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Particle size characteristics of fluvial suspended sediment

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ABSTRACT Although an increasing body of data has become available on the magnitude of suspended sediment yields under different environmental and climatic conditions, little attention has been given to the particle size characteristics of the sediment involved. There is a need for further work on the "effective" particle size of suspended sediment in transit, on the relationship between the particle size characteristics of suspended sediment and those of the source material, and on temporal variations in particle size. The growing awareness of the role of suspended sediment in the transport of nutrients and contaminants and as a non-point pollutant further underlines the importance of such information. The relationship between the particle size characteristics of source and sediment is investigated by considering data from a number of small drainage basins in the USA and from two small basins in Devon, England. These demonstrate the importance of soil type and catchment characteristics in controlling this relationship. Temporal variations in the particle size distribution of suspended sediment are considered by highlighting the varied evidence presented in existing studies and by considering in detail data from the two small drainage basins in Devon which exhibit markedly different responses.

INTRODUCTION

Recent expansion of river monitoring programmes has provided a growing body of information on suspended sediment yields and their variation according to climatic and environmental conditions (e.g. Walling & Kleo, 1979). Considerably less is known about the particle size characteristics of the sediment involved. Such data are sometimes included in data compilations, but few attempts have been made to study this facet of sediment yield in detail. Many sediment transport equations provide for a suspended load component of bed material transport, but it is generally accepted that the majority of the suspended load will consist of fine material (<62 μm) or wash load, eroded from within the drainage basin. This is effectively a non-capacity load, and is therefore not amenable to the application of simple transport equations, in order to elucidate particle size behaviour.

In looking in more detail at this topic, a distinction can be made between two themes which warrant further study. The first relates to the *mechanisms* of transport and deposition and must be concerned with the actual particle size distribution existing in the river. This has been termed the "effective" particle size by Ongley *et al.* (1981) and it may differ considerably from the particle size distribution obtained using traditional laboratory techniques. These generally involve removal of the organic fraction and chemical dispersion of the remaining mineral sediment. Recent work by the authors has indicated that aggregation may be extremely important under natural conditions and that this is closely controlled by the nature and magnitude of the organic fraction. The development of an improved understanding of sediment conveyance and deposition clearly necessitates investigation of the "effective" particle size distribution and factors controlling aggregation processes.

The second theme relates to the *nature* of the material transported as suspended sediment and in this case it is generally more convenient to focus on the ultimate particle size characteristics of the chemically dispersed mineral sediment since this provides an absolute standard for comparison. Within this theme there is a need for information on the typical size distribution of suspended sediment and the factors controlling inter-basin variations, the relationship between the particle size characteristics of the sediment and those of the source material, and the nature and extent of temporal variations in the particle size distribution.

Studies of "effective" particle size characteristics are heavily dependent upon the development of suitable techniques for obtaining representative measurements of sediment in transit. This poses considerable problems and is beyond the scope of this paper. Attention will be given to the second theme and, more particularly, to the relationship of the particle size of sediment and source material and to temporal variations in the particle size characteristics of suspended sediment.

The relevance of such information has been emphasized by the increasing awareness of the role of suspended sediment in the transport of nutrients and contaminants and as a non-point pollutant (e.g. Shear & Watson, 1977; USDA, 1975; Knisel, 1980) and is further demonstrated in Fig.1. Fig.1A illustrates the major importance of particle size in reflecting the mineralogy and surface chemistry of mineral sediment and Fig.1B provides an indication of the relationship of chemical activity to particle size by considering the specific surface area of various sediment sizes. Frere *et al.* (1975) have suggested typical specific surface areas of 200 m^2g^{-1} for clay, 40 m^2g^{-1} for silt and 0.5 m^2g^{-1} for sand. The potential impact of these two factors on sediment chemistry is shown in Fig.1C, D, and E which present typical differentiations of phosphorus, copper and pesticide concentrations in soils according to various size fractions. Assuming that such soils provide the major source of suspended sediment, it is clear that the particle size characteristics of the sediment will exert a major control on its phosphorus, copper and pesticide content.

THE RELATIONSHIP OF SEDIMENT TO SOURCE MATERIAL

Two major factors will influence the relationship between the

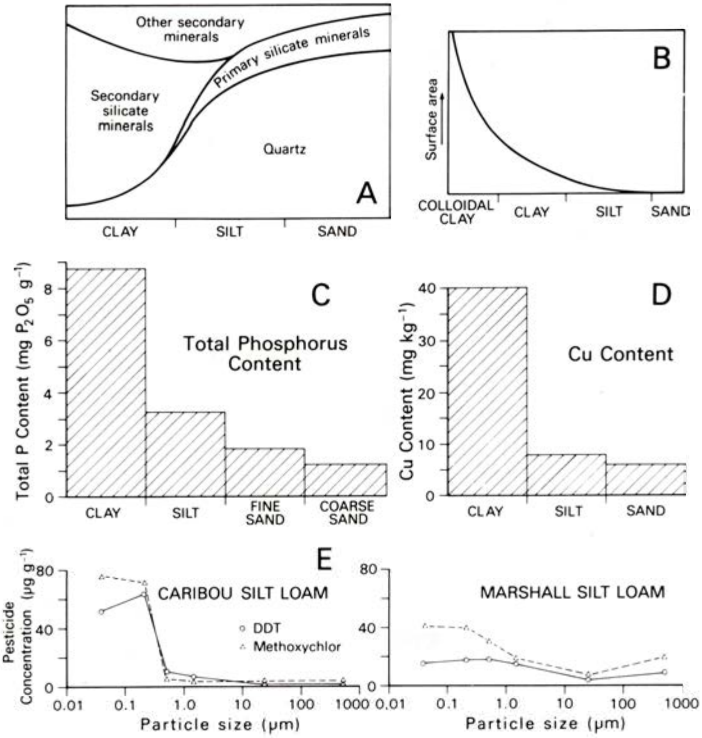

FIG.1 Schematic relationships between particle size and mineralogy and specific surface area of sediment particles (A,B), and typical distributions of total phosphorus, copper and pesticide in soils according to particle size fractions. (Based on Brady, 1974 (A,B); Williams & Saunders, 1956 (C); Le Riche & Weir, 1963 (D); and Pionke & Chesters, 1973 (E).).

particle size characteristics of suspended sediment and those of the source material. The first is the incidence of selective erosion and associated enrichment of fines which has been widely documented in soil erosion studies (e.g. Lal, 1976; Young & Onstad, 1978). The second is the preferential deposition of coarser material that could be expected to occur during the process of sediment delivery to the basin outlet. Both will result in the suspended sediment load of a river exhibiting a larger proportion of fine grained material than the source, although this simple situation will also be influenced by the "effective" particle size of the transported sediment. Large aggregates deposited during sediment delivery may be composed almost entirely of clay-sized particles.

It is difficult to distinguish the effects of selective erosion from preferential deposition during sediment delivery when studying sediment yield at the basin outlet and for convenience the two mechanisms can be considered together. Fig.2 provides an illustration of the potential contrasts in the particle size of suspended sediment and source material (chemically dispersed mineral fraction). It compares the proportions of clay, silt and sand in suspended sediment samples collected by the US Geological Survey in

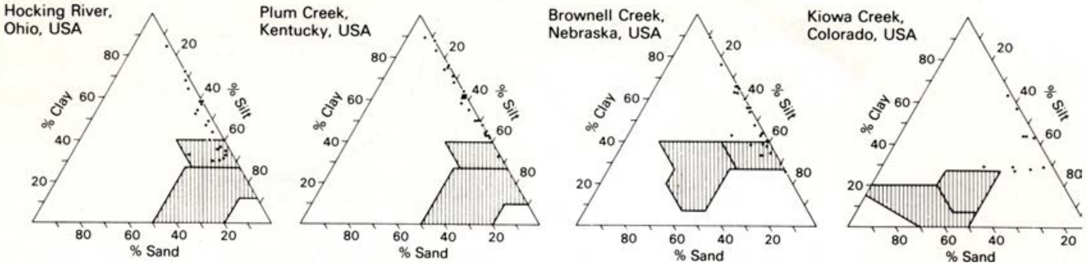

FIG.2 Comparison of the particle size composition of suspended sediment and soils for four US drainage basins. The textural classes of the dominant soils are denoted by shaded zones. (Based on data contained in Flint, 1972; Anttila, 1970; Mundorff, 1964, 1966.).

four sediment yield studies of small basins, with equivalent information on the soils based on their textural classification. This simple comparison involves a number of limitations; firstly, in the comparison of plotted points for the sediment with generalized fields representing the soils; secondly, in assuming that the soil data are representative of the actual sediment sources; and thirdly, in the equivalence of the particle size data, in that an upper limit of 62 μm has been employed for silt in the sediment analysis, whereas the soil classification employs a value of 50 μm. Notwithstanding these limitations, Fig.2 clearly demonstrates the tendency for suspended sediment to be enriched with clay-sized particles and depleted of silt- and sand-sized material when compared to its source. To some extent the precise composition of the sediment is influenced by the soil character, since the proportion of sand reflects 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.

All four basins illustrated in Fig.2 exhibit relatively high suspended sediment yields (Table 1), and certain tentative conclusions concerning the sediment delivery ratios of the basins may be drawn from the particle size information. If the effects of

TABLE 1 Characteristics of the four US drainage basins cited in Fig.2

Basin	*Area (km^2)*	*Mean annual sediment yield (t $km^{-2}year^{-1}$)*
Hocking River subwatershed 1 (Ohio)	*2.66*	*467*
Plum Creek subwatershed 4 (North-Central Kentucky)	*ca. 1.80*	*1250*
Brownell Creek subwatershed 1 (Nebraska)	*ca. 0.32*	*ca. 976*
Kiowa Creek subwatershed K79 (Colorado)	*ca. 2.56*	*ca. 200*

selective erosion in increasing the clay content of eroded material are ignored, and it is assumed that all clay-sized particles move through the conveyance system without deposition, then the delivery ratio for a particular basin may be calculated from the proportions of clay in the sediment (C_{sed}) and in the soil (C_{soil}) viz:

$$DR(\%) = C_{soil}(\%)/C_{sed}(\%) \qquad (1)$$

Taking a mean clay content for the soils in each catchment, the ratios range from 50% for Brownell Creek, through 40% for the Hocking River and 33% for Plum Creek, to 30% for Kiowa Creek. The effects of selective erosion in enhancing the clay content of eroded sediment would mean that these values of delivery ratio are minimum values, but, equally, the likelihood of clay being deposited within natural aggregates during the conveyance process would mean that the true values could be considerably lower. However, if the effects of these two opposing influences are assumed to balance, then the cited values may represent realistic estimates of the sediment delivery ratios of the basins concerned.

Bearing in mind the lack of precision in the estimates of the clay content of the soils, the contrasts in delivery ratio values between the catchments may be more apparent than real, but an attempt can be made to account for the differences encountered. These could be expected to reflect both the particle size characteristics and other properties of the source material, as well as the drainage basin characteristics. Thus the lower delivery ratios obtained for Kiowa Creek and Brownell Creek could be ascribed to the greater proportions of sand in the soils of these two basins. More information on the channel and basin conditions would be necessary to evaluate the influence of the drainage basin characteristics.

In an attempt to look in more detail at the influence of basin characteristics on values of sediment delivery ratios calculated in this way and therefore on the relationship between the particle size characteristics of sediment and source material, results from a study of two small basins in Devon, UK, undertaken by the authors, may be introduced.

The two basins of the River Dart (46 km^2) and the Jackmoor Brook (9.8 km^2) are within 5 km of each other, but exhibit a number of contrasts in their basin characteristics including geology and land use, the most significant of which is probably their relief (Fig.3). The Dart basin evidences steep dissected terrain, whereas the basin of the Jackmoor Brook is more lowland in character. Mean annual suspended sediment yields are estimated at 75 t $km^{-2} year^{-1}$ for the River Dart and 50 t $km^{-2} year^{-1}$ for the Jackmoor Brook.

Fig.4 illustrates typical particle size distributions of suspended sediment and source material (chemically dispersed mineral fraction) from these two basins. The size distributions of source material are relatively similar, except that the Jackmoor Brook evidences a higher proportion of fine clay (<0.5 μm), but the average size distributions of suspended sediment exhibit more significant contrasts. That for the Jackmoor Brook evidences considerably greater enrichment of fines and depletion of coarse particles. The delivery ratios calculated from the particle size data in accordance

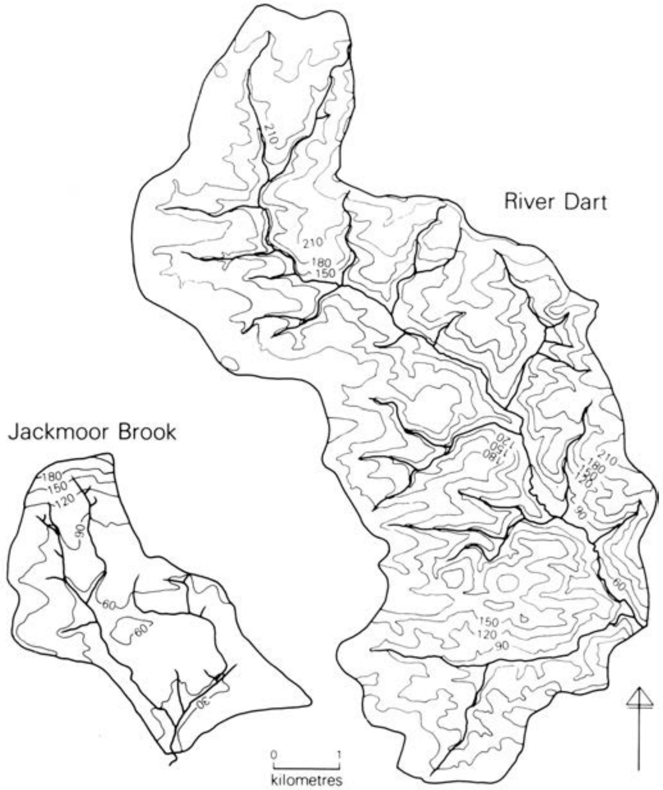

FIG.3 Relief of the River Dart and Jackmoor Brook basins (contours in m).

with equation (1), but using the proportion of fine clay (<0.5 µm) rather than the total clay fraction, are 70% and 85% for the Jackmoor Brook and River Dart respectively. Further detail on the enrichment and delivery ratios of individual particle size classes are provided in Fig.4. The contrasts in sediment delivery between the two catchments do not conform to the inverse relationship between sediment delivery ratio and basin area proposed by many workers (e.g. ASCE, 1975) and must be ascribed to the differences in relief between the two basins. The steep slopes and channels of the River Dart could be expected to afford a more efficient sediment delivery system than that of the Jackmoor Brook.

TEMPORAL VARIATION IN THE PARTICLE SIZE OF SUSPENDED SEDIMENT

A knowledge of temporal variations in the particle size of suspended sediment is important for analysing sediment-associated transport of nutrients and contaminants and sediment-water quality interactions. Traditionally, attempts have been made to relate such variations to water discharge or total concentrations since this in turn reflects energy conditions and transport capacity. However, considerable diversity exists in the precise form of relationships reported in the literature. For example, Doty & Carter (1965) report a positive

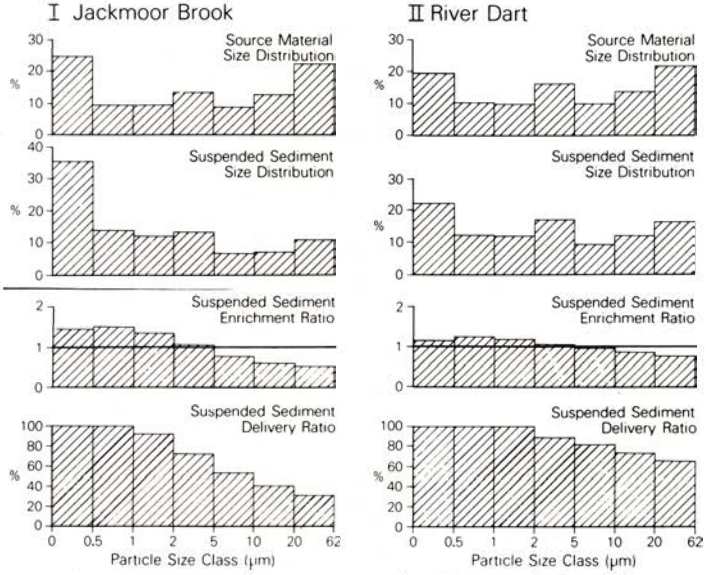

FIG.4 A comparison of typical particle size distributions of suspended sediment and source material for the River Dart and Jackmoor Brook basins. (Enrichment ratios are calculated as the ratio of the content of a particular size fraction in the sediment to that in the source material.).

relationship between proportion of coarse particles and sediment concentration and Brown & Ritter (1971) report a similar trend for a relationship with discharge, whereas Mundorff & Scott (1964) describe an increase in the proportion of fine material with increasing discharge. The latter trend would confound any attempt to relate the particle size characteristics to transport capacity, but is not surprising in view of the non-capacity nature of the wash load component of sediment transport.

Any explanation of temporal variations in the particle size of suspended sediment must consider the dynamics of erosion and sediment delivery operating throughout the entire basin, rather than hydraulic conditions in the channel. Thus, one could visualize a situation embodying the variable source area model of storm runoff production (cf. Kirkby, 1978), wherein the expansion of the storm runoff contributing area into zones of finer source material or into zones not already depleted of fines by recent storm events could produce finer suspended sediment and therefore a positive relationship between the proportion of fines and stream discharge. Similarly, contrasts in the particle size characteristics of recently deposited sediment remobilized during the rising stages of a flood event may differ considerably from those of sediment delivered to the channel from the slopes during subsequent stages of the flood, and therefore introduce hysteresis into the relationship between particle size and discharge. The nature of the "effective" size distribution could also add further complexity to the apparent relationship between the particle size characteristics of primary mineral particles and discharge. Furthermore, Skvortsov (1959) and Ongley *et al.* (1981) have described seasonal variations in particle size characteristics related to changing source areas and largely independent of discharge.

Information obtained from measurements of suspended sediment transport in the River Dart and the Jackmoor Brook (Fig.3) can be introduced to further illustrate the nature of temporal variations in the particle size of suspended sediments. Again the particle size data relate to the chemically dispersed mineral fraction. Bulk suspended sediment samples have been collected from both drainage basins during a wide range of flow conditions over a period of several years. No clear evidence of seasonal variation in particle size characteristics exists. This contrasts with the findings of Ongley *et al* (1981) and may be related to the lack of a marked seasonal distinction between spring melt and normal rainfall-produced flood conditions.

Graphical relationships between the percentage finer than 2 μm and 10 μm and both discharge and sediment concentration for the two basins are presented in Fig.5. A contrast between the response of the River Dart and the Jackmoor Brook is immediately apparent, in that the latter evidences a positive relationship between the proportion of fines and both discharge and sediment concentration, whereas the former evidences a relatively constant proportion of fines over a wide range of discharge and concentration. The contrast in behaviour between the two basins is also apparent at the level of the individual storm event (Fig.6). Here the River Dart again demonstrates a relatively constant proportion of fines during the two events depicted, whereas the percentage finer than 2 μm tends to increase through the hydrograph for the same events on the Jackmoor Brook.

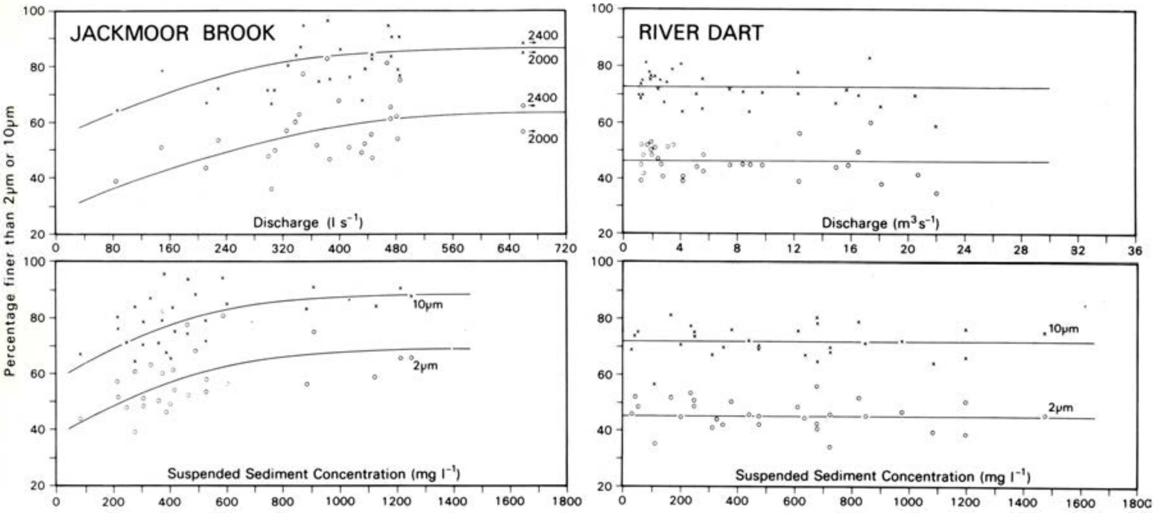

FIG.5 Relationships between the particle size composition of suspended sediment and sediment concentration and discharge for the River Dart and Jackmoor Brook basins.

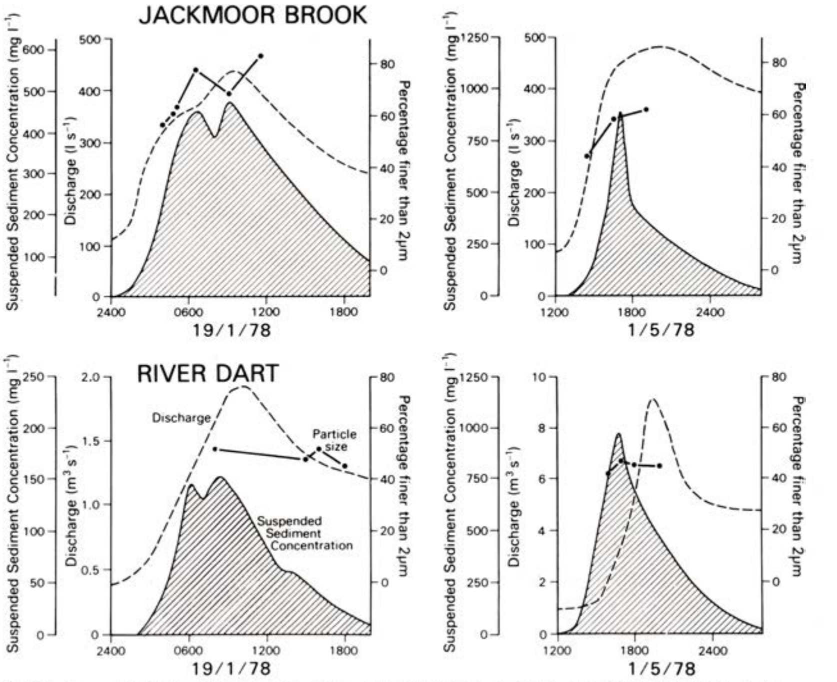

FIG.6 Variation of the particle size composition of suspended sediment during storm runoff events in the River Dart and Jackmoor Brook basins.

Detailed investigations will be required to provide a conclusive explanation of this contrast in response between the River Dart and the Jackmoor Brook, but some suggestions may be advanced. These relate to the interaction of a variable source area contributing to storm runoff and sediment delivery conditions. Burns (1979) has proposed that the efficiency of sediment delivery will tend to decrease with an increase in the distance between the source and the stream channel. In the basin of the Jackmoor Brook, increased discharges will commonly be associated with an expanded contributing area and the relief of the basin is such that this may incorporate areas with relatively low slope angles and therefore reduced sediment delivery efficiency. This in turn would result in an increased loss of coarse particles and therefore an increasing percentage of fines. The relief of the Dart basin, in contrast, is such that the expanding contributing area will in many instances embrace steeper slopes and will therefore not exhibit any overall reduction in the efficiency of sediment delivery.

An improved understanding of the particle size characteristics of suspended sediment clearly necessitates an appreciation of the detailed interaction of storm runoff generation and the processes of erosion and sediment delivery. Whereas considerable effort has been directed towards the development of realistic models of on-site erosion (e.g. Morgan, 1980) much less is known about the processes of sediment delivery or conveyance interposed between on-site erosion and sediment yield at the catchment outlet.

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