fraction or the median particle size (cf. Horowitz, 1985). If however, it is accepted that the suspended sediment load of a river is commonly a non-capacity load and is therefore supply controlled, this view must be questioned. If the particle size characteristics of sediment supplied to a river by slope processes remain essentially constant, then no relationship with flow may exist. Equally, where the erosion dynamics of a drainage basin are such that slope erosion (fine sediment) becomes increasingly dominant over channel erosion (coarse sediment) during major storm events, or the area experiencing erosion expands into areas with finer source materials during these events, a negative relationship between water discharge and the proportion of coarse sediment or the median particle size may exist. Furthermore, where seasonal variations in erosion processes and source areas occur, such as in areas experiencing floods generated by both spring melt and summer storms, seasonal variations in sediment character may override any relationship with discharge.

A review of avaible empirical data indicates that rivers indeed exhibit considerable variety in the response of the particle size characteristics of their suspended sediment loads to increasing discharge (Table 3). Whilst cases where the coarser fractions assume increasing importance as discharge increases dominate, examples where the finer fraction increases or where little or no change in the particle size distribution occurs are also evident. Fig. 12 illustrates in more detail contrasting examples of rivers where suspended sediment becomes either coarser or finer as water discharge increases, or remains essentially uniform in size over a wide range of flows. Similarly, Fig. 13 presents three examples of contrasting behaviour of median particle size. The independent variables involved in the relationships depicted in Fig. 13 (i.e. total concentration, water discharge and sediment discharge) vary, but each example essentially reflects the trend associated with increasing flow. In the case of the Niobrara River in Nebraska reported by Colby & Hembree (1955) there is almost an order of magnitude difference between the relatively high median particle size associated with periods of low sediment discharge and the much lower values occurring during periods of high sediment discharge. These authors ascribed this trend to the increasing importance of sediment derived from slope sources during times of high sediment discharge.

Other studies reported in the literature describe

Table 3. Some examples of relationships between the particle-size characteristics of suspended sediment and water discharge.

River	Response to increasing discharge	Author
Eel River, California, USA	Proportion of sand increases and proportion of clay decreases	Brown & Ritter (1971)
Rio Puerco, New Mexico, USA	Mean particle size increases	Nordin (1963)
Upper Tees, UK	Mean grain size increases during floods	Carling (1983)
Scott Run, Virginia, USA	Proportion of sand increases and proportion of clay decreases	Vice *et al.* (1969)
River Clyde, Scotland	Mean and median particle size remain relatively constant	Fleming & Poodle (1970)
Niobrara River, Nebraska, USA	Median particle size decreases at high sediment discharges	Colby & Hembree (1955)
Lower Kansas River, Kansas, USA	Proportion of clay and silt increases	Mundorff & Scott (1964)
Blue Ridge region, Georgia, USA	Proportion of clay-size material increases	Kennedy (1964)

rivers where the pattern of variation of the particle size composition of suspended sediment is dominated by a seasonal influence on sediment supply rather than a simple relationship with flow magnitude. This situation may be particularly significant in areas where the annual flow regime includes periods of high discharge generated by both spring snowmelt and summer rainfall. Ongley *et al.* (1981) for example, report the case of Wilton Creek, Ontario, Canada where suspended sediment transported during the spring was considerably coarser than that transported during the summer and fall. These authors accounted for this seasonal contrast in terms of the dominance of channel sources in spring and of slope sources during the summer and fall. Skvortsov (1955) describes a somewhat similar pattern for the Rion River in the USSR. This river flows to the eastern coast of the Black Sea and its suspended sediment evidences a maximum clay content during the period November to February, minimum levels during the months of March to May and intermediate values during the remaining part of the year (June–October). This pattern was related to seasonal variations in the zone contributing to the sediment yield within this relatively large (ca. 13000 km^2) basin.

A local case study

As in the discussion of spatial variation in the particle size characteristics of suspended sediment, evidence from a local case study undertaken by the authors in the Exe basin, Devon, UK can be usefully introduced to further demonstrate the potential complexity of temporal variations in sediment composition. Fig. 14 presents plots of the relationships between the percentage clay and sand content of suspended sediment and water discharge at the time of sampling for the eight study sites (Table 1). In the nearly all cases discharge exerts a substantial influence on particle size composition, but the variability in the trend of these relationships within this relatively small area is striking. In the case of the River Exe at Pixton, Stoodleigh and Thorverton, the sand content of suspended sediment increases with water discharge whilst the clay content decreases. The reverse trend of decreasing sand and increasing

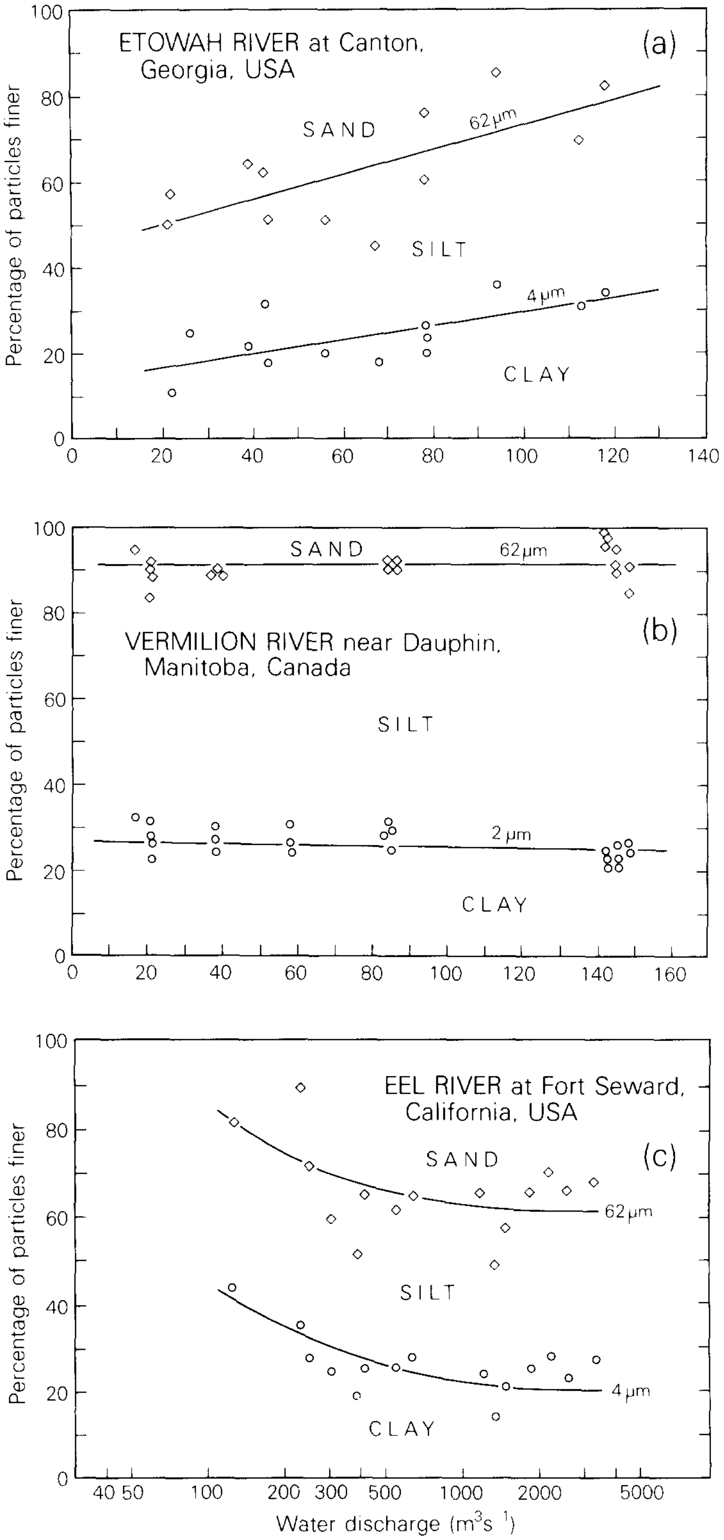

Fig. 12. Contrasting examples of the response of the particle size composition of suspended sediment to changing discharge (Based on data presented by Kennedy (1964), Environment Canada (1975), and Brown & Ritter (1971).

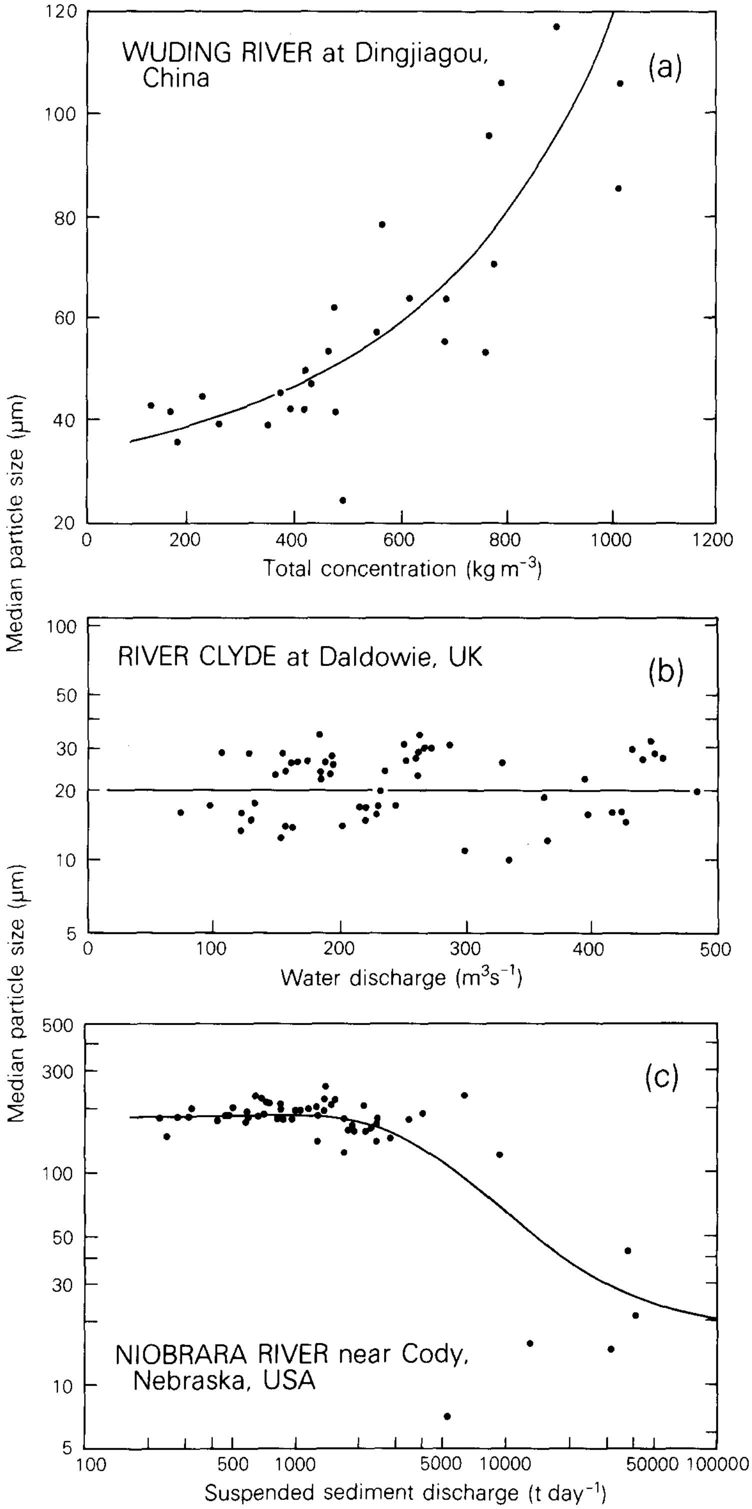

Fig. 13. Contrasting examples of the respons of the median particle size of suspended sediment to changing flow conditions or sediment transport. (Based on data presented by Long & Qian (1986), Fleming & Poodle (1970) and Colby & Hembree (1955)).

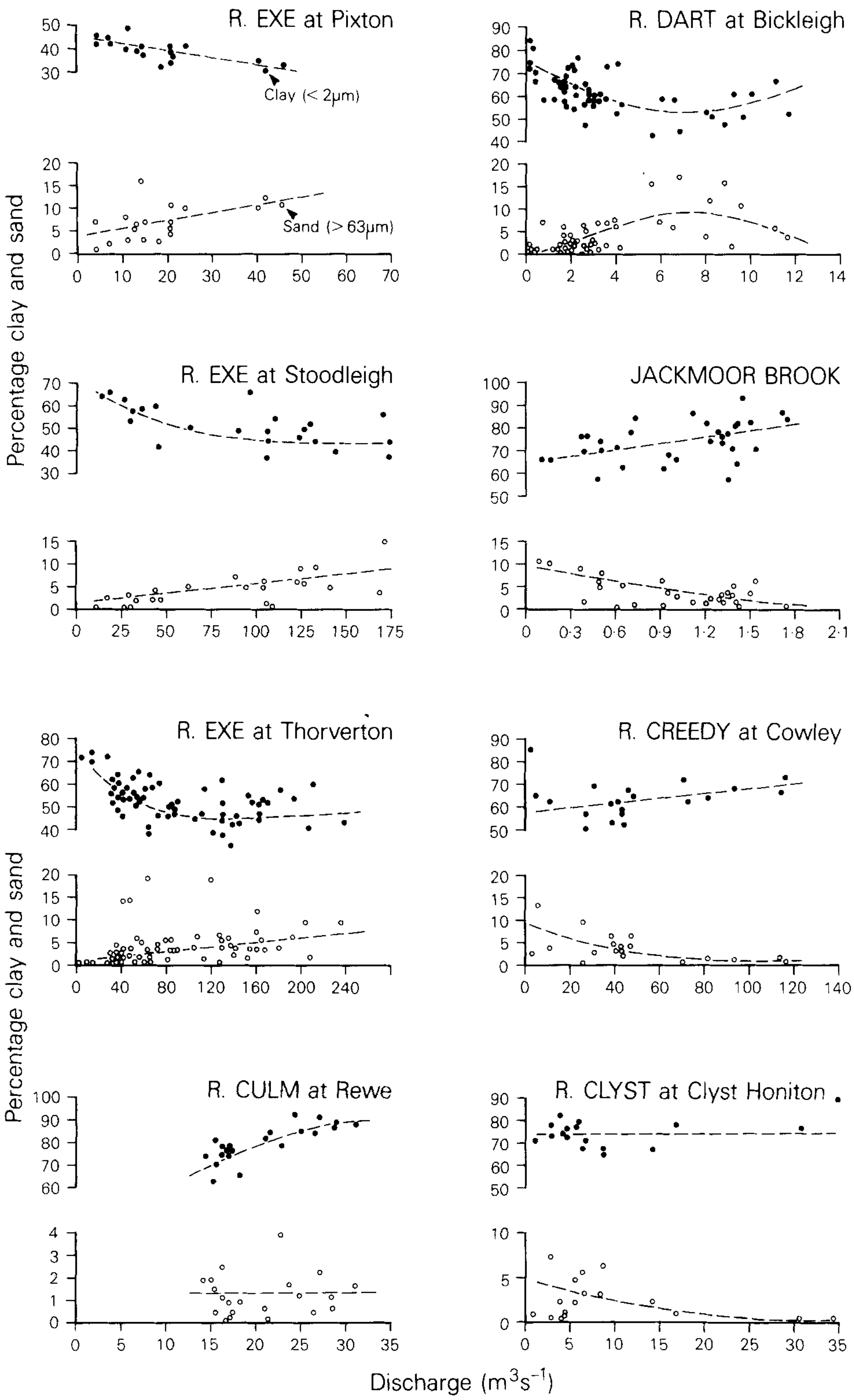

Fig. 14. Relationships between the clay and sand content of suspended sediment and water discharge at the time of sampling for eight measuring sites in the Exe basin.

clay content is found for the River Creedy at Cowley and the Jackmoor Brook. In the River Culm at Rewe, clay content increases with water discharge but the small sand content remains essentially constant over the range of discharge represented. Conversely, clay content stays relatively constant whereas sand content decreases with increasing discharge for the River Clyst at Clyst Honiton. Finally the River Dart at Bickleigh introduces a more complex relationship where the tendency for clay content to decrease and sand content to increase as discharge increases is reversed at higher flows. Virtually all forms of the relationship between discharge and particle size composition of suspended sediment that have been reported in the literature are represented within this 1500 km^2 basin.

Explanation of the various trends depicted in Fig. 14 must account for the two contrasting trends of firstly, increasing sand and decreasing clay content and, secondly, decreasing sand and increasing clay content, as water discharge increases. As noted above, a basic hydraulic control reflecting the increased turbulence or shear velocities occurring at high flows can explain the increased sand transport and reduced proportion of clay. The reverse trend could be accounted for in terms of either the erosional behaviour of cohesive (fine-grained) material, wherein increased flow velocities possess a greater capacity for entrainment of fine-grained material (cf. Hjulstrom, 1935) or of dynamic contributing areas within the basin. In the latter case, expansion of the areas contributing surface ruunoff and sediment to the streams during times of increased flow could result in either reduced delivery efficiency, and therefore a preferential loss of the coarse fraction, or the inclusion of areas providing greater reserves of fine sediment because of a difference in soil type or a lower frequency of erosion and sediment removal (cf. Walling & Webb, 1982). The marked increase in clay content evident at high discharges for the River Culm at Rewe must also reflect the impact of floodplain inundation and the associated preferential deposition of the coarser fraction. More detailed investigations are, however, required to substantiate these suggestions, to account for the existence of contrasting patterns in different basins and to explain the various hybrid patterns of response depicted in Fig. 14.

Effective versus ultimate particle size

The context

The preceding discussion of the particle size characteristics of suspended sediment and of source materials has focussed on traditional particle size data, namely that relating to the chemically dispersed mineral fraction. Such data may be referred to as ultimate particle size data since they relate to the discrete particles comprising the sediment. There is, however, an increasing body of evidence which suggests that a considerable proportion of the fine-grained suspended sediment in a river may be transported as aggregates rather than as discrete particles. In such circumstances it is clearly important to also consider what Ongley *et al.* (1981) have termed the effective particle size distribution of the sediment since this will govern its behaviour in the river. For example, the fall velocities of any aggregates may be considerably greater than those of the constituent discrete particles and the former rather than the latter will control the transport and deposition processes.

The potential contrasts between the ultimate and effective particle size distribution of suspended sediment have been recognised in many studies by drawing attention to differences between the results of laboratory analysis undertaken on chemically dispersed sediment and on sediment dispersed in native water (cf. Guy, 1969). Fig. 15, for example, illustrates the results of some analyses of the particle size distribution of suspended sediment transported by the Euphrates River at Tabqa in Syria reported by Sundborg (1964). Here, the distributions associated with sediment dispersed in natural river water are considerably coarser than those obtained using chemically dispersed sediment. In the more extreme case of the samples with the higher suspended sediment concentration (8814 mg l^{-1})

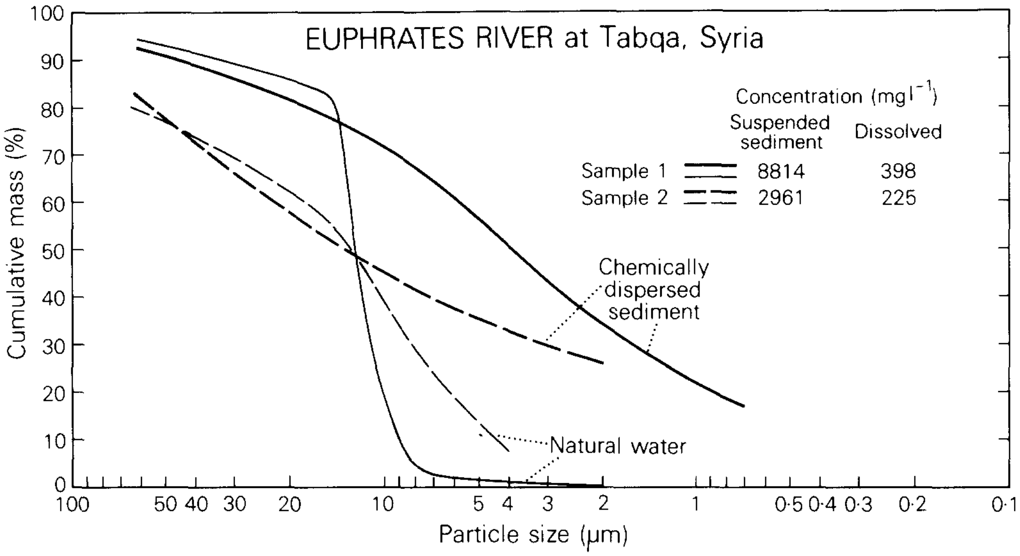

Fig. 15. Contrasts in the particle size composition of chemically dispersed suspended sediment and of suspended sediment in natural river water reported by Sundborg (1964) for the Euphrates River.

collected on 10 June 1963, the distribution for the chemically dispersed sediment indicated a clay ($< 2\ \mu$m) content of approximately 35 percent whereas the measurements undertaken on sediment in natural Euphrates water had a zero clay content. In comparing these and other similar distributions it must, however, be recognised that the effective particle size data are based on the measured fall velocities of the aggregates and relate to their 'equivalent spherical diameters' rather than their actual size.

In the case of this example from the Euphrates, the high incidence of aggregates was ascribed by Sundborg (1964) to the high salinity and high sediment concentrations. Guy (1969) has also emphasised that aggregation may be a common feature in rivers with high salinity, and he suggests that the incidence of aggregation may be of minimal importance in rivers with low dissolved solids concentrations or relatively high sodium concentrations. Recent work (e.g. Walling & Kane, 1984) does, however, suggest that important contrasts between ultimate and effective particle size distributions may exist even in rivers with low solute levels. In view of the non-linear relationship between particle size and fall velocity, an order of magnitude difference between the median particle size of the ultimate and effective particle size distributions, as described by Walling & Kane (1984), could result in an increase in equivalent fall velocities by two orders of magnitude. Such an increase could have very important implications for depositional processes (cf. Sundborg, 1956).

A local case study

Considerable uncertainty surrounds the selection of a method for measuring the effective particle size characteristics of suspended sediment since these essentially relate to *in situ* conditions within the river channel (cf. Walling & Kane, 1984). However, the authors' experience suggests that on-site measurements undertaken immediately after sample collection using a bottom withdrawal sedimentation tube technique (cf. Owen, 1976) provide one means of overcoming many of the problems involved and of obtaining a meaningful representation of the effective grain size distribution. It must, however, be recognised that the data obtained again relate to the equivalent spherical diameters of the aggregate particles involved rather than the actual size of these aggregates.

Fig. 16 compares the mean effective particle size distributions obtained at these seven sites with the equivalent mean curves for the ultimate particle size distributions. In both cases the sand fraction has been included, but it must be recognised that, whereas the ultimate grain size curves are based on a large number of samples, only a limited number of effective particle size determinations were available for each site. In spite of this limitation it is clear that very considerable contrasts exist between the effective and ultimate grain size distributions for all rivers, despite the low solute concentrations that characterise this area (30–300 mg l^{-1} TDS). In all cases there is a difference of almost an order of magnitude between the median particle size of the two distributions. Although the effective grain size distributions for the seven sites exhibit a similar relative ranking to those for the absolute particle size, contrasts exist in the degree of difference between the two curves at individual sites (Fig. 17). Minimum contrasts occur at sites 1 and 3, whereas the maximum contrasts occur at sites 4 and 5. Further work is in progress to elucidate the factors controlling the degree of contrast between the two distributions at a given site, but existing ideas suggest that both the particle size composition (ultimate) of the suspended sediment and its organic matter content exert a significant effect. The influence of aggregation in causing contrasts between the two curves is at a maximum at those sites with a relatively large clay fraction and a relatively high organic matter content.

Further work is also required to determine the mechanisms involved in particle aggregation and to evaluate the relative importance of in-stream processes. The presence of aggregates may reflect both secondary aggregation processes occurring in the stream itself or the survival of primary soil aggregates during the process of erosion and transport of sediment to the stream. One indication of the significance of the aggregation evident in Fig. 16 and 17 to sediment transport in the study area is provided by a study of floodplain deposition currently being undertaken along the lower reaches of the River Culm (Walling *et al.*, 1986). Measurements of the suspended sediment load and its grain size composition obtained from the River Culm at Rewe (Site 4, Fig. 9) have been compared with equivalent measurements for a site at Woodmill 13 km upstream (cf. Table 2). These

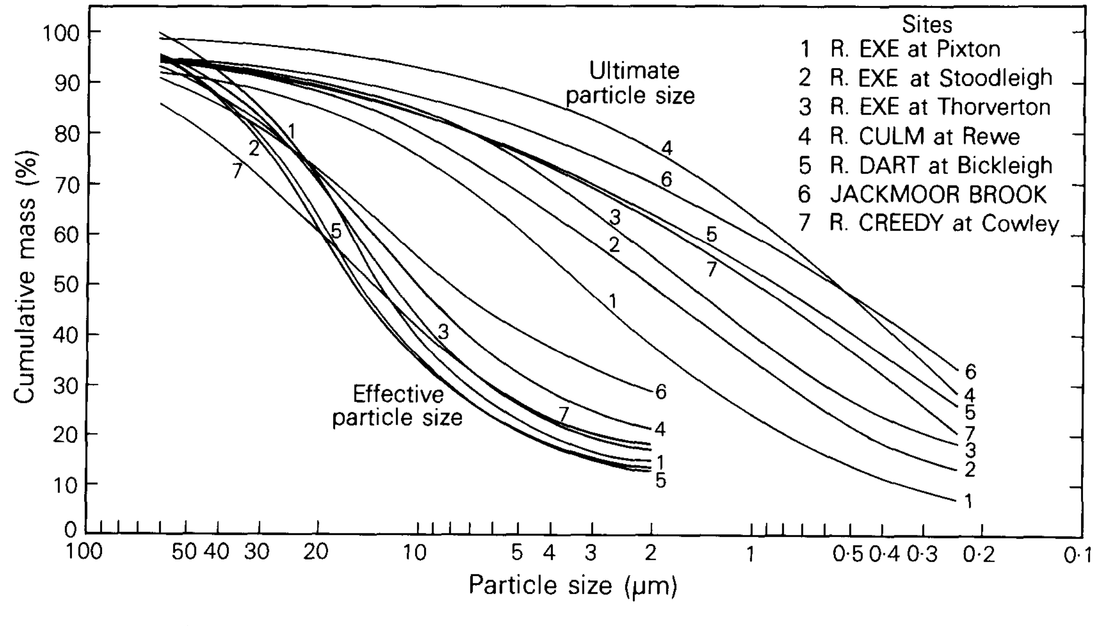

Fig. 16. A comparison of the ultimate and effective particle size distributions of suspended sediment collected from seven measuring sites in the Exe basin.

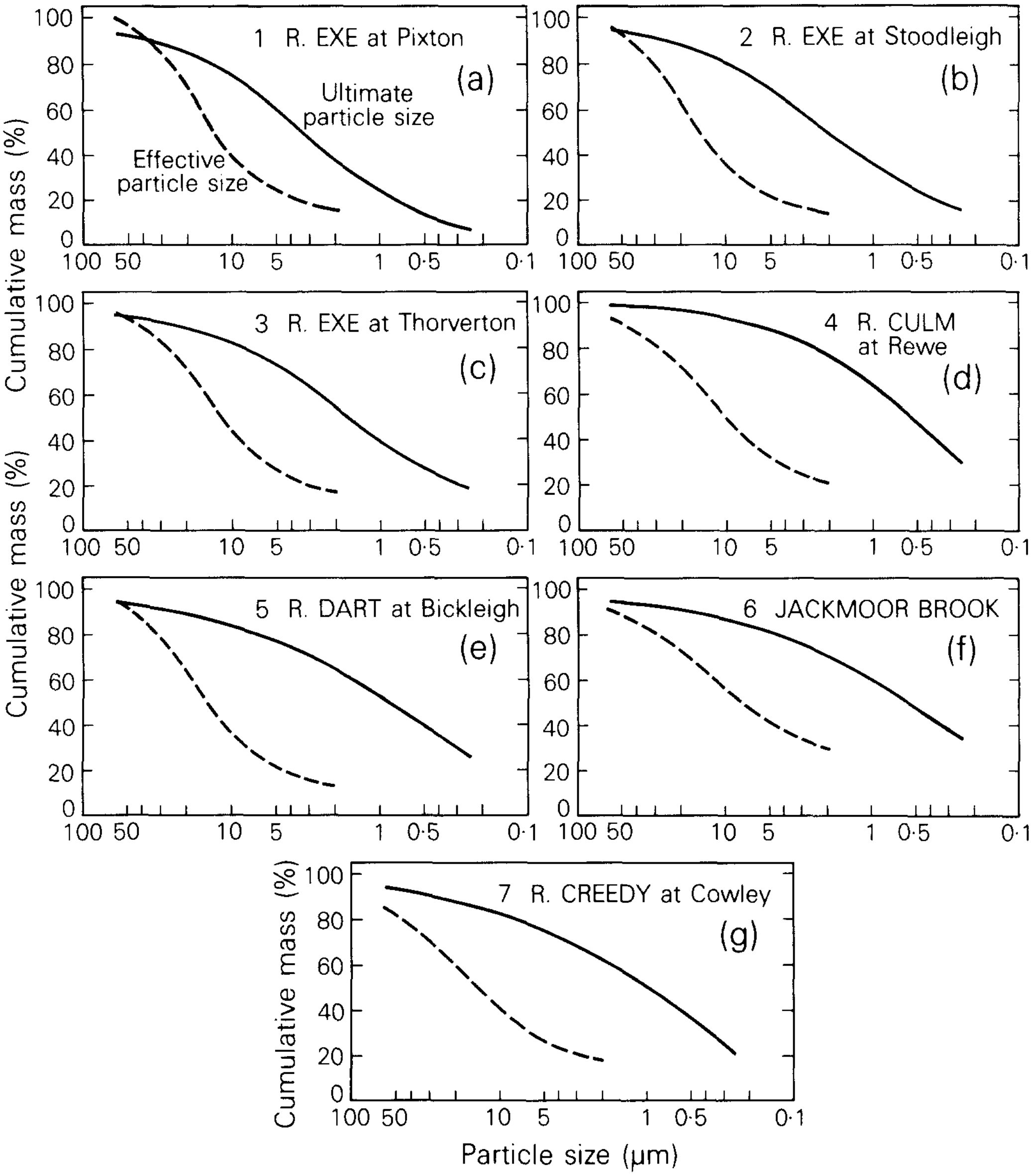

Fig. 17. A comparison of the ultimate and effective particle size distributions of suspended sediment for the individual measuring sites in the Exe basin.

indicate that approximately 28 percent of the annual load passing the upper station is deposited in the intervening reach. Comparison of the mean particle size composition of the upstream and downstream loads (Table 4) indicates that a large proportion of this loss is associated with the deposition of clay-sized particles rather than the coarser fractions. This may be accounted for by the fact that much of the clay is undoubtedly transported within larger aggregates and that these aggregates are deposited within the floodplain reach.

Conclusion

This review of existing knowledge of spatial and temporal variations in the particle size charac-

Table 4. Estimate of the particle size composition of the conveyance loss of suspended sediment between the gauging stations at Woodmill and Rewe based on a comparison of the magnitude and the grain size composition of suspended sediment loads at both sites (cf. Table 2).

Conveyance Loss	Particle size fraction				
	< 2 μm	2–6 μm	6–20 μm	20–63 μm	63 μm
Magnitude (t)	10.4	6.4	5.4	3.4	2.4
Proportion (%)	37	23	19	12	9

teristics of fluvial suspended sediment and of the potential contrasts between the effective and ultimate particle size distributions has emphasised the complexity of this aspect of fluvial dynamics. An improved knowledge of the particle size characteristics of suspended sediment is undoubtedly required in view of the fundamental significance of grain size characteristics to interactions between sediment and water quality and sediment-associated transport of nutrients and contaminants. In the past the hydrologist has been primarily concerned with measuring the *magnitude* of the sediment loads transported by rivers and such data were clearly appropriate for dealing with reservoir sedimentation and other problems reflecting the amount of sediment transported. Acceptance of the wider environmental significance of suspended sediment (cf. Golterman *et al.*, 1983) and of the enlarging interface with geochemical investigations underscores the need for increased attention to the physical and chemical properties of the sediment and more particularly its grain size characteristics.

Acknowledgements

The sediment measurements in the Exe basin reported in this paper were undertaken with the financial support of a Research Grant from the Natural Environment Research Council (DEW) and a Postgraduate Studentship frorm the Northern Ireland Department of Education (PWM). The assistance of South West Water in providing river flow data for the Exe basin and of local landowners in permitting access to sampling sites is gratefully acknowledged.

References

Allan, R. J., 1979. Sediment-related fluvial transmission of contaminants: some advances by 1979. Inland Waters Directorate, Environment Canada, Scientific Series No. 107.

Anttila, P. W., 1970. Sedimentation in Plum Creek subwatershed No. 4, Shelby County, North-Central Kentucky. US Geological Survey Water Supply Paper 1798 G.

Ball, J., 1939. Contributions to the geography of Egypt. Government Press, Cairo.

Brown, W. M. & J. R. Ritter, 1971. Sediment transport and turbidity in the Eel River basin, California. US Geological Survey Water Supply Paper 1986.

Carling, P. A., 1983. Particulate dynamics, dissolved and total load, in two small basins, northern Pennines, UK. Hyd. Sciences J. 28: 355–375.

Colby, B. R. & C. H. Hembree, 1955. Computations of total sediment discharge Niobrara River, near Cody, Nebraska. US Geological Survey Water Supply Paper 1357.

Dedkov, A. P. & V. T. Mozzherin, 1984. Eroziya i stok nanosov na zemle. Izdatelstvo Kazanskogo Universiteta.

Environment Canada, 1975. Sediment Data, Canadian Rivers, 1972. Inland Waters Directorate, Ottawa.

Fleming, G. & T. Poodle, 1970. Particle size of river sediments. J. Hydraul. Div. ASCE 96: 431–439.

Flint, R. F., 1972. Fluvial sediment in Hocking River subwatershed 1 (North Branch Hunters Run) Ohio. US Geological Survey Water Supply Paper 1798 I.

Forstner, U. & G. Wittmann, 1979. Metal pollution in the aquatic environment. Springer-Verlag, New York, 486 pp.

Foster, G. R., R. A. Young & W. H. Neibling, 1985. Sediment composition for nonpoint source pollution analyses. Trans. am. Soc. agric. Engrs. 28: 133–139, 146.

Fournier, F., 1960. Climat et érosion. Paris, Presses Universitaires de France.

Gibbs, R. J., 1977. Transport phases of transition metals in the Amazon and Yukon Rivers. Geol. Soc. am. Bull. 88: 829–843.

Golterman, H. L., P. G. Sly & R. L. Thomas, 1983. Study of the relationship between water quality and sediment transport. UNESCO Technical Paper in Hydrology no. 26.

Gong, S. & G. Xiong, 1980. The origin and transport of sediment of the Yellow River. Proceedings of the International Symposium on River Sedimentation, Beijing, March 1980. Beijing, Guanghua Press, 43–52.

Guy, H. P., 1969. Laboratory theory and methods for sediment analysis. US Geological Survey Techniques of Water Resources Investigation. Book 5, chapt. C1.

Hjulström, F., 1935. Studies of the morphological activity of rivers as illustrated by the River Fyris. Bull. geol. Inst. Univ. Uppsala 25: 221-527.

Horowitz, A. J., 1985. A primer on trace metal-sediment chemistry. US Geological Survey Water Supply Paper 2277.

Kennedy, V. C., 1964. Sediment transported by Georgia streams. US Geological Survey Water Supply Paper 1668.

Lal, R., 1976. Soil erosion problems on an alfisol in Western Nigeria and their control. International Institute of Tropical Agriculture Monograph no. 1.

Long, Y. & N. Qian, 1986. Erosion and transportation of sediment in the Yellow River basin. Int. J. Sediment Research 1: 2–38.

Malcolm, R. L. & V. C. Kennedy, 1970. Variation of cation exchange capacity and rate with particle size in stream sediment: J. Wat. Pollut. Cont. Fed. 2: 153–160.

Meade, R. H., 1985. Suspended sediment in the Amazon River and its tributaries in Brazil during 1982–84. US Geological Survey Open-File Report.

Meyer, L. D., G. R. Foster & M. J. M. Romkens, 1975. Source of soil eroded by water from upland slopes. In Present and prospective technology for predicting sediment yields and sources, US Dept. Agriculture Pub. ARS-S-40: 177–207.

Moore, J. W. & S. Ramamoorthy, 1984. Heavy metals in natural waters. Springer-Verlag, New York.

Mundorff, J. C., 1964. Fluvial sediment in Kiowa Creek basin, Colorado. US Geological Survey Water Supply Paper 1798 A.

Mundorff, J. C., 1966. Sedimentation in Brownell Creek subwatershed No. 1, Nebraska. US Geological Survey Water Supply Paper 1798 C.

Mundorff, J. C. & C. H. Scott, 1964. Fluvial sediment in the Lower Kansas River basin. Kansas State, Water Research Board Bulletin no. 7.

Nordin, C. F., 1963. A preliminary study of sediment transport parameters, Rio Puerco, near Bernado, New Mexico. US Geological Survey Prof. Paper 462 C.

Nouvelot, J. F., 1969. Mesure et étude des transports solides en suspension au Cameroun. Centre ORSTOM, Yaounde.

Olive, L. J. & W. A. Rieger, 1986. Low Australian sediment yields – a question of inefficient sediment delivery? In Drainage basin sediment delivery, IAHS Publication no. 159: 335–364.

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

Owen, M. W., 1976. Determination of the settling velocities of cohesive muds. Report no. IT 161, Hydraulics Research Station, Wallingford, UK.

Skvortsov, A. F., 1959. River suspensions and soils. Soviet soil Science 4: 409–416.

Soeharto, I., 1982. Supporting report on discharge and suspended sediment observations of Citarum River at Nanjung, Saguling and Palumbon. Institute of Hydraulic Engineering, Bandung.

Strakhov, N. M., 1967. Principles of lithogenesis. Oliver & Boyd, Edinburgh.

Sundborg, A., 1956. The river Klaralven. A study of fluvial processes. Geografiska Annaler 38: 127–316.

Sundborg, A., 1964. Euphrates Dam, Vol. 6, Sedimentation. Project Report to Euphrates Project Authority, Syrian Arab Republic.

Sundborg, A., 1986. Sedimantation processes. J. Water Resources (Iraq) 5: 728–754.

UNESCO, 1985. Recent developments in erosion and sediment yield studies. UNESCO Technical Document in Hydrology, UNESCO, Paris.

Vice, R. B., H. P. Guy & G. E. Ferguson, 1969. Sediment movement in an area of suburban highway construction, Scott Run basin, Fairfax County. US Geological Survey Water Supply Paper 1591 E.

Walker, P. H., K. D. Woodyer & J. Hutka, 1974. Particle-size measurements by Coulter Counter of very small deposits and low suspended sediment concentrations in streams. J. sedimentary Petrology 44: 673–679.

Walling, D. E., 1983. The sediment delivery problem. J. of Hydrol. 69: 209–237.

Walling, D. E., S. B. Bradley & C. P. Lambert, 1986. Conveyance losses of suspended sediment within a flood plain system. In Drainage basin sediment delivery, IAHS Publication no. 159: 119–131.

Walling, D. E. & P. Kane, 1984. Suspended sediment properties and their geomorphological significance. In T. P. Burt & D. E. Walling (eds.), Catchment Experiments in Fluvial Geomorphology. Geobooks, Norwich: 311–344.

Walling, D. E. & B. W. Webb, 1982. Sediment availability and the prediction of storm-period sediment yields. In Recent developments in the explanation and prediction of erosion and sediment yield, IAHS Publication no. 137: 327–337.

Ward, P. R. B., 1980. Sediment transport and a reservoir siltation formula for Zimbabwe-Rhodesia. The Civil Engineer in South Africa, Jan 1980: 9–15.

Young, R. A., 1980. Characteristics of eroded sediment. Trans. am. Soc. agric. Engrs. 19: 1071–1075.

Young, R. A. & C. A. Onstad, 1978. Characteristics of rill and inter-rill eroded soil. Trans. am. Soc. agric. Engrs. 21: 1126–1130.

Zhang, Q., N. Jiang & B. Lin, 1986. Environmental problems associated with sediment deposition in Guanting Reservoir. Int. J. of Sediment Research 1: 67–78.